SODIUM-NaK ENGINEERING HANDBOOK

Volume III

SODIUM-NaK ENGINEERING HANDBOOK

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SODIUM-NaK ENGINEERING HANDBOOK

Volume III

Sodium Systems, Safety, Handling, and Instrumentation

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Director, Engineering
Liquid Metal Engineering Center

Prepared under the auspices of the
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Preface

Since publication of the *Sodium–NaK Supplement* to the *Liquid Metals Handbook* in 1955, liquid metal technology has expanded in depth, in spectra, and in the size of equipment that has been developed. Even so, further expansion is needed to satisfy the requirements of the Liquid Metals Fast Breeder Program. Reliable components, with engineering capabilities up to an order of magnitude greater than those developed to date, are required, an expansion of capability beyond the mere extrapolation of laboratory devices.

The capability increase now demanded renders the admonition contained in the Foreword to the 1955 supplement that only test will demonstrate satisfactory performance of a component constructed for an advanced technology as vital now as it was in 1955. Testing alone can demonstrate that all facets of sound engineering have been incorporated into the design and manufacture of the final product.

Through the technology described in this *Sodium–NaK Engineering Handbook,* it is hoped that designers will have a basis for freeing their imaginations from the bonds of small-scale experience and create systems and components which incorporate the lessons of the past into the industrial requirements of the future.

Robert W. Dickinson, Director
Liquid Metal Engineering Center

Editor's Preface

This handbook, comprised of five volumes, is intended for use by present and future designers in the Liquid Metals Fast Breeder Reactor (LMFBR) Program and by the engineering and scientific community performing other type investigation and experimentation requiring high-temperature sodium and NaK technology. The arrangement of subject matter progresses from a technological discussion of sodium and sodium—potassium alloy (NaK) to discussions of various categories and uses of hardware in sodium and NaK systems.

Emphasis is placed on sodium and NaK as heat-transport media; other applications of these metals are treated in the final volume. Several thousand documents were reviewed in accumulating and compiling information; those believed to be most valuable are cited as references.

Sufficient detail is included for basic understanding of sodium and NaK technology and of technical aspects of sodium and NaK components and instrument systems. Information presented is considered adequate for use in feasibility studies and conceptual design, sizing components and systems, developing preliminary component and system descriptions, identifying technological limitations and problem areas, and defining basic constraints and parameters. Preparation of a finished design, however, will require more extensive research into the reference literature.

The handbook includes the work of some 50 contributors; the efforts of each were coordinated to facilitate an end product with a common theme, each part consistent in perspective with the whole, but considerable individual license was permitted in presentation of that material. Therefore each volume and chapter reflects the style of its author and, to this extent, differs from other volumes and chapters.

In many instances, the data from various sources were in conflict and the authors had no basis for selecting those which were most valid. In such instances explanations and references are supplied in sufficient detail to permit the reader to perform independent research. Attention is invited to the existence of the Liquid Metals Information Center, located at the Liquid Metal Engineering Center, as a continuing source of current information.

O. J. Foust

Note to Reader

The reader is advised that, although the publication of this volume is in the late 1970's, the material in it was written in 1968. Although most of the information is still valid and useful, on certain topics the material is appreciably out of date. Therefore more recent publications should be consulted for the current status of some topics.

Chapter 4 Instruments

The following additional references were supplied by the author, K. A. Davis:

1. K. A. Davis, B. E. Fischer, F. L. Fletcher, G. E. Turner, and G. J. Twa, Development and Testing of Instrumentation Sensors for Sodium Coolant Systems, International Conference on Liquid Metal Technology in Energy Production, Champion, Pennsylvania, May 3–6, 1976, ERDA Report CONF-760503-P2, pp. 746-754, November 1976.
2. C. R. F. Smith, W. J. Richardson, and J. T. Holmes, On-Line Sodium and Cover Gas Purity Monitors as Operating Tools at EBR-II, International Conference on Liquid Metal Technology in Energy Production, Champion, Pennsylvania, May 3–6, 1976, ERDA Report CONF-760503-P2, pp. 770-776, November 1976.
3. R. Hans, W. Haubold, J. Jung, and H.-J. Weiss, The Present State of Experiments Development and Installation of the LMFBR Sodium Impurity Monitoring Devices, paper presented at International Atomic Energy Agency Specialists Meeting on In-Core and Primary Circuit Instrumentation of LMFB Reactors, Risley, England, January 27–29, 1976.

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Chapter 1

Sodium and NaK Systems

Principal Authors: K. L. ADLER, J. J. AULETA, AND H. O. CHARNOCK

Contributing Authors: J. H. CAMPO, J. M. HOWARD, H. A. ROSS-CLUNIS, AND L. GOODMAN

1-1 INTRODUCTION

Other chapters of this handbook are concerned with the properties and behavior of the liquid metals sodium and NaK and with the design, fabrication, operation, and maintenance of components and facilities that employ these materials. This chapter discusses the design of systems in which sodium or NaK is used as a heat-transfer medium and describes how the information presented in other chapters is integrated and applied in the design of a liquid-metal-heat-transport system. Other applications, such as those in which the liquid metal is used as a thermal or electrical conductor or as a thermodynamic working fluid, will be taken up in Vol. V, Chap. 5.

This chapter emphasizes the known problem areas and critical requirements in the design of liquid-metal systems, particularly sodium-cooled fast breeder reactor systems. The system components are discussed in detail elsewhere in this handbook. Purification systems and storage are covered in Vol. V, Chap. 1, and Vol. III, Chap. 3, and are therefore not discussed extensively here.

1-2 SYSTEM DESIGN CRITERIA AND CONSIDERATIONS

1-2.1 *Use of Liquid Metals for Reactor Systems*

Liquid metals are considered for heat-transfer media in reactor systems for a number of reasons [1]. The liquid metals under consideration, sodium and NaK, are relatively noncorrosive and compatible with normal materials of construction such as austenitic and ferritic steels (Vol. V, Chap. 2) [2,3]. Since liquid metals can operate at high temperatures under low pressure, low system design pressure and high pressure and temperature of steam-turbine-design conditions can be used. The normal boiling point of sodium is 1621°F, which far exceeds anticipated future steam operating temperatures.

The high thermal conductivity of sodium results in high heat-transfer coefficients and minimizes heat-transfer surfaces. Sodium has a relatively high heat capacity and is relatively inexpensive.

Liquid metals are highly resistant to radiation and thermal damage. However, liquid metals are chemically very reactive with many elements found in the normal system environment. Safety precautions in design and operation must be carefully observed. In particular, hot sodium or NaK will react violently with water or even dry air (Vol. III, Chap. 2) [4].

Both sodium and potassium become radioactive when exposed to a neutron flux (Vol. I, Chap. 1) [5]. As a result, liquid metals that have passed through a nuclear reactor must be treated as radioactive materials.

NaK is a liquid at room temperature and will spread throughout an area in the event of a leak, whereas sodium will tend to solidify on cold surfaces. NaK will spontaneously ignite in air much more easily than sodium. For these reasons, NaK is considered somewhat more hazardous to handle in the event of leakage.

In addition, the solidification of sodium at ambient temperature may allow loop repairs and maintenance without draining the system, but NaK systems generally require drainage [6].

Since sodium is a solid at room temperature, preheating equipment is used in the sodium systems to permit filling and initial operation. Over a range of compositions, including the eutectic, NaK alloys are liquid at room temperature and generally do not require preheating (Vol. I, Chap. 1).

1-2.2 *Main Heat-Transfer System*

The main heat-transfer system for a power reactor removes the heat generated in the nuclear reactor and transfers it to the steam system.

Types of main heat-transfer systems can be many and varied, depending on the use of the reactor. The major factors in determining the selection of specific systems are safety, application, and economics. In general, main sodium heat-transfer systems can be subdivided into single-and double-loop systems.

In the single-loop system (Fig. 1.1) [7] the main primary sodium heat-transfer system transfers its heat directly to the thermodynamic working fluid used in the power-conversion portion of the plant. In the double-loop system (Fig. 1.2)[7],

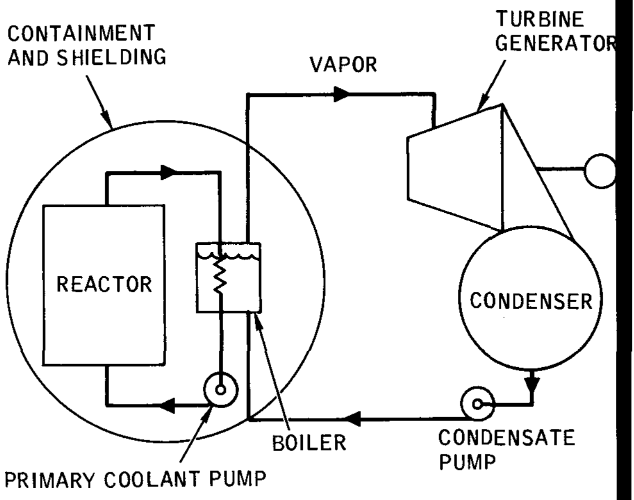

Fig. 1.1 Indirect-cycle liquid-metal heat-transport system without intermediate loop. (From J.G. Yevick (Ed.), *Fast Reactor Technology:Plant Design*, p. 122, The M.I.T. Press, Cambridge, Mass., 1967.)

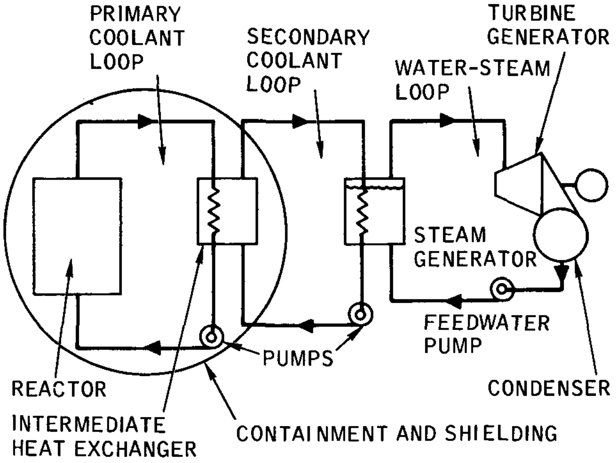

Fig. 1.2 Indirect-cycle liquid-metal heat-transport system with intermediate loop. (From J.G. Yevick (Ed.), *Fast Reactor Technology:Plant Design*, p. 123, The M.I.T. Press, Cambridge, Mass., 1967.)

the main primary sodium heat-transfer system transfers its heat to a main secondary, or intermediate, heat-transfer system , which in turn transfers the heat to the thermodynamic working fluid. Basically, the double-loop system is used in power-plant reactor systems as a safety requirement: Should a water or steam leak occur in the steam generator, the product of the sodium-water reaction (Vol. II, Chap. 4) will be nonradioactive, and no radioactive hazards will be encountered in the disposal of the reaction products. For reasons of plant safety and flexibility, the double-loop system is often used, even though steam is not the ultimate heat sink. For example, in certain test reactor plants, heat from the main primary sodium is transferred to a secondary sodium system, which, in turn, rejects the heat to the atmosphere through an air-cooled heat exchanger. The secondary loop ensures that, if leakage occurs in the air-cooled heat exchanger or external piping systems, only nonradioactive sodium will be dispersed to the atmosphere. A nonradioactive secondary heat-transfer system simplifies design since the heat-dump area need not be shielded.

The main heat-transfer systems can be designed as piped or pot systems. In the piped concept (Fig. 1.3) [8] the primary sodium is removed from the reactor vessel through a piping system and intermediate heat exchanger and back to the reactor through a cold-leg piping system. In the pot concept (Fig. 1.4) all primary sodium heat-transfer-system components are located in a large sodium-filled tank; the secondary sodium is passed through an intermediate heat exchanger (IHX) that is immersed in the primary vessel [9]. The amount of piping required for the primary sodium in the pot system is considerably less than in the piped system, which may require a somewhat

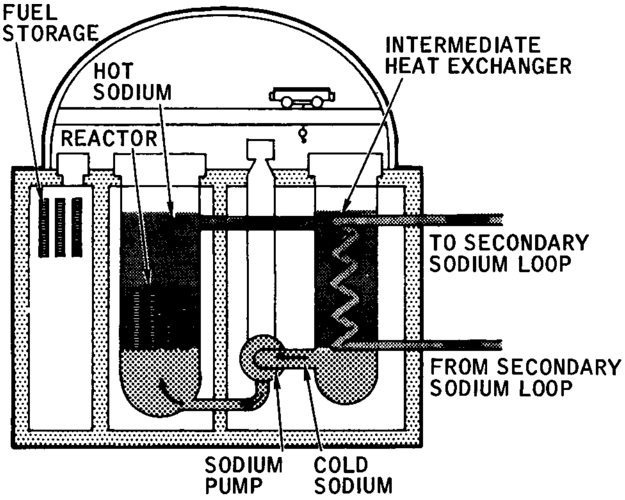

Fig. 1.3 Piped arrangement of primary heat-transport system. [From M. Shaw and M. Whitman, *Science and Technology*, No. 75: 31 (March 1968).]

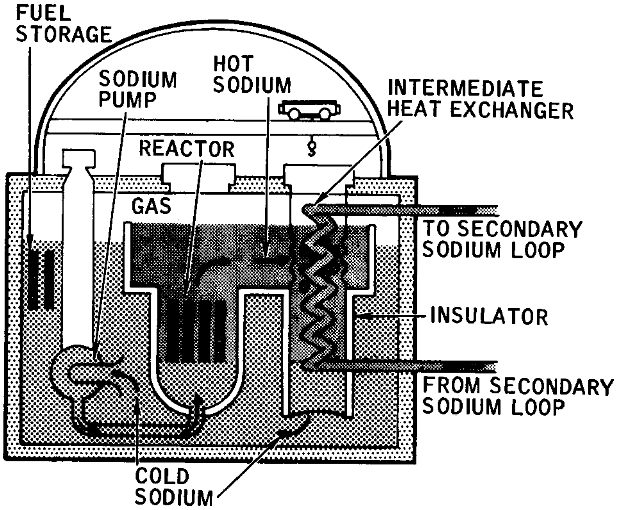

Fig. 1.4 Pot arrangement of primary heat-transport system. [From M. Shaw and M. Whitman, *Science and Technology*, No. 75: 31 (March 1968).]

larger reactor building and higher costs of primary sodium piping. The piped system, however, has advantages in maintainability, since primary-system components are accessible during shutdown, and in cost, since the support structure for the reactor vessel is simplified [10].

The pot system requires a larger reactor vessel, and thus a higher reactor-vessel cost. Its inherent thermal capacity minimizes thermal transients during malfunction. Pumping power is lower with this system, but there is an engineering problem of protecting the heat-transfer-system parts (pumps and heat exchangers) from excessive activation due to neutron radiation. Some pot-system layout could render fuel handling difficult or more expensive [8].

Selection of the basic system has motivated complex engineering trade studies for analyzing the safety, engineering, and economic factors in volved [10]. The pot system has been chosen for the Dounreay Fast Reactor (DFR), Experimental Breeder Reactor No.I (EBR-I), and Experimental Breeder Reactor No. II (EBR-II). The piped system has been chosen for the Enrico Fermi Atomic Power Plant (EFAPP), Breeder Reactor-5 (BR-5), and BN-350. It is not yet clear whether either concept is superior for all applications. These trade studies are performed at system and component levels. The results of one must be closely interrelated with the other.

(a) *Establishing Basic System Parameters*. The primary reactor system selected determines the economic and design criteria to be used. The criteria for evaluation and design of a test facility are considerably different from those for a nuclear power-generating station.

The main objective of the test facility is to obtain maximum experimental data with minimum capital and operating costs. The safety and reliability criteria are limited to an operating life varying from 5 to 10 years. Special design features and instrumentation are dictated by the test program.

The main objective of the nuclear power plant is to generate electricity at a minimum energy cost. Safety, reliability, and high availability are of primary importance in obtaining this minimum energy cost during the 20- to 30-year life of the plant. The design of the plant is dictated by minimum and simplified maintenance requirements and must maximize thermal efficiency while minimizing capital and operating cost.

At the inception of the test-facility study, the interested agency establishes the test goals, requirements, site, schedules, budgets, and expected termination date. In case of the nuclear power station, the interested utility establishes, by economic and engineering studies, many of the requirements for the plant. Among these are the following basic requirements:

1. Rated and maximum power capability based on the projected electric-system demand.
2. Expected plant-capacity factors during the planned operating life.
3. Guaranteed requirements as to fuel-cycle and inventory costs, plant start-up date, plant thermal efficiency, start-up schedule, plant availability, etc.
4. Plant site and yearly cooling-water temperatures.
5. Loading and unloading requirements and expected number of cycles.
6. Economic factors.

Trade studies are made by the architect and engineering firm or by the manufacturers of the reactor or its major components to determine the system design which will meet the requirements imposed by the utility and which is consistent with the existing safety and technical limitations. System trade studies are made to establish the following design features:

1. Turbine type, speed, and last-stage bucket length.

2. Steam-cycle configuration, steam conditions, and feedwater temperature.
3. Reactor outlet temperature.
4. Reactor ΔT and secondary-system ΔT combination.
5. IHX outlet sodium temperature.
6. Steam-generator type and temperature differences.
7. Number of heat-transfer loops and arrangement (pot vs. piped).
8. Sodium and steam velocities and pressure drops.
9. Maximum fuel burnup, refueling shutdowns, and fuel cycle.
10. Reactor core height and configuration.
11. Reactor, IHX, and steam-generator thermal requirements and net plant efficiency.
12. Heat losses and pumping requirements.

Close integration between the utility, the architect and engineering firm, and the manufacturer of the reactor and major equipment must exist to obtain meaningful trade studies conducive to a successful design.

(b) *Establishing the Major Component Designs* [11]. Component trade studies are made in parallel with the system economic evaluations to establish the following design features:

1. Reactor-vessel configuration.
2. Reactor fuel handling and refueling.
3. Reactor flow direction and distribution.
4. Reactor power density.
5. Reactor core height and configuration.
6. IXH configuration, sodium velocities, pressure drops, and heat-transfer areas.
7. Evaporator, superheater, and reheater configuration; sodium and steam velocities; pressure drops; and heat-transfer areas.
8. Type and location of pumps and drive arrangement.
9. Main pipe sizes, arrangements, materials, insulation, and pressure drops.
10. Control- and stop-valve sizes and pressure drops.
11. Reactor containments and building arrangement.
12. Condenser type and cooling-water cycle.

Close integration between the component and the system trade studies must exist for a successful plant design.

(c) *Safety, Technology and Operational Limitations* [11]. The design features and parameters established during the progress of the trade studies are limited by such safety, technological,and operational boundaries as the following:

1. Maximim fuel pin center and cladding temperatures.
2. Maximum reactor outlet temperature.
3. Maximum steady-state temperature gradients.
4. Maximum rates of pressure and temperature changes.
5. Maximum number of pressure and temperature cycles.
6. Maximum pressures and temperature in the system.
7. Maximum and minimum control reactivity rates.
8. Maximum excess reactivity required.
9. Maximum flow velocities.
10. Criteria for pipe-rupture accident.
11. Loss of pumping-power accidents.
12. Normal load reductions.
13. Step load reductions.
14. Emergency turbine-generator tripout from 100% rated load.
15. Spurious reactor trips due to equipment malfunctions or operator error.
16. Start-up and shutdown sequences.
17. Accidents with single control-rod insertion.
18. Reactor trip without reduction of sodium flow.
19. Loss of primary and/or secondary sodium flow.

a. One primary loop of three (example).
b. Two primary loops of three (example).
c. Two secondary loops of three while primary flow continues (example).
d. Simultaneous loss of primary and secondary loop flow.

20. Accidents with control-rod withdrawal.

a. One rod, initially at rated power.
b. One rod, hot restart.
c. One rod, cold restart.
d. Bank of rods, initially at full power.

21. Containment of the design base accident (DBA).

22. Provisions for removal of reactor decay heat.

(d) *Decay-Heat-Removal Concept.* Once the basic heat cycle for the plant has been optimized and the thermal power of the reactor has been established, the number of loops required for the plant can be determined. A reactor plant must include as a minimum one main heat-transfer loop and also means of removing decay heat. Decay heat can be removed with a specific decay heat loop, auxiliary (pony) motor pump drives, or natural circulation.

In small plants a design could consist of one main loop and a small loop capable of removing heat. For large plants, two, three, or more equal size loops are generally provided. At least two loops must be in use during power operation. Should only one loop be operable the plant is shut down immediately.

Unless an emergency power supply is guaranteed, the heat-transport system should be designed to ensure the removal of decay heat by natural circulation due to the difference in density of the two columns of liquid metal (hot leg and cold leg) comprising the heat-transport loop. If the relative elevations of the reactor, IHX, and steam generator and the system pressure drops are carefully selected, the natural-circulation decay heat can be removed under a given thermal driving head [12, 13].

The selection of the number of loops results from a detailed study of overall economics, safety, plant availability, failure probability, size of commercially available components, plant layout, total flow, and allowable pressure drop and velocities [7].

(e) *Selecting Flow Velocities.* After design parameters and number of loops have been established, sodium flow velocities and pressure drops can be determined. The sizing of the piping and components requires an economic balance between capital cost of the equipment, pumping cost, and reliability.

The following range of flow velocities is generally used in current practice in the design of sodium piping systems:

1. In a small pipe, 4 in. and less in diameter, velocities may range from 4 to 8 ft/sec.
2. In piping from 4 to 16 in. in diameter, economic designs permit velocities up to 15 ft/sec.
3. In piping 18 in. and larger in diameter, pressure drops are reasonable for velocities up to 20 ft/sec.

Velocities above 20 to 25 ft/sec, even in large piping, are normally not used without detailed study for the specific application. At high temperatures and high velocities, material-corrosion and mass-transfer effects are accelerated (Vol. V, Chap. 2) [14]. Figure 1.5 is a typical plot of corrosion effects in stainless or carbon steels as a function of flow velocity and oxygen content in flowing sodium. High velocities can also cause flow-induced vibrations that could damage piping.

Since velocities in the reactor core and control valves may be higher for

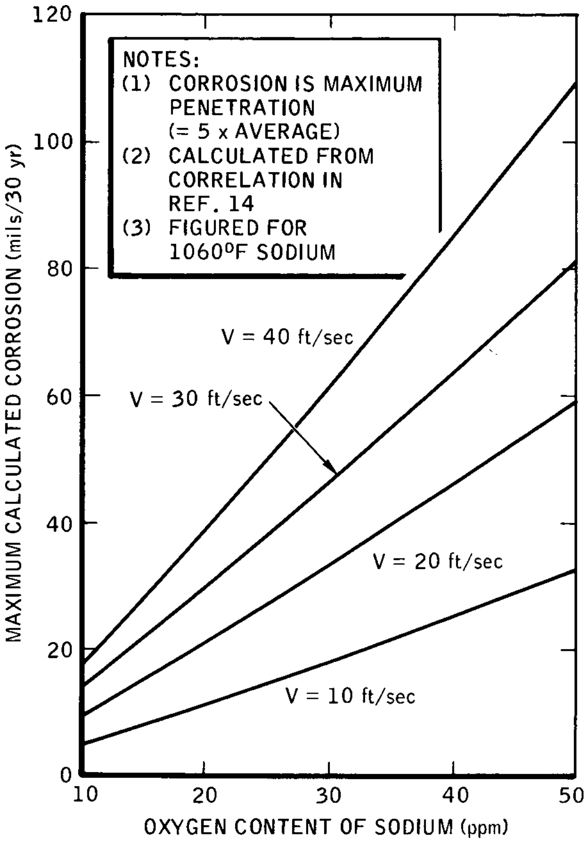

Fig. 1.5 Corrosion of steel as a function of sodium velocity and oxygen content (30-year plant life).

other reasons, they are provided for in the design by detailed analysis and test. In headers, where flow distribution is an important consideration, low velocities are utilized, or orificing arrangements are provided to ensure proper distribution between units. Two or more large orifices in series can be used to perform the function of a single smaller one to avoid orifice cavitation [15].

(f) *Pump Location.* Main primary sodium pumps can be installed in the hot sodium leaving the reactor or in the relatively cool sodium leaving the intermediate heat exchanger. The pump location requires an economic evaluation based on the following considerations. If the pump is placed in the hot coolant leg, the level control of a free-surface mechanical pump is less difficult. If low velocities are used in the pump-suction lines, problems of pump suction, pressure drop, and pump cavitation are reduced. Location of the pump in the hot leg improves flow distribution when natural-convection decay removal is a design objective.

If the pump is located in the cold leg, the pump cost may be reduced. This reduction in cost must be evaluated against the additional complexity of the level control system, problems in establishing sufficient pump-suction pressure, and decay-heat-removal capability by natural convection.

(g) *Diagrams.* After the design parameters have been established by the evaluation studies, flow diagrams are prepared for the main heat-transfer system. These diagrams include: (1) a process diagram that shows process-design information such as mass flows, temperatures, pressures, and pipeline sizes for the system; (2) a process and instrumentation diagram, that shows all details, including vent, drain, fill, and other connections, all instrumentation, valving and other components required in the heat-transfer system; and (3) an elevation diagram of the various major components to determine locations for vents and drains, to provide sufficient information to calculate pressure on the various components, and to establish capability for removing decay heat. This elevation diagram is developed in conjunction with the plant-layout drawings.

1-2.3 *Auxiliary Systems*

Liquid-metal heat-transfer systems require a number of auxiliary systems for operation [7,9]. The most important of these auxiliary systems are discussed in this section.

(a) *Sodium Service Systems.* The sodium service systems provide three basic functions: (1) receive, store, and process the coolant for the main heat-transfer system (Vol. III, Chap. 3); (2) provide for purification of the coolant (Vol. V, Chap. 1) and (3) provide for monitoring the coolant with respect to possible deleterious contaminants (Vol. III, Chap. 3) [16].

(1) *Storage System.* Normally the sodium storage systems are separated into two completely isolated systems: one for the radioactive primary coolant system and the other for the nonradioactive secondary coolant system.

In certain systems some part of the primary storage system is connected to the reactor where a continuous or an intermittent overflow tank accommodates fluctuations in sodium level [6]. These tanks are designed to the same code and pressure requirements as the reactor vessel when connected directly to the reactor during operation. For economy, such overflow tanks or equipment may be separated from the dead storage tankage, and thus the dead storage tanks can be designed to less stringent requirements.

Some part of the storage system may be available for emergency transfer of sodium to the reactor during reactor operations. The sodium is in storage at operating temperature with preheated fill lines. The dead storage tanks can be divided into hot and cold storage portions for economic reasons and can be located outside the reactor containment building to reduce building cost.

Primary sodium storage facilities and other primary sodium service systems are generally installed in inert-gas-filled cells for protection from radioactive sodium fire in the event of leakage (Vol. III, Chap.3) [17].

(2) *Distribution System.* Sodium service systems normally include small liquid-metal pumps that are used (1) to supplement the main heat-transfer pumps when pressure is not sufficient to operate purification and monitoring equipment; (2) to transfer sodium to and from the storage facilities; (3) to automatically make up sodium to the heat-transfer systems; and (4) to provide an emergency supply of hot sodium to the main heat-transfer systems.

Electromagnetic pumps are normally used for the sodium service systems [6]. These pumps are small, and operation is intermittent. Linear induction, conduction, and helical-rotor-type pumps are available for this service (Vol. IV, Chap. 1) [18]. Hermetically sealed canned rotor pumps of the centrifugal type are also available and can be considered for this application [19, 20].

Nozzles are placed on top of the sodium storage tanks to avoid the possibility of tank drainage should the nozzles or piping leak. Dip legs are used for pump-out lines. The result is an inverted syphon. Provision must be made for priming the pumps. In addition, a syphon breaker may be required to assure that the tank will not syphon if the pipe fails. The service pumps and piping systems must provide adequate net positive suction head to assure proper pump operation without cavitation. The piping configuration must provide complete drainage.

For the design of the sodium-service system, maintenance and access must be considered since these systems become radioactive during operation. The components are installed in shielded vaults and are operated remotely. For critical service, redundant equipment is provided in separated shielded vaults to permit maintenance.

For isolation during maintenance, small pipe lines are provided with means to freeze the sodium in a section of the pipe. The frozen-sodium plug acts as a positive means of shutoff to supplement closed valves [6].

(3) *Sodium Purification System.* The sodium purification system (Chap. 6) removes impurities from the sodium in th heat-transfer systems and thus controls corrosion and mass-transport phenomena. The presence of undesirable impurities

can also be detected, and guidance in operation of the sodium purification system is thus available.

Pure sodium is relatively compatible with normal construction materials in the sodium heat-transfer systems (primarily carbon steel, alloy steel, stainless steel, and hard-facing alloys). However, certain contaminants, notably oxygen, even in trace quantities, can render the sodium active and precipitate deleterious attack (Vol. V, Chaps. 1 and 3) [21]. Oxygen content should be kept as low as practical and for high temperature sodium certainly below about 10 ppm. An O_2 increase from 12 to 50 ppm resulted in a fourfold increase in corrosion in one test series [14].

Carbon contamination in the sodium is of concern because carbon transfer can occur from ferritic to austenitic steels, from steel to refractory metals, and from the hot to the cold end of single metal systems [22]. Decarburization reduces the strength of steels, and carburization embrittles steel and refractory metals. This is of particular concern in thin metal sections such as fuel cladding or bellows [23].

One basic piece of equipment for the sodium purification systems is the cold trap. Sodium oxide, sodium hydride, and other miscellaneous contaminants in sodium become quite insoluble at temperatures approaching the melting point of sodium. Thus, when the sodium passes through a cold zone, many of the deleterious contaminants precipitate out, and their concentrations can be reduced to very low values [21, 24-26]. A typical cold trap would be filled with stainless-steel mesh to adsorb the contaminants and would be either liquid or gas cooled. Forced circulation is standard for the sodium in major cold-trap systems. Small test loops often operate with diffusion cold traps. The larger sodium systems would probably contain automatically controlled equipment to maintain the temperature in the trap at some point approximately 50°F below the oxide precipitation temperature of the sodium in the system but not less than approximately 250°F. The lower limit is required to avoid complete freezing of the sodium. NaK cold traps operate at lower temperatures. Cold traps are normally disposable when exhausted. Primary-system cold traps must be installed to permit remote handling. Carbon steel is suitable for cold traps since they operate at relatively low temperatures and are disposable. Primary-system cold traps are designed to the same pressure and code requirements as the reactor if they are to be in service during reactor operation.

Cold traps cannot precipitate out enough oxide, however, to prevent oxidation of zirconium or other refractory metals if they are included in the sodium system. Therefore, other means for removing oxide are provided. An appropriately sized hot trap filled with zirconium foil* and operating at elevated temperatures in the range of approximately 1000°F will react with essentially all the oxygen in the system, and will leave the system oxygen content below 1 ppm. Use of zirconium hot traps along with cold traps is not advisable since oxygen may be redissolved from the cold trap to react in, and thus deplete, the zirconium hot trap (Chap. 6) [27].

Pump seals and other points where carbon materials (for example, lubricants) may be introduced into the system are very carefully designed. The best way to remove carbon* is to pass the sodium through a hot trap filled with stainless-steel foil operating at or above 1200°F, a method that can maintain carbon concentration in the sodium at a reasonable level (Vol. V, Chap. 1) [21, 28, 29].

(4) *Monitoring*. Plugging meters are usually installed in sodium systems to

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*Possible detrimental effects of system decarburization are discussed in Chap. 6.

indicate the impurity content of the sodium (Vol. III, Chap. 4, and Vol. V, Chap. 1) [21]. These meters do not record the concentration of any one contaminant specifically, but they do react to precipitation of both sodium oxide and sodium hydride and perhaps to other contaminants. Plugging-meter readings give the general degree of contamination of the sodium [30]. Abnormal changes in the plugging temperature indicate the possibility of abnormal contamination.

Hydrogen meters presently under development can be used to detect hydrogen in sodium utilizing the permeability of a membrane such as pure nickel for separation (Vol. III, Chap. 4, and Vol. V, Chap. 1) [21]. Hydrogen in the sodium indicates a source of contamination. Hydrogen in the secondary sodium system of a power plant using steam as a working fluid tends to indicate a steam-generator leak.

United Nuclear Corporation is developing an in-line carbon meter to detect carbon contamination of sodium before it causes damage to major components. The meter consists essentially of a thin-walled probe immersed in the sodium stream, a controlled flow of decarburizing gas, and a gas analyzer. At high temperature, carbon from the sodium diffuses through the probe wall and reacts with the gas. The carbon content in the flowing gas stream is continuously monitored to indicate the carburizing potential of the sodium impurity (Vol. III, Chap. 4)[31].

(b) *Cover-Gas Systems.*

Since liquid metals are highly reactive with components of the atmosphere, air must be kept from the system. Most reactor designs provide an inert-cover-gas blanket over the reactor-system free-sodium surface.

In certain systems the cover gas acts as a disengagement volume for dissolved gases, including radiolytic gases. Normally, the cover-gas systems are operated at a small positive pressure to ensure the complete absence of air inleakage into the system.

Of a number of cover gases considered, helium, argon, and nitrogen are the most acceptable (see Vol. I, Chap. 2, and Vol. III, Chap. 3). Generally, nitrogen is used only at low sodium temperatures to avoid nitriding steel surfaces in contact with nitrogen-bearing sodium at high temperatures (Vol. V, Chap. 2).

Sodium systems must be absolutely leaktight in the regions containing liquid. The gas-containment envelope must be as nearly leaktight as practical Primary sodium cover gas usually contains radioactive gases, that must be contained. Helium and argon are expensive, and even minor leakage can be intolerable economically; even leakage to radioactive vent systems is undesirable. Inleakage is not permissible, because the atmosphere contains oxygen, moisture carbon dioxide, and other constituents that are reactive with sodium.

Usually the cover-gas pressure is low (less than 1 psig) to minimize the possibility of outleakage unless there are overriding reasons for higher pressures. (Although bulk outleakage can be minimiz by minimizing the pressure differential, outleakage due to diffusion from an area of high partial pressure to one of low partial pressure must not be overlooked. This phenomenon could be significant for radiolytic gases.) Higher pressures are used where required to provide additional pump-suction pressure, to provide a pressure differential between primary and secondary systems, or perhaps for other reasons. The cover-gas system may require initial purification, depending on the quality of makeup gas available. High-purity gases generally do not require extensive purification, although drying may be desirable.

Reactor systems generally are supplied with a minimum of two independent pressure-control devices to introduce the cover gas into the reactor and to release excess radioactive gases. The lines are relatively large (2 in. in diameter and more) where practical to minimize the possibility of plugging from sodium vapors. Gas lines are protected from sodium frost by vapor traps (Vol. IV, Chap. 5) [32] which trap sodium vapor from the hot sodium systems; thus the possibility of plugged gas lines and malfunctioning is minimized. The gas lines between the hot sodium system and the vapor traps are heated to prevent deposition of solid sodium at these points. The vapor traps are generally installed in a limited-access area where maintenance can be performed during shutdown. The vapor traps can be heated remotely and melted out during reactor operation, when access is not feasible [33].

Often gas lines must be connected to sodium systems at normally wetted points (e.g., vents required on sodium piping or sodium-filled equipment). Freeze traps are frequently used at these locations to prevent sodium from entering gas lines. The freeze traps permit gas passage during fill. Sodium that enters the trap freezes and plugs the trap; this plug prevents furthur flow of sodium into the gas lines (or vice versa). The thermal design of the freeze trap must ensure that the trap will freeze promptly during fill and will not melt out inadvertently during normal operation. Special heaters melt out the traps for draining operations.

In the radioactive-waste-gas systems and in the inert-gas-supply systems, no aqueous material may be allowed to enter the sodium system. Ideally a separate waste-gas system would be preferred for sodium-containing equipment and a completely isolated vent system for aqueous-containing equipment. Generally, for economy, compromises are made by using float valves, check valves, pressure-reducing stations, and other means of ensuring isolation.

It is desirable to isolate the cover-gas supply system for radioactive systems from nonradioactive systems. This can be done by separating the two systems at the source through pressure-reducing stations, possibly backed up by check valves.

Cover-gas systems are generally constructed of carbon steel, which is quite satisfactory for inert-gas systems at the temperatures and pressures under consideration. All-welded construction is utilized to minimize leakage. Bellows-seal valves are generally used. Quite often resilient seat valves are preferred to ensure tight shutoff and to minimize seat leakage. Where resilient seat construction is used, liquid-metal vapors must be kept from the valves, or the compatibility of nonmetallic materials with liquid metals and their vapors must be examined.

(c) *Cover-Gas Supply and Purification.*

Cover gas from liquid-metal systems can become excessively contaminated with use. Once-through use of the cover gas could be prohibitively expensive because of the cost of the gas itself, the cost of storage and treatment for disposal, or both. Under these conditions purification systems are being considered for future plants. Possible contamination can be categorized into three general groups: particulate or aerosol contamination; chemical contamination; and radiological gaseous contamination. Within each grouping, possible specific contaminants must be studied to determine whether removal is necessary and if so, to what degree.

Aerosols and sodium vapors are removed by vapor traps located near the equipment being serviced (Vol. IV, Chap. 5) [33]. Thus far, vapor traps have been built only for low flows (<1 scfm). For the large flows envisioned for cover gas purification systems, larger vapor traps must be developed. Current vapor traps consist of mesh-filled vessels through which the hot, vapor-laden gas passes. The gas is cooled in the mesh, and condensed liquid metal adheres to the mesh. Experiences at the Hallam Nuclear Power Facility (HNPF) and other plants indicate that this principle may not be adequate for larger flows unless intermittent meltout capability is provided. Continuous refluxing impingement condensers are being developed by Argonne [32]. The vapor is converted to the liquid state but is not solidified. Therefore this trap should not plug as does the accumulating type.

Potential chemical contamination of the cover gas includes, primarily, the following gases:

1. Hydrogen.
2. Oxygen.
3. Water vapor.
4. CO and CO_2.
5. Hydrocarbons.
6. Nitrogen.
7. Noble gases.

Of these, the first five will react chemically with the liquid metal and, in fact, can thus be removed. Nitrogen can dissolve in liquid metals, notably in a chemical complex with other contaminants such as carbon or calcium, and can result in nitriding of metal surfaces at high temperatures. The noble gases are relatively inoffensive from a chemical standpoint. Sources of potential gaseous contamination include:

1. Contaminants in the helium supply.
2. Residual contamination during initial fill, either from incomplete purge or as a result of adsorbed gases or surface oxidation on metal parts.
3. Inleakage during fuel-handling or maintenance procedures.
4. Permeability of metal wall surfaces.
5. Diffusion past seals.
6. Contamination with water vapor from a steam-generator leak.
7. Gaseous fission products or volatile material desorbed from the sodium.

A typical analysis of raw grade "A" helium in tank cars is as follows [34]:

Helium	99.9965%
Neon	7 to 19 VPM*
H_2O	3 to 7 VPM
H_2	< 1 VPM
N_2	< 1 to 5 VPM
O_2 + Ar	< 1 VPM
CO_2	< 1 VPM
Hydrocarbons	< 1 VPM

*VPM (volumetric parts per million) $\cong$ mole fraction × 10^6.

Apparently the only significant chemical contaminant from this source is water, which is removed by the sodium itself.

Residual contamination is, primarily, oxygen, nitrogen, moisture, and possibly hydrocarbons. Inleakage during fuel transfer could be assumed to be normal atmospheric components, oxygen, nitrogen, moisture, and CO_2. The contribution from the other sources mentioned is probably of only minor importance.

Quite probably helium gas for power reactors in the immediate future will not need chemical purification, considering the purification effected by the sodium itself. However, means are available, if required, to purify the helium [35]. In general, hydrogen, oxygen, and moisture are removed by copper-copper oxide catalysis followed by molecular-sieve drying. Residual moisture, CO_2, and hydrocarbons are removed in cryogenic freezers. Residual hydrogen and nitrogen and noble gases can be removed by use of adsorption beds operating at liquid-nitrogen temperature. Nitrogen can also be removed by gettering on metals such as titanium sponge at high temperature [36].

The requirement of removing noble fission gases is established by studying probable leak rates to occupied areas, coupled with a determination of probable cover-gas activity, and permissible activity in the occupied areas. Gaseous activity is due primarily to ^{133}Xe, ^{135}Xe, ^{133m}Xe, and ^{85}Kr [37]. The xenon can be removed and delayed for a suitable period of time in carbon-filled delay tanks operating at elevated pressures. If krypton generation exceeds the amount that can be released to the atmosphere at the plant, the krypton can be removed in charcoal-filled adsorption traps operated at a liquid-nitrogen temperature and then transferred to storage bottles for shipment and permanent storage or disposal [38]. Provision is made for complete removal of the xenon before removal of krypton in the liquid-nitrogen-cooled cold trap. Otherwise, the cold trap will not be particularly effective for the removal of krypton because of the interference between the two gases [39].

Design of the purification system is a separate technical and economic study that is generally unique for each plant and each set of conditions.

It is generally more difficult to purify argon than helium because of the interference effect due to the relatively high adsorption coefficient of the argon itself. Thus, where nuclear requirements and economic considerations dictate a need for cover-gas purification, an economic study will often favor helium in the United States, even though argon may be less expensive initially and may be less susceptible to leakage losses through infinitesimal paths. In foreign economies, such as European countries, the cost of helium is much greater than in the United States, and economics probably favor argon.

(d) *Radioactive Vent-Gas Systems.* Exhaust gases from primary coolant systems and from certain auxiliary systems within the plant contain radioactive gaseous and particulate material. These waste gases evolve during normal breathing of the system, during purging operations, and during certain cleaning operations. If steam or water is used for cleaning, the waste-gas stream may contain hydrogen, oxygen, and moisture. A radioactive vent-gas collection and disposal system disposes of these streams in a safe manner [17].

Gases released from hot primary liquid-metal systems contain liquid-metal vapors and possibly aerosols which must be removed to prevent downstream contamination or plugging. These vapors can be removed by suitably designed vapor traps. Effluents from wash cells are usually passed through vent condensers to remove excess moisture.

In the design of the collection systems,certain separations of the streams must be maintained or other measures must be taken to assure safety of the plant; essential points are as follows:

1. Vents from liquid-metal-containing equipment must be isolated from those venting aqueous material in such a manner that water or moisture cannot syphon or flow into the liquid-metal system or vice versa.
2. Vents containing liquid-metal vapor must be isolated from those containing moisture or oxygen to prevent formation of oxide or hydroxide in the vent system.
3. Vents containing hydrogen must be isolated from those containing oxygen to prevent the buildup of explosive concentration of these gases in confining equipment.

The entire vent collection system must be analyzed carefully from the point of view of pressure interactions and their effect on relief-valve set points. For example, pressure in collection systems upstream of the waste-gas compressors must be controlled at some minimum pressure; otherwise, spring-loaded relief valves may open when not required. Conversely, high purge-flow rates through certain lines may increase pressure in the vent collection system to the extent that the set point of relief valves becomes excessive relative to the atmosphere.

Radioactive vent streams are disposed of by compression into pressurized storage tanks for storage, decay, monitoring, and controlled release to the atmosphere [9]. Normally, streams are filtered through high-efficiency filters to remove particulates before monitoring and before release.

Carbon steel is normally used for the radioactive vent-gas systems. All-welded construction is preferred to ensure leaktightness. Resilient seat valving is often used to minimize seat leakage.

(e) *Preheating Systems.*

Reactor systems using sodium require preheating of the process systems before operation. In general, electric preheat systems consisting of resistance heaters attached to the sides of the piping and equipment are used (Vol. IV, Chap. 5). Induction heat may be considered for ferritic systems but does not seem optimal for austenitic systems. Austenitic systems have been preheated in this manner by wrapping or cladding the austenitic pipe with ferritic material. This has proved rather expensive and has resulted in high-temperature gradients along the pipe [40]. An induction preheater can be designed which makes use of the sodium coolant as the secondary turn of the transformer [41, 42]. Steam, organic, or NaK-traced equipment or gas-heated equipment have been used in other designs [43, 44].

In the design of the preheating systems for large equipment, such as heat exchangers, the stress problems associated with differential heating must be examined carefully. Preheating systems include sensing and control equipment to ensure that both the rate of temperature change and the temperature limits are not exceeded.

The main considerations in preheating-system design are (1) preheating empty systems (before they are filled with sodium) and (2) maintaining suitable temperatures in the sodium-filled system but without internal heat sources such as a nuclear reaction. Generally, the first consideration is more critical since the sodium in a filled system acts as a heat distributor and ensures relatively uniform heating of the equipment. Ideally, the heat-input rating of the heater is sized to prevent equipment from exceeding permissible temperature. Before an excessive temperature is reached, the heat losses from the system should equal the heat input by the heaters.

(f) *Inert-Gas-Filled Cells.*

Molten sodium is highly reactive with the atmosphere, forming sodium peroxide (Na_2O_2), which, in turn, is extremely corrosive to most metals, including steel and stainless materials [45]. Most sodium systems are contained in inert-gas-filled cells. Nitrogen is commonly used. The basic reasons for this type of containment are to prevent fire and the resulting dispersal of radioactive sodium and to prevent damage to equipment. Radioactive sodium systems are generally contained in closed, shielded vaults to confine the radioactivity and to prevent excessive radiation levels in the occupied portion of the plant.

The cells are generally designed to prevent leakage at a differential pressure of about 2 psi. Generally, concrete is not satisfactory as a sealing medium since it will leak gas at appreciable rates through the pores of the material itself and through construction joints or minor defects. These cells are usually lined with steel sheet or other suitable material and maintained at a very slight negative pressure so that there can be no outleakage of radioactive contamination to the surroundings. Pressure buildup due to inleakage is released through suitable pressure-control valves.

Since the cells are completely sealed, internal cooling equipment is necessary to keep the cells within acceptable temperature limits. The nuclear heat generated in primary sodium (gamma heating), together with sensible heat released from high-temperature sodium piping is appreciable. The cooling system must be designed so that water cannot enter the cells. Such heat-transfer media as organic coolants, gas, or NaK are sometimes used.

(g) *Steam-Generator Leak-Relief System.*

Leaks between the water-steam side and the sodium side of the steam generators can be predicted during the lifetime of the plant. Various aproaches have been used to prevent such leaks. Double-wall steam-generator construction with monitoring capability between walls was provided at HNPF, Sodium Reactor Experiment (SRE), EBR-I, and EBR-II. More-advanced designs have, in general, utilized single-wall construction for economy and have provided a relief system to accommodate the pressures in the event of a leak (Vol. II, Chap. 4) [6, 17, 46].

Basic requirements of the steam-generator leak-relief system include:

1. Rapid means of relieving the excess pressure buildup in the event of a major leak and sodium-water reaction.
2. Means of containing and safely disposing of the reaction products from a sodium-water reaction.
3. Safe means of disengaging the gaseous products (notably hydrogen) and of disposing of the hydrogen.
4. Means of purifying and/or disposing of the solid and liquid reaction products (sodium, sodium oxide, sodium hydride, sodium hydroxide) and of cleaning up the equipment to facilitate rapid repair and return to service.

The overriding design objective of the system is plant safety. In particular, the potential release of radioactivity (radioactive sodium or other species) to the surroundings must be minimized. The secondary safety objective is to minimize potential secondary damage to equipment in the plant. Of paramount importance are:

1. Need to prevent damage to the intermediate heat exchanger, to safeguard the integrity of the primary-sodium-system containment.
2. Need to confine secondary damage to the leaking loop so that unaffected loops can still remove decay heat from the reactor core.

Analytical studies [47, 48, 49] and available test data [46, 49] indicate that pressure on the sodium side of a steam generator rises rapidly (order of milliseconds) to approximately steam pressure at the point of a major leak. Rupture disks are installed on the steam generators to accommodate this pressure and to attenuate the pressure wave in other parts of the secondary sodium system (notably the IHX). At the Fermi plant, the disks were installed in the gas space. Some newer designs may have no gas space in the steam generators, and the disks may be wetted by sodium. No cases are known where rupture disks have been installed in this manner for long periods of time, although some experience is now being gained in this area at the Sodium Component Test Installation. Calculations [50] indicate that properly sized and located disks will attenuate the pressure waves so that pressure in the IHX's reaches no more than about 300 to 500 psi.

Discharge from the rupture disks must be piped to a suitable disengaging tank where the gaseous products are disengaged and sent to a vent stack for disposal. The entire disengaging system is kept filled with nitrogen at all times to keep oxygen out, and the probability of a secondary hydrogen explosion is thus minimized. Stack discharge is situated so that, should the hydrogen gas ignite, no damage would ensue to adjacent structures or facilities. Check valves or other devices prevent the backflow of air into the system after an incident.

The disengaging structure is designed to minimize entrainment of sodium or oxide in the gas stream and subsequent fallout. Such sodium compounds can damage automobile paint, insulation, vegetation, structures, and can possibly injure personnel. The disengaging tank must have provision for segregating, purifying, reacting, and neutralizing or otherwise disposing of the solid and liquid residues.

All piping in the rupture-disk system is assumed to be covered with a film of sodium and sodium oxide after an incident. The collection piping system and disengagement tank must be equipped to permit cleaning and drying of all surfaces before return to service.

The reaction outlined is quite rapid. Thus it is highly desirable to provide for automatic action to secure the plant in the event of an incident. Actions include:

1. Stop the flow of feedwater, isolate the steam header, and drain the water side.
2. Stop the flow of secondary and primary sodium in the affected loop and drain the secondary system.
3. Reduce plant output or scram the reactor.
4. Isolate the IHX (if possible) to minimize possible corrosion damage.
5. Flood the stream side and sodium side with nitrogen to minimize corrosion and to prevent air from entering the system.

1-2.4 *Safety and Reliability*

Safety is a paramount consideration in the design of any nuclear plant (Vol. III, Chap. 2) with the primary objectives of protecting the public from possible radioactivity exposure and protecting plant personnel from both radioactivity and conventional hazards. The following considerations must be kept in mind during the plant design:

1. All radioactivity must be kept within the plant under all conditions of plant operation, normal or abnormal, including casualty conditions. For this purpose a containment building is generally built around the entire reactor and primary coolant system. No active fuel or radioactive sodium is permitted outside this building (except in shielded transfer equipment), and the design is such that these radioactive materials can be kept within the building under all conditions.
2. Since decay heat must be removed from the core under all conceivable nor and abnormal conditions, the core must completely covered with sodium irrespective of what credible abnormal condition may be postulated. One approach is to provide a secondary containment vessel for the primary system [6] which would surround the primary containment vessel and extend above the top of the core. If a leak should develop in the primary containment vessel, the sodium would be retained in the secondary containment vessel and the sodium level would not drop below the top of the core. Also the sodium level must be maintained above the pump-suction nozzles in the reactor vessel to maintain suction to the pump for removing decay heat. A second approach would be to provide an entirely contained primary system within a complete secondary containment barrier.
3. The main heat-transfer system (or decay-heat-removal system, if it exists) must be highly reliable and able to remove decay heat under all conceivable modes of failure or malfunction.
4. The heat-transfer medium in a liquid-metal primary cooling system is radioactive because of neutron activation of the liquid metal. Therefore primary sodium systems are installed in shielded vaults and are completely inaccessible during operation and for 10 days thereafter. The vaults are leaktight and blanketed with an inert cover gas (generally nitrogen) to prevent the spread of radioactivity in the event of a spill or leak of primary sodium. The cover gas excludes oxygen and thus ensures that a leak will not result in either a sodium fire and generation of radioactive sodium oxide smoke or a rapid oxidation of the sodium to sodium peroxide, which, in turn, would result

in rapid erosion and possible major failure of the primary containment barrier. Remote monitoring instruments, such as leak detectors, are required so that the operator can monitor the condition of the equipment within the vaults even though the equipment cannot be seen or approached.

5. Water or steam must never enter the equipment cells for sodium systems. Limitations are thus imposed on the space cooling equipment for the cells since heat-transfer media other than water are preferred.

6. Owing to the high heat-transfer coefficients associated with liquid metals, the temperatures of piping and vessels follow the temperature of the liquid-metal heat-transfer media very closely. Thus rapid temperature transients in the sodium coolant result in rapid temperature transients in the containing metal. Sudden changes in cross section or other configurations that could result in thermal-stress damage must not be permitted. There must be highly reliable and redundant control systems to avoid inadvertent scrams or sudden thermal shocks to the system. Since the inertia of a sodium system prevents sodium flow from decaying as rapidly as heat generation decreases during a reactor scram, quick-response valves or eddy-current brakes are sometimes provided to assist in flow reduction to minimize the possible effects of thermal shock [51].

1-2.5 *Control and Instrumentation*

Control systems for liquid-metal-reactor steam-generating systems are similar to those in other types of power plants. Control systems for the large liquid-metal-cooled plants will probably be fully automatic; computerized control systems with automatic data logging can be used for recording essential information. The following points are unique to the design of these systems [52-57]:

1. Primary sensing elements are, in general, designed specifically for use in liquid-metal service. The sensing signals are converted to electric signals, which are transmitted to the control systems in a conventional manner.

2. Control-system components are duplicated so that component failure will not cause false setback or scram. This redundancy minimizes the frequency and intensity of thermal shock in the system.

3. Sensing devices and control systems must be extremely fast acting and reliable to avoid nuclear excursions in fast-reactor systems and resulting thermal shocks.

Primary sensing elements that do not require penetration into the sodium containment systems are preferred [58, 59]. For example, temperature is sensed by thermocouples mounted in all-welded thermocouple wells. Where possible, pressure is detected by pressure-sensing devices installed in the gas space rather than in the liquid metal. Electromagnetic flowmeters are used in liquid-metal systems, where possible, instead of differential-pressure instruments that require penetration (Vol. III, Chap. 4) [60]. Liquid-metal level detectors commonly consist of induction coils inside welded thimbles, welded electrical conduction-type instuments (J-tube), or bubbler-type instruments in which signals are generated in the gas space (Vol. III, Chap. 4) [61, 62].

The control system actuates a valve or eddy-current brake to minimize thermal shock in the system following a scram. The control system often includes a "setback" mode of fixed-rate control-rod insertion as a safety action to avoid a scram where it is not absolutely necessary [6, 7].

The control system is designed to minimize thermal swings of the sodium in the reactor and also at critical points throughout the heat-transfer system. Most liquid-metal systems are designed for constant operating temperature throughout the various process systems to accomplish this. This is an idealized case since some temperature swings will be required either in the hot leg or in the cold leg of the reactor or in both as a function of plant load. Minor swings may be required for control. One mode of operation would be to maintain the primary-sodium-system hot-leg temperature constant and to permit the cold-leg temperature to vary over a relatively small temperature range throughout the plant operating-load range.

Pressure-relief devices in sodium systems are preferably placed in the cover-gas space rather than in the wetted portion of the system. Diaphragm-sealed spring-loaded pressure-relief valves and diaphragm-type pressure-control valves are used; rupture disks are included to override the other relief devices in the event of a malfunction. Normally, the relief devices discharge to the radioactive-gas disposal system. The discharge from rupture disks is often released to the equipment galleries. In the relief systems, care must be taken to ensure against backflow of air into the sodium systems after the pressure-relief action has taken place. Spring-loaded relief devices are provided for this function. Check valves can be used as backup for control valves or rupture disks if required.

In the design of sodium systems, the problem of maintaining the instrumentation must be considered. Instruments installed in primary sodium systems are subject to gamma and neutron radiation and to elevated temperature. The use of nonmetallic components should be discouraged. The parts of the detection instrument subject to this type of environment must be accessible for preventative maintenance and repair. Some instrument components in the primary reactor containment must be suitable for operation throughout the plant lifetime. In this case, duplicate primary sensing devices should be installed during construction. Where later replacement of the thermocouples will not be possible, thermocouples are provided in duplicate with lead-outs to accessible junction blocks. Also, leak detectors are provided on sodium piping and equipment, particularly if installed in inaccessible vaults. Here again it is desirable to have duplicate primary sensing instruments.

1-2.6 *Maintenance of Liquid-Metal Systems*

(a) *Introduction.*

Mechanical procedures for maintenance in liquid-metal systems are analogous to procedures in other similar types of equipment. Emphasis here is on the various complicating factors unique to liquid-metal systems. These might be broadly categorized as follows:

1. *Fire hazard*
   a. Nonradioactive sodium or NaK fires.
   b. Radioactive sodium or NaK fires.
   c. Hydrogen fires resulting from sodium-water reactions and hydrogen generation.
2. *Problems with radioactivity*
   a. Radioactive sodium or NaK.
   b. Plated-out fission products or corrosion products.
   c. Neutron activation of components themselves or lack of accessibility to the component because of its location or proximity to other radioactive equipment.
   d. Cover-gas activity.
3. *Problems with cleaning of components during maintenance*
   a. Cleaning for protection of personnel.
   b. Cleaning for purposes of maintenance (i.e., before welding or other operations).
   c. Cleaning during or after maintenance to prevent corrosion.
   d. Design to permit complete drainage of low points and pockets as well as to permit complete venting of high points.

e. Mechanical design to prevent areas where foreign material may collect during fabrication, installation, or operation.

(b) *Fire Hazard* (see Chap. 2, this volume, and Vol. I, Chap. 2).

Both hot NaK and hot sodium oxidize spontaneously in air. Moisture in the air accentuates this reaction. The exact temperature at which sodium or NaK will ignite spontaneously is a complex phenomenon and probably cannot be stated precisely but is of the order of 400°F for sodium. Obviously it would be hazardous to attempt maintenance on hot systems. Sodium systems can be exposed to room-temperature air without excessive risk of fire. The NaK systems present a greater hazard since NaK will flow and react spontaneously at lower temperatures. Thus it is vitally important that NaK equipment be fully drained before being cut; such drainage must be provided for in the design. Sodium pipes are often cut while full of frozen sodium [63]. Such a procedure limits the extent of oxidation in the system. Where sodium systems are to be opened in the drained condition, nearly complete drainage capability is highly desirable.

(c) *Radioactivity Problems in Maintenance* (see Chap. 2).

The following are potential sources of radioactivity that can complicate maintenance procedures:

1. Induced radioactivity in the coolant (^{22}Na and ^{24}Na in sodium and ^{42}K in potassium).
2. Fission products and daughter decay products in the coolant, notably ^{141}Ce, ^{131}I, ^{137}Cs, ^{140}Ba/^{140}La, ^{90}Sr, ^{95}Zr/^{95}Nb, and ^{103}Ru [64 - 66].
3. Component activation and corrosion products from core components, including ^{60}Co, ^{59}Fe, ^{56}Mn, ^{51}Cr, ^{63}Ni, ^{54}Mn, and ^{58}Co.
4. Cover-gas activity.

(1) *Coolant Activity*. There are two significant neutron-activation reactions of sodium: (1) $^{23}\text{Na} + n \rightarrow {}^{24}\text{Na} + \gamma$ and (2) $^{23}\text{Na} + n \rightarrow {}^{22}\text{Na} + 2n$.

The first reaction is the more important because it is caused by thermal neutrons and thus its probability of reaction is enhanced by the substantial ^{23}Na thermal-neutron absorption cross section of 0.5 barn. The ^{24}Na decays with a 15-hr half-life to ^{24}Mg by beta decay, accompanied by the emission of two gamma rays of 1.4 and 2.8 Mev. Coolant activity resulting from this reaction in thermal reactors typically runs about 1 mc/g-Mw(t). The second reaction occurs only with neutrons that have an energy of 13 Mev or higher. The cross section for this reaction ranges from 0 at energies less than 13 Mev up to 72 mb at 21 Mev; a weighted average for a fission spectrum is only 6 μb. The ^{22}Na decays with a 2.6-year half-life to ^{22}Ne by release of a positron with the accompanying emission of a single gamma ray of 1.3 Mev. In thermal reactors the ratio of ^{24}Na activity to ^{22}Na activity is about 10^6: 1; in fast reactors this ratio is about 10^5:1. Thus, during operation and shortly thereafter, ^{24}Na provides the dominant activity. During extended shutdowns, ^{22}Na quickly becomes dominant.

Neutron activation of potassium produces two radioactive species: (1) $^{39}\text{K} + n \rightarrow {}^{40}\text{K}$ and (2) $^{41}\text{K} + n \rightarrow {}^{42}\text{K}$. The ^{40}K decays with a half-life of 1.2×10^9 years and therefore contributes very little to coolant activity. The ^{42}K decays with a 12.5-hr half-life and emits a 1.5-Mev gamma ray as well as a relatively high energy (3.6-Mev) beta particle.

These relatively short-lived activation products make primary coolant systems unapproachable for maintenance for approximately 10 days after shutdown.*

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*Decay in excess of approximately 10 days is of little value since the activity of the sodium in a fast reactor system is thereafter predominantly caused by the 2.6-year half-life ^{22}Na.

Thus, if maintenance is required, an appreciable plant downtime is necessary. Various means are available to the designer to mitigate this problem. One is to use highly rugged and reliable equipment that will require little or no maintenance. Where possible, the equipment and the plant layout should be designed so that components requiring maintenance can be removed into shielded casks for cleaning to remove the activated coolant without waiting for decay. This method is used quite generally in the design of free-surface sodium pumps. Another approach is to install multiple coolant-loop systems with each system located in an individually shielded vault. This would permit shutdown and draining of an individual loop for the required delay period while the remainder of the reactor system continues to operate. Absolute isolation of the inoperative loop from the remainder of the activated-sodium system is necessary and can be accomplished with highly reliable valving, double valving with bleedoff, frozen sections of pipe, or combinations of these. After a single loop is shut down, particular precautions must ensure that the active sodium in the remaining portion of the system cannot enter the vault during maintenance.

(2) *Fission-Product Plate-Out.* Fission products from leaking or vented fuel elements can be carried from the reactor vessel in the flowing sodium stream and can deposit, or plate out, on the cold surfaces of the process systems [65 - 67]. This effect has been noted with plutonium, strontium, cesium, and a number of other isotopes. Experience with the BR-5 indicates that the plated material is strongly adherent and may even tend to alloy with the tube surface material. At present the only known way of removing this material is by chemical cleaning [67]. Thus the designer must plan for the components to be remotely removed and chemically cleaned in a separate cleaning cell with a suitable cleaning agent or for chemical cleaning of the entire primary sodium system in place. The latter method is exceedingly expensive since the entire system must be completely drainable and capable of being isolated to ensure that aqueous cleaning media cannot inadvertently enter portions of the system containing large quantities of sodium or vice versa. Reliable line blinds should ensure isolation of the sodium storage facilities from the aqueous media. The cleaning media must be completely removed and the system completely dried before the sodium is recharged. The problem of fission-product plate-out will undoubtedly become more serious as the vented-fuel-element concept for large liquid-metal-cooled reactors becomes more common.

Most fission products and daughter products of interest in this respect are volatile at fuel temperature or are daughter products of volatile materials and thus can escape from vented fuel elements. These, as well as the fissionable materials or fission products can be released from damaged or leaking fuel pins.

Activation products of significance, notably ^{60}Co, are components of core alloys, such as fuel cladding, or structural components. These materials become activated under the neutron irradiation in the core and subsequently are released to the flowing coolant stream by many mechanisms, including corrosion, wear, and fretting.

In general, components in the core are activated and are treated as such. The cost of maintaining these components often outweighs their value, and generally components are replaced rather than repaired.

(3) *Component Activation.* Of more importance to the system designer are the radiological effects outside the core area. Where possible, components requiring maintenance are so located and/or shielded that neutron activation is minimal.

Certain construction materials become activated in a neutron field. This is particularly important in the case of cobalt-bearing materials. All stainless steel contains small amounts of cobalt. More important, most hard-surface materials, such as the Stellites, contain relatively large quantities of cobalt. Other elements, such as iron, nickel, chromium, and manganese, which are contained in the various steels used, also undergo neutron activation. Thus items that require removal from the sodium systems for maintenance work must be designed to minimize activation.

For example, hard facings used for pump bearings, valve seals, or other applications can be installed outside any possible neutron field, and neutron flux can be minimized in the area of cobalt-bearing materials installed in the reactor cavity.

Protecting cobalt-bearing materials from neutrons must be considered in design of the shield configuration inside the reactor cavity and also in terms of neutron streaming through the pipeways where the mechanical equipment is installed outside the reactor cavity. Since induced activation is caused primarily by thermal neutrons, localized shielding with a good absorbing material for the thermal spectrum (such as $CaBO_4$, boron steel, or Boral) can alleviate the activation of susceptible components.

(4) *Cover-Gas Activity.* Two considerations concerning the cover gas are activity of the cover gas itself and activity of possible contaminants in the cover gas. If helium is the cover gas selected, then cover gas activity per se is a minor consideration. Argon becomes activated in a neutron flux by transmutation of ^{40}Ar to ^{41}Ar, which decays with a 1.8-hr half-life to stable ^{41}K. In general, the ^{41}Ar itself is not a primary problem in comparison with the other radioactive products that could contaminate the cover gas. Also, shielding for the ^{24}Na activity is generally adequate for the ^{41}Ar.

Important activated contaminants in cover gas of sodium systems generally consist only of sodium vapor, ^{85}Kr, and ^{133}Xe. Occasionally, cesium is also detected as a daughter product of xenon decay. Other fission products are relatively unimportant in the cover gas over sodium systems because, having relatively short half-lives, they have decayed before reaching the cover gas or because the sodium has chemically trapped the products.

The problems with cover-gas activity can be subdivided into those anticipated with nonvented but leaking fuel elements and those connected with vented fuel elements, the difference being a matter of degree. The ^{24}Na can be removed from the cover-gas by suitably designed vapor traps on all vapor lines leading from a sodium system [33, 38]. Vapor traps are necessary for two reasons: (1) If the sodium vapor passes into cover-gas or radioactive-waste-gas lines, the lines may plug eventually; (2) in addition, the lines will become activated due to the ^{24}Na. Activation of the lines may be a problem, for example, in radiation-detection instruments, valves, or purification systems. Initially ^{133}Xe is the predominant gaseous source of radioactivity in cover-gas systems. The other xenon and krypton isotopes are relatively insignificant initially since they decay in the fuel or the sodium. Krypton-85 becomes the predominant source of radioactivity after approximately 30 to 35 days.

The xenon can be removed by adsorption on activated charcoal for decay or by storage and monitoring and subsequent release to the atmosphere. Approximately 30 to 35 days decay of waste cover-gas should be satisfactory to decay this isotope and permit direct release to the atmosphere.

During operation ^{85}Kr, with a half-life of approximately 10.5 years, is a relatively minor constituent of the cover-gas activity when compared with the ^{133}Xe. Owing to its long half-life, however, ^{85}Kr becomes the major cover-gas problem after a decay of approximately 35 days. For small plants and for those with nonvented fuel elements, the ^{85}Kr can generally be disposed of by monitoring and controlling release after xenon decay. For large plants, particularly those with vented fuel elements, the total quantity of ^{85}Kr generated becomes excessive, and facilities will probably be required to locate, concentrate, store, and ship this material for permanent storage. Adsorption trains, operating at liquid-nitrogen temperature, are now being developed for this purpose [35, 39, 68].

(d) *Cleaning Components for Maintenance.*

Some components can be neither adequately shielded nor located out of a neutron field. If the item has been activated to the extent that maintenance is not feasible, it must be disposed of as radioactive waste and replaced.

Components that require periodic maintenance are designed to be removed into shielded casks for transfer to wash cells for decontamination. For example, pumps are designed for removal and decontamination to permit bearing maintenance. The pumps, lifting mechanisms, shield casks, and wash cells are designed as an integrated system to facilitate the decontamination operation.

When sodium systems are opened for maintenance, all interior surfaces are covered with a film of sodium. When air enters these systems, this film oxidizes. More significantly, water and CO_2 in the air result in formation of sodium carbonate and sodium hydroxide. In turn, metal beneath these surface films can corrode. To the maximum extent possible, air entry is precluded by plastic films, glove boxes, temporary seals, rubber balloons, or inert-gas blankets at the openings.

After the system has been reassembled and closed, the residual oxidized films are removed by the sodium itself. The oxides are then removed from the sodium in cold traps provided for such maintenance operations.

The chemical-cleaning procedure used on BR-5, [67] which provided sufficient decontamination to permit maintenance operations, required a large amount of equipment, including tanks, pumps, piping, and connections. Positive isolation (as by capped pipes) prevented leakage of aqueous media into sodium-containing equipment or vice versa. Isolations, connections, and shielded waste tanks should be designed for the decontamination operation.

Plans for such a decontamination procedure must include provision for sodium-system components that are not adaptable to cleaning media or vice versa. For example, freeze-seal valves freeze seals, and vapor traps may not be adequate in the cleaning media. Thus this equipment must either be isolated or designed to accommodate both sodium and the cleaning media. The primary sides of the intermediate heat exchangers are predicted to be coated with plated radioactive materials to a degree that will preclude approach even after ^{24}Na decay. Maintenance on these units will be possible only by remote means or after decontamination.

If necessary to isolate by blanks, accessible locations must be provided so the blanks can be installed before decontamination. For example, to install blanks close to intermediate heat exchangers may not be feasible because of the high plate-out activity and the extensive surface in these units.

Particular attention must be given to low points, or pockets, where sodium could collect in quantity and thus complicate the steaming procedure. Such pockets could collect and retain aqueous media as well and thus complicate drying. In addition, if appreciable quantities of aqueous material "pocket" and dry, the residue could be corrosive.

1-2.7 *Materials*

The selection of materials (Vol. V, Chap. 2) for sodium systems is basically an economic balance coupled with the engineering properties and capabilities of the materials. The following physical properties and requirements must be considered to arrive at suitable candidates:

1. High strength, good ductility, and other suitable mechanical properties at operating temperatures.
2. Compatibility with sodium at operating conditions.
3. Acceptable cost, commercial availability, and ease of fabrication.
4. Resistance to exterior corrosion at operating temperatures in the ambient media.
5. High thermal conductivity and low thermal coefficient of expansion.

The materials used in the primary systems for some of the existing sodium- and NaK-cooled reactors are compared in Table 1.1 [69].

In general, the carbon steels are quite satisfactory for liquid-metal service at relatively low temperatures (below about 700°F). At intermediate temperatures, up to approximately 1000°F, the alloy steels, such as 2 1/4 Cr-1 Mo or 5 Cr-1/2 Mo, are satisfactory. The strength of these materials falls off and the decarburization rate becomes excessive in the 1000 to 1100°F range [3]. Austenitic stainless steels are generally used for the higher temperatures. In the reactor plants built so far, stainless steel has been the standard construction material primarily because of its compatibility with sodium, its resistance to external corrosion and its availability and ease of fabrication. Type 304 stainless steel is often preferred for general service [70]. Above approximately 1200 to 1300°F, depending on the exact alloy used, the strength of these materials also falls off rather rapidly and other materials must be used. Incoloy 800 and some of the other high-alloy high-temperature materials have been considered. At very high temperatures, the refractory metals may be satisfactory in pure sodium although some of these materials will oxidize in the usual inert atmospheres, which are seldom pure, presenting external-corrosion problems. Even at oxygen contents much less than 1%, these materials will oxidize rather rapidly at such elevated temperatures. Some of the refractory metals are also highly subject to attack by oxygen or hydrogen in sodium and require absolute sodium purity if they are to be included in the system.

New developments in the alloy steels, such as 2 1/4 Cr-1 Mo-1 Nb, indicate that stabilized chromium-molybdenum alloys may be quite useful in future reactor systems [3]. As more plants are built and as knowledge is gained about the capabilities of materials in sodium, it appears that the ferritic alloys will be more common. Specific advantages of the stabilized ferritic alloys include their potential lower cost, low coefficient of expansion, and high thermal conductivity. Becoming widely recognized is their relative resistance to chloride stress corrosion as compared with stainless steel for use in sodium-heated steam generators [71 - 73].

If dissimilar metals are used in reactor systems, the problem of mass transport must be considered, particularly with respect to carbon [73, 74]. This effect results in the dissolution of elements from the hot portions of the system and their deposition on, or absorption into, the metal at the lower temperature portions of the system or vice versa. Thus, in a system containing a stainless-steel hot section (for example, fuel-element cladding) and a ferritic alloy low-temperature section

TABLE 1.1 - Materials for Primary Coolant Systems in Liquid-Metal-Cooled Reactor Plants [69]

	SRE	HNPF	EBR-I	EBR-II	EFAPP	LAMPRE-1	DFR	BR-5	Rapsodie
Power, Mw(t)	20	240	1.4	62.5	430	1	72	5	20
Turbine steam conditions: temp., °F/pressure, psig	825/600	825/800	529/390	840/1250	780/900	Air heat dump	535/185	Air heat dump	Air heat dump initially
Coolant	Na	Na	NaK (22.5-77.5)	Na	Na	Na	NaK (70-30)	Na	Na
Reactor inlet temp., °F	500	602	442	700	600	750	392	707	840
Reactor outlet temp., °F	960	945	600	884	900	950	662	842	1000
Pipe and vessel materials	304 S.S.	304 S.S.	347 S.S.	304 S.S.	304 S.S.	316 S.S. 316L S.S.	347 S.S.	321 S.S.	316 S.S.

(intermediate heat exchanger), carbon can be transported from the ferritic sections to the stainless-steel sections, resulting in decarburization and degradation of the ferritic material and carburization and embrittlement of the stainless-steel material [3]. Other elements, such as chromium, nickel, and iron, are also known to participate in the mass-transport phenomena. Thus, this aspect must be studied carefully in selecting materials for a sodium system, particularly where dissimilar metals are used in the same system. Mass transport can also occur in similar-metal systems fabricated of a single alloy. If temperature differences exist in the system, an alloying element can go into solution in the hot section and precipitate in the cold section.

A more detailed discussion of materials is given in Vol. V, Chap. 2.

1-2.8 *System Layout*

Many factors enter into the plant layout of a sodium-cooled reactor plant. Some of the more important considerations are (1) containment of the primary sodium system, (2) space for fuel-handling operations, and (3) space for the necessary auxiliary systems and functions in the reactor containment building. Designs of the systems outside the reactor containment buildings are based on the same general considerations used for a conventional plant, augmented by the need for radiological safeguards. In Vol. IV, Chap 4, the piping layout is discussed in detail.

All potentially radioactive material should be contained in the containment structure; this includes the radioactive auxiliary sodium systems, radioactive-gas-handling systems that must be connected directly to the reactor, and auxiliary cooling systems that must be connected to the reactor during operation.

A minimum amount of cooling water and steam should be used for decontamination in the reactor containment building. There must be no possibility of cross-contamination between the sodium and aqueous systems. Minimum protection would be double-barrier containment between the two systems. In addition, no water or steam should be permitted in the vaults that normally contain sodium-processing facilities.

Layout of the reactor building is strongly affected by which system is selected, a pot or a piped system. In general, a pot system results in a more compact arrangement and a smaller reactor containment building. Inherent problems with the pot system include the need for isolation of the secondary-system equipment. Maintenance procedures are more complicated with the pot system since the equipment is less accessible than equipment installed in isolated cells. Reactor design of the pot system is difficult because of the larger reactor vessel and loading-face shield. The piped system can be arranged in isolated cells so that the equipment can be approached after a suitable delay for ^{24}Na decay for contact maintenance. The penalty in piped systems is the additional cost of shielded cells and of a larger reactor building.

Layout is somewhat affected by the design of the pumps and heat exchangers. In the heat exchangers, the primary sodium may be on either the tube or the shell side. If unbalanced flow is used between the primary and the secondary system, pressure-drop considerations will affect the determination of which is to be on the tube side. If the primary sodium is on the tube side, two barriers are provided in the tube bundle between the sodium in the tubes and leakage to the cell, and this may be a valid safeguard consideration, especially if the shell side has an expansion joint. Nuclear-code cases (as of April 1968) do not sanction expansion joints in primary sodium service (Case 1177-5 and

Case 1330-1).

1-3 MECHANICAL DESIGN CRITERIA AND CONSIDERATIONS

Basic mechanical-component design criteria are discussed in other chapters of this book and will not be discussed in detail here. Rather, an attempt is made to point out the mechanical design details that are unique in designing liquid-metal-coolant systems.

The materials (Vol. IV, Chap. 5, and Vol. V, Chap. 2) available for design of liquid-metal systems are generally limited to the metallic materials owing to the chemical nature of liquid metals, which is quite reactive toward most nonmetallic materials, including those of a carbonaceous nature and the ceramic materials such as glass. Of the metallic materials, the ferritic and austenitic steels are of major importance. Final selection is based primarily on temperature and economics. At relatively lower temperatures, the ferritic steels usually have an advantage in terms of susceptibility to chloride stress corrosion, heat-transfer properties, and thermal expansion. At higher temperature, stainless steels, Hastelloys, Stellites, and other materials must be used because of the need for strength at the higher temperatures.

Insulation for sodium service is generally similar to that used for other types of materials for the temperatures under consideration. However, the probable chemical reactions between the sodium and the insulation in the event of leakage must be considered [45]. Fireproof insulation is generally required. The chloride content of the insulation must be weighed carefully to ensure that no chloride contamination of austenitic piping will result from the insulation selected [72, 75].

One critical point in the design of expansion provisions (Vol. IV, Chap. 4) is the reactor vessel itself. The designer has two basic choices. The first is to anchor at the top of the vessel and to allow thermal expansion downward, in which case the top shield structure and supports must carry the full weight of the vessel and its contents. Differential radial expansion necessary between the relatively hot vessel walls and the relatively cool loading-face shield and floor structure may or may not require the use of large-diameter expansion joints.

The second approach would be to support the reactor and its internals from the bottom, in which case vertical expansion must be provided for between the support vessel and the loading-face shield assembly at floor level. In general, this requirement makes a large-diameter expansion joint mandatory. High reliability and rugged expansion joints are required for a DBA of appreciable pressure level. It is not clear at present whether such expansion joints will be permitted in future designs.

The expansion between the anchored portions of the reactor vessel and the anchored portions of the circulating pumps may be relatively simple in the pot-type concept but can become critical in a piped system. The upper portions of the pump and drive are normally rigidly anchored to the floor structure. Thus the radial and axial expansion of the reactor vessel itself and the expansion of the piping between the reactor vessel and the pump casing must be so designed that differential motion between the piping at the bottom of the pump barrel and the anchored upper end of the pump barrel do not cause misalignment that could cause pump binding.

Free-surface pumps have a high-temperature gradient between the anchored portion of the upper pump barrel and the hot sodium in the pump bowl. This thermal gradient must be accommodated without excessive stress. It must be uniform around all sides of the pump. Otherwise, the pump barrel may tend to bend and cause pump binding.

In dissimilar-metal systems high metal stresses can develop at the junction between dissimilar metals owing to the differential radial expansion between the two metals. Dissimilar-metal welding has been developed to a relatively satisfactory state of the art.

Piping supports must be provided for all anticipated motions of the pipe because of thermal expansion. The temperature changes anticipated during normal operation and preheating of the plant, both full of sodium and empty before fill, have to be considered. Thus the predicted motions on the support points must be calculated while the plant is both full and empty. Constant-load spring hangers are frequently used for sodium systems. They may require readjustments after system fill to accommodate the weight of the sodium. Certain spring hangers require adjustment after preheat, depending on their design, location, and function.

1-3.1 *Heat Transfer and Thermal Shock*

The high heat-transfer capability, high heat capacities, and low viscosity of sodium result in unique design problems in avoiding thermal shock to the system. Sharp changes in cross section must be avoided, where possible, since rapid changes in sodium temperature cause rapid changes of temperature in thin sections of metal. Temperatures do not necessarily change rapidly in thick sections of metal, particularly metals with low thermal conductivity such as stainless steel. Thus severe thermal-transient-stress conditions can be generated at points of sudden change in metal cross sections in the system.

Sudden changes of cross section are serious at the pipe nozzles of the reactor vessels where relatively thin pipe studs enter vessels of thick-metal cross section. Thermal-shock liners, often used at these points (Vol. IV, Chap. 5), place a stagnant layer of sodium between the flowing sodium stream, which is subject to rapid temperature changes, and the critical point in the containment vessel, which must be protected from such rapid changes. These thermal-shock liners are of thin material and are designed to absorb the shock without significant damage. Other points to be considered are all tube sheets, such as those in the intermediate heat exchangers and those in the steam-generator complex. Tube sheets in intermediate heat exchangers are thick sections connected to relatively thin tubes and shells. Sudden unbalancing of flow for any reason (for example, sudden failure of secondary coolant flow while the primary coolant continues to flow) would result in a rapid temperature transient and a high temperature difference across the relatively thick metal sections, and, in turn, high internal stress. Other casualty conditions, such as scram or turbine trip, can result in such severe transients. The systems designer must know the potentialities of this effect and must analyze each critical point with respect to each credible set of normal or abnormal conditions to assure that the section will not be damaged and must include in the control system any necessary provisions to avoid this damage.

Serious thermal problems exist in the design of double-wall, or secondary-containment, piping systems. The outer pipe, under static conditions, may be approximately the same temperature as the inner pipe. However, under thermal transient conditions in the liquid-metal system, the temperature of the inner pipe can change very rapidly relative to the temperature of the outer pipe and thus induce severe thermal stresses at the junctures between the two walls unless adequate provision has been made to absorb the stresses.

If the outer and inner pipe walls are of different materials, the different coefficients of expansion result in a continuous potential source of thermal stress unless this has been considered in design. Suspension in such systems is also a thermal-stress problem since the inner pipe must often be supported through the outer pipe, and provision must be made for differential expansion between the two.

Many tools are available to the designer to avoid these problems. Expansion joints are widely used on the outer, or secondary, containment wall to absorb the expansion. Special sliding supports inside the outer wall support the inner pipe. Both full and empty systems are analyzed for temperature and pressure stresses to ensure adequate expansion provisions at all points.

Preheating of double-wall pipe and equipment is also a thermal-stress problem, particularly if electric heaters outside the outer containment are used. In this instance the heat from the heater must be transmitted to the outer pipe, which heats up rather rapidly, and thence by conduction and radiation through a gas space to the inner pipe. Thus the inner pipe can only heat up more slowly. The heaters must be accurately controlled to assure that the differential expansion between the two walls is not excessive during preheating. Monitoring of the temperature of the inner-pipe wall is also a problem. Thermocouples located on the inner pipe, with pressure- and sodium-tight bulkhead connectors in the outer wall, are used for this monitoring. The instrument leads must be flexible.

Obviously, serious problems in assembly of double-wall systems are to be encountered when considering the necessary support and instrumentation equipment that must be included in the design. Therefore the designer must constantly be cognizant of the problems of the fabricator, as well as those encountered in inspection of the double-wall construction, particularly where X-ray, dye-penetrant, helium-leak-check, and other inspection procedures are required for the welds on the inner pipe.

Tubular heat exchangers for sodium service must be designed to provide for possible differential expansion between shells and tubes. Where sodium is in the shell side, the temperatures of the shell and tube walls follow each other quite closely because of the high heat-transfer coefficients in the sodium. Even in fixed tube-sheet construction, expansion joints may not be required. However, these units must be analyzed for thermal-transient conditions to ensure this condition. For conservative design, expansion between the shell and tubes is often provided for, even though analyses may indicate that it is not necessary under normal condition of operation.

Preheating stress conditions must be considered in the design of tubular heat exchangers, especially if external electric heaters are used, since the walls of the shell will heat up much more rapidly than the tubes in the inner portions of the bundle. The shell is heated by direct contact and by radiation from the electric heaters, whereas the inner tubes are heated by a combination of radiation and convection through a gas gap with possible minor assistance by conduction through the tube sheets. Thus preheat can be an overriding factor in the design of the heat exchangers with respect to thermal-stress problems.

Expansion joints have failed because of poor quality control during the manufacture and heat-treatment process [76]. Sodium removes the protective oxide layers of the stainless-steel surface, and the stainless steel is thus subject to attack by minor constituents in the sodium stream at operating temperatures. It is sometimes necessary for expansion joints to operate in thermal-transition temperature zones of the metal. The design metallurgist must appraise this effect since it could cause premature failure, particularly in the thin sections of expansion joints.

1-3.2 *Casualty Conditions*

The system designer must be cognizant of, and analyze for, all conceivable conditions of normal and abnormal operation. Some of the significant areas to be considered are discussed in the following paragraphs.

The safeguard analysis for the plant would generally establish a maximum design casualty condition for the plant, called the design base accident (DBA). One formulation of the DBA is to assume an explosion of a certain quantity of TNT in the reactor to simulate the possible effects of a nuclear excursion. This approach provides a design tool for establishing the design pressures of the various portions of the plant. Based on this assumption, design pressures are established for the primary systems. The compressed gases resulting from the DBA can be rapidly released to the shielded and contained equipment cells, which contain the products of the reaction and prevent the release of radioactive materials to the surroundings. The designer must be cognizant of the potentiality of a secondary sodium-water reaction after the DBA has taken place.

Potential leakage in the steam generator must be considered. In general, the steam-water side of the steam generator is designed for, and operates at, steam pressures in the 2400- to 3500-psi range, whereas the sodium side of the steam generator is designed for relatively low pressures in the 100- to 200-psi range. Thus, should a steam generator leak, the high-pressure water or steam, or both, would leak into the relatively low-pressure sodium-containing system. The result could be immediate failure of the entire secondary sodium containment system due not only to the steam-water pressure but also to the hydrogen pressure that would build up immediately as a result of the sodium-water reaction. In addition, this rapid buildup of pressure on the sodium side could result in hammer effects on various points in the sodium system and could conceivably result in damage and failure to the tube walls between the primary and secondary sodium systems in the intermediate heat exchanger, which then would result in failure of the primary containment system.

Two basic approaches have been used to prevent this occurrence: The first is a double-wall construction in the steam generators with leak-monitoring equipment between, as used at both HNPF and SRE, where helium and mercury, respectively, were used as the intermediate monitoring agent. Thus failure of either wall of the double-wall construction will be noted in the monitoring system, and complete failure will not occur. The double-wall construction is quite expensive, however, and present-day design is directed toward single-wall construction in which rupture disks located on the sodium side of the system permit relief of the rapid buildup of pressure if the system leaks. This method was used at the EFAPP and proved quite effective in actual leak incidents. The rupture-disk system must be designed to permit occasional replacement and inspection of the rupture disks. The downstream side of the rupture disks must be piped to ensure that the sodium and water will not spread throughout the area. In addition, the hydrogen generated in the sodium-water reaction must not be allowed to cause a secondary explosion of hydrogen, which could conceivably result in even more drastic damage than the primary sodium-water reaction itself. The rupture-disk discharge lines can be connected to inert-gas-filled (nitrogen) separation tanks; the separation tanks, in turn, have a relief device which permits exit of the steam-hydrogen mixture into the atmosphere in a safe location and manner and which provides positive reverse-flow shutoff to prevent entry of air into the system after the initial reaction has been relieved. The efficiency of this system has been proved both at EFAPP and at Atomics International's test facilities in the ESADA series of tests [77].

1-4 SPECIFIC SYSTEM DESIGNS

This section contains brief descriptions of specific sodium and NaK systems. Much of the information presented here was obtained from Ref. 7.

1-4.1 *The Sodium Reactor Experiment*

The Sodium Reactor Experiment (SRE) [78] was a sodium-cooled graphite-moderated reactor built at Santa Susana, Calif., by Atomics International (AI). The reactor was designed for a thermal power of 20 Mw; the plant's electrical output was about 6 Mw. The reactor, which began operation in April 1957, was designed primarily as an experimental facility to irradiate fuel materials, to study neutron behavior in this type of reactor, and to develop and test sodium-system components. The SRE achieved full-power operation in June 1958. In February 1964 the reactor was shut down to replace the core and to modify the heat-transfer system to permit 30-Mw(t) operation at 1200°F reactor outlet temperature. These modifications were completed, and the systems were refilled with sodium in May 1965. In January 1967 the USAEC directed that the SRE be deactivated.

The SRE employed two sodium circuits (Fig. 1.6) [79], a main and an auxiliary loop. The auxiliary loop could remove about 5% of the total heat output of the reactor; it served to remove decay heat from the reactor when the main circuit was shut down. Each of these two circuits had an intermediate heat exchanger where the heat of the radioactive primary sodium was transferred to nonradioactive secondary sodium. Heat was dissipated from the secondary sodium loops through air-cooled heat exchangers. The steam generator of the steam-electric plant was connected in parallel with the air-cooled heat exchanger in the main secondary circuit [79].

The temperature of sodium from the reactor was about 960°F. The secondary loops operated at about 60°F below this temperature. Each main and auxiliary loop had a centrifugal pump to circulate the sodium. The secondary loops had expansion tanks, whereas the reactor tank itself acted as an expansion tank for the primary loops. The primary and secondary loops each had a separate fill-and-drain tank; the tank of the primary loop was shielded since it contained the radioactive sodium drained from the reactor.

The reactor was located below grade with the upper surface of the top shield at floor level in the reactor building. Sodium entered the lower plenum of the reactor and flowed upward through channels containing the fuel elements and into a 6-ft-deep pool of sodium above the reactor core. Outlet pipes from this pool of sodium led to the primary loops. The core tank was positioned inside a thermal shield of cast steel, an outer tank, thermal insulation, a steel liner, and a concrete shielding. The outer tank served to contain sodium should the core tank leak.

Steam was generated at 600 psig and 825°F. Flow in the main loops was 1100 gpm.

1-4.2 *Hallam Nuclear Power Facility*

The Hallam Nuclear Power Facility (HNPF) [52, 78] was built by AI for the USAEC as part of the Power Demonstration Reactor Program and was

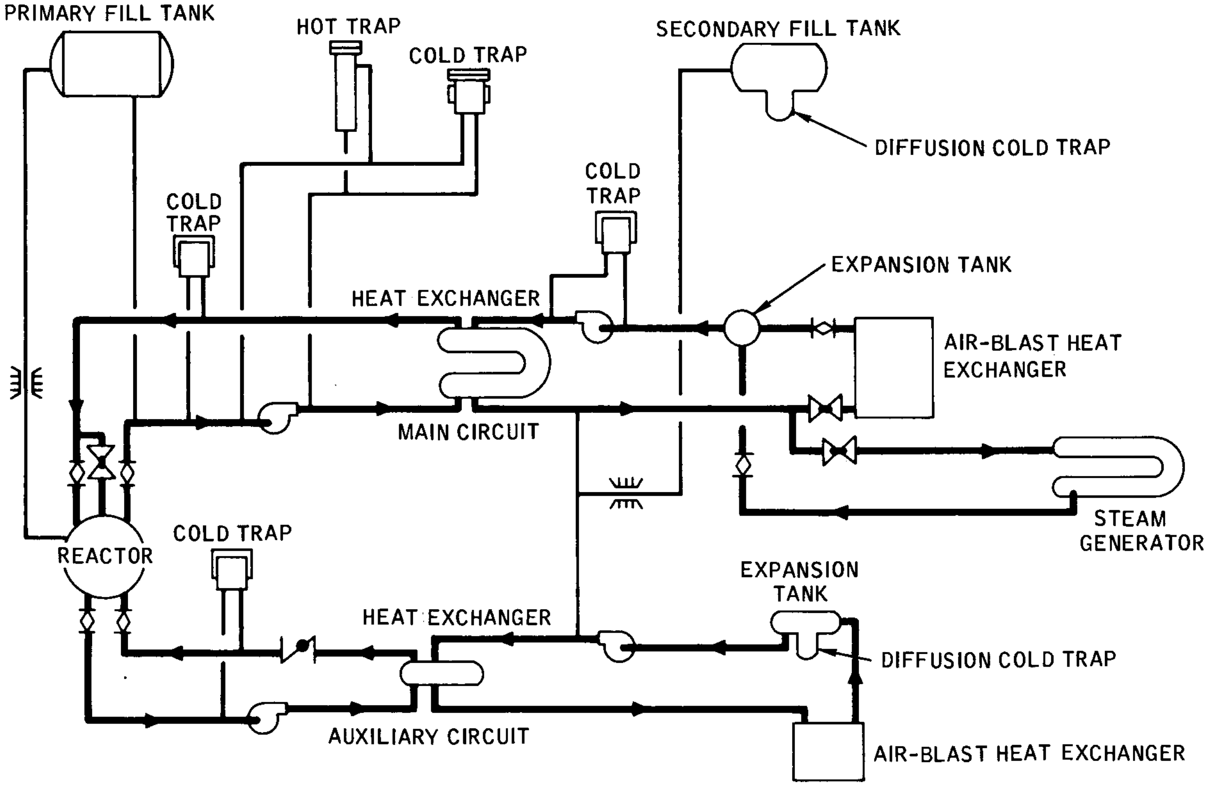


Fig. 1.6 Flow diagram for the SRE. (From R.L. Loftness, *Nuclear Power Plants*, p. 308, D. Van Nostrand Company, Inc., Princeton, N.J., 1964.)

operated for the USAEC by the Consumers Public Power District at Hallam, Nebr. The 256-Mw(t) reactor was sodium-cooled and graphite-moderated. The plant's net electrical output was 76 Mw.

The reactor began operation in 1962 and reached full power in July 1963. Power operation continued until the end of September 1964, when the reactor was shut down to replace seven ruptured moderator elements. The cause of the failure was determined to be long-term stress rupture, and plans were made for in-place modifications to prevent further failures. However, the USAEC directed retirement of the HNPF in June 1966.

A primary system consisting of three independent loops, each directly connected to the reactor vessel, was chosen for flexibility of operation. Thus, if one loop was out of service, the reactor could be operated at about 80% of full power with the remaining two loops. If two loops failed, the reactor was shut down, and the third loop removed decay heat.

Each primary loop (Fig. 1.7) included a variable-speed centrifugal pump, an intermediate heat exchanger, power-actuated valves in the reactor inlet and outlet lines, and a check valve in the inlet lines. The inlet-line throttling valve was used mainly during reactor shutdown to control convective sodium flow for the removal of decay heat from the reactor core. The check valve prevented reverse flow. The reactor vessel served as an expansion tank for the primary loops. The reactor vessel was pressurized to a positive pressure of 1 to 6 in. H_2O by a helium atmosphere above the surface

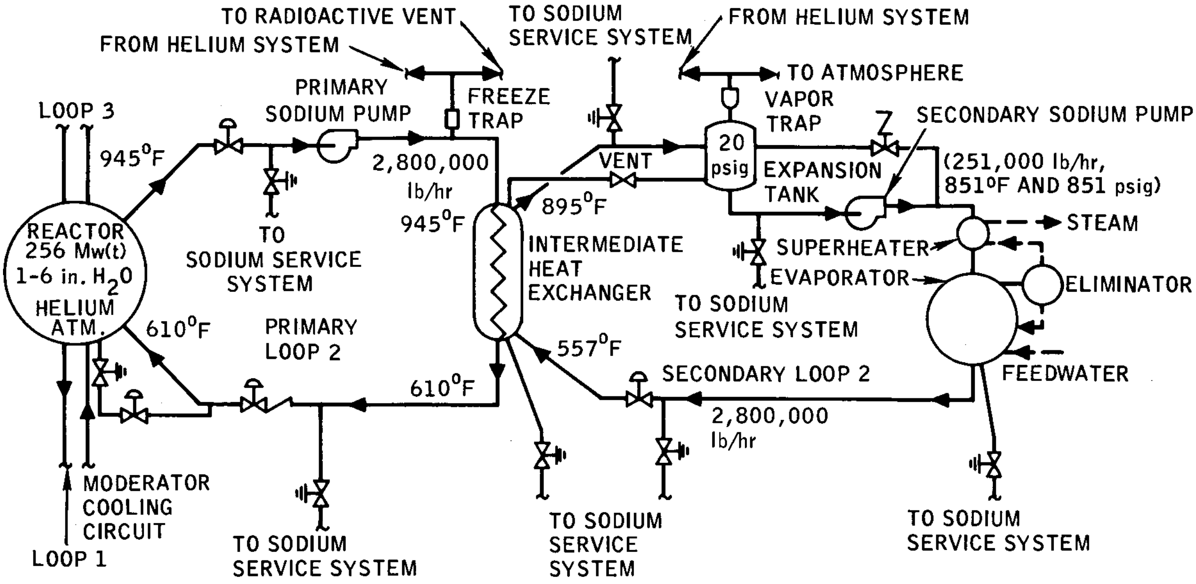


Fig. 1.7 Hallam heat-transport system. (From J.G. Yevick (Ed.), *Fast Reactor Technology*: *Plant Design*, p. 136, The M.I.T Press, Cambridge, Mass., 1967.)

of the sodium pool to prevent inleakage of air.

The reactor outlet temperature during normal full-power operation was maintained constant at 945°F by the plant control system. At this temperature the sodium pool extended approximately 11 ft above the top of the stainless-steel-clad graphite moderator cans. During normal operation the sodium flow rate in each loop was adjusted by varying the pump speed to maintain the desired steaming rate of the turbine; a minor trim on the primary loop maintained a scheduled reactor inlet temperature (610°F for 100% load). Since all three circuits were controlled from a single control system, flow in the three circuits was balanced unless the operator desired to run any circuit at constant load or at a given ratio to the other two circuits.

All piping and components of the primary loops were located in shielded cells below the floor level of the reactor room. In these cells a nitrogen atmosphere was maintained, and the pressure was kept slightly above atmospheric. The reactor cavity and the pipe tunnels were separated by a diaphragm-seal assembly. Immediately outside the diaphragm seal were the inlet-line throttling valves and the outlet-line blocking valves. The piping passed through shielded pipe tunnels to three individually shielded cells, each containing the lower portion of the pump and the intermediate heat exchanger of one of the primary loops. If the sodium piping and the intermediat heat exchanger of a shutdown loop were intact, the loop could be drained and its cell could be entered on a controlled basis while the reactor and the two remaining loops were in operation.

The secondary system operated at a higher cover-gas pressure and at a higher elevation than the primary system so that, in case of a leak, flow was backed toward the reactor.

The compartments containing the radioactive-sodium components were lined with steel to prevent spalling of the concrete if the sodium leaked. Concrete access plugs to these areas were gasketed to minimize leakage of nitrogen.

Pump drives for the primary sodium pumps were located above the reactor floor. The sodium coolant lines leaving the reactor vessel were positioned abouve the core to prevent any loss of coolant from the core if the coolant piping failed.

1-4.3 *Experimental Breeder Reactor No. I*

The Experimental Breeder Reactor No. I (EBR-I) [7] was the first fast reactor project undertaken by the USAEC. It should be borne in mind that the design effort for this reactor was pioneering in nature; much of the present nuclear-reactor technology had not yet been developed.

The technical feasibility of operating a fast reactor with a net breeding gain was demonstrated by the EBR-I, which was designed by Argonne National Laboratory and began operation in 1951 at the National Reactor Testing Station in Idaho.

This fast breeder reactor had a thermal output of 1.4 Mw; NaK was used as the coolant. The normal flow of NaK through the reactor was 290 gpm ($\sim$128,000 lb/hr). The heat-transport system (Fig. 1.8) consisted of a primary NaK coolant loop that removed heat from the reactor, a secondary NaK loop that removed heat from the primary NaK loop, a steam system that removed heat from the secondary NaK loop, and a turbine generator. The primary NaK flowed from an elevated constant-head tank into the reactor, through the inner blanket, and then through the core. From the reactor the NaK flowed through the intermediate heat exchanger and then into a receiving tank. It was pumped continuously from the receiving tank up to the constant-head tank, which contained an overflow line to the receiving tank.

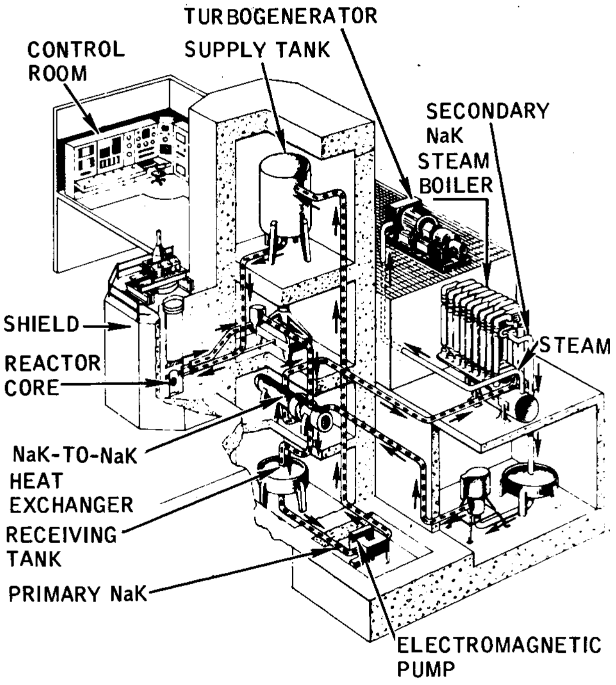


Fig. 1.8 Experimental Breeder Reactor No. I heat-transport system.

The NaK-to-NaK intermediate heat exchangers were of a shell-and-tube design with primary flow through the tubes. The steam generator was divided into an economizer, a boiler, and a superheater. NaK passage through these units was countercurrent to the flow of water and steam. Heat-transfer tubes in each component were similar and consisted of a composite assembly of inner nickel, intermediate copper, and outer nickel tubes. The tubes were assembled by a mechanical drawing process, together with a thermal-diffusion bonding process, which resulted in good heat transfer between the tubes. The tube wall thickness was 5/16 in., of which 3/16 in. was nickel. An outer stainless-steel tube made up the shell of the heat exchanger, and a bellows was used to allow for differential thermal expansion. Thus each heat exchanger was of a "single tube in a shell" type, where NaK flow was on the shell side and water or steam was in the tube.

A forced-circulation falling-film-type boiler was used to limit the quantity of water in the system and to increase the heat-transfer rate. The heat exchangers were in a vertical position, A baffle was used to establish a water film at the upper end of the internal tube on its inner surface. The film ran to the bottom where excess water and generated steam were piped into a drum. Steam was led through a separator in the drum out to the superheater, which consisted of horizontal heat exchangers with NaK in the shell side. The economizer was a horizontal unit and served to heat the feedwater from the deaerating tank to steaming temperature before injection into the boiler drum.

The primary NaK entered the reactor tank at 440°F and left the core region at 600°F. The secondary NaK at 598°F produced steam at 405 psia and 529°F which was fed to the turbine generator.

At the end of 1963, after more than a decade of use as a source of basic data on fast reactor physics and on the performance of plutonium as well as enriched-uranium fuel in a fast reactor system, the EBR-I was finally retired from service.

1-4.4 *Dounreay Fast Reactor*

The Dounreay Fast Reactor (DFR) [80] of the United Kingdom Atomic Energy Authority (UKAEA) at Dounreay, Scotland, is a NaK-cooled fast reactor with a thermal output of 72 Mw and a gross electrical output of 15 Mw. The reactor began operation in 1959. It was designed and constructed as an experiment to provide UKAEA engineers with an opportunity to assess problems that could not be solved (or even necessarily defined) in the design office. The reactor achieved a high load factor and has been firmly established as a valuable irradiation facility, the advantages of which are not confined to fast reactor investigations. The high ratings achievable are making possible accelerated rates of data accumulation compared with those possible with existing material test reactors.

The heat-transport system (Fig. 1.9) has two notable features, downflow in the core and 24 primary loops. The multiplicity of loops ensures continuous cooling. If the flow is normally downward and the pumps fail, there is a progressive changeover from downward to upward natural-circulation flow. A small liquid-metal heat exchanger in each primary circuit is connected to a system that rejects its heat to air by a natural draft through a stack. This system is always in operation. The 24 primary circuits each contain an electomagnetic pump, a main heat exchanger, a flowmeter, and a bypass circuit containing an expansion tank, a flowmeter, and either a hot trap or a cold trap or one of several types of meters for checking the oxide content in the coolant. Each circuit handles 3 Mw of heat.

The layout and design of the primary circuit has been dominated by the necessity to guard against coolant loss. Experience gained in the construction of the Windscale chemical-separation plants using stainless steel showed that, with proper control of materials and fabrication techniques, a leaktight and completely drainable primary system could be built, provided it was welded throughout and the circuit was designed for butt welding so that every weld could be radiographed and tested.

The primary-secondary intermediate heat exchangers consist of one tube inside another. Because of their potential weakness, no valves were used. Components subjected to heavy working or welding stresses were stress relieved, and, in addition to being X-raye all welds were pressure tested and leak tested with nitrous oxide or a halogen gas. Stainless steel was chosen as the construction material because there was little information available in the mid-1950's on the behavior of carbon steels in a liquid-metal circuit. The UKAEA had also had considerable experience in the controlled fabrication of large plants made of stainless steel.

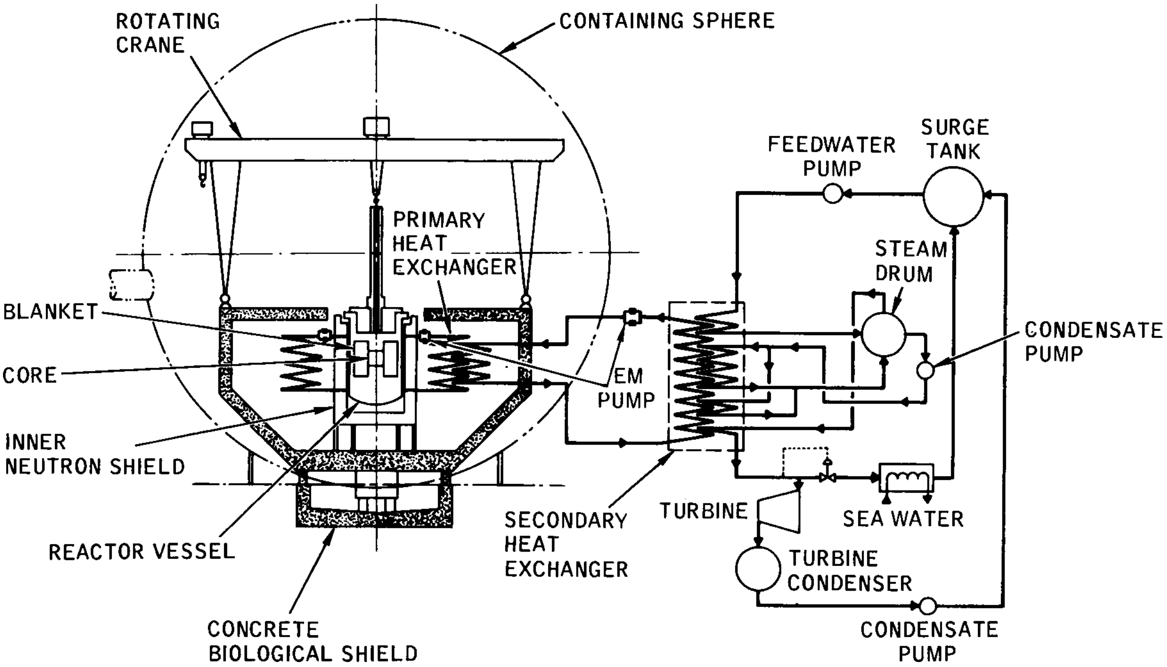


Fig. 1.9 Dounreay heat-transport system. (From J.G. Yevick (Ed.), *Fast Reactor Technology: Plant Design*, p. 132, The M.I.T. Press, Cambridge, Mass., 1967.)

Stainless steel would also make it easier to keep the circuit clean during erection, and hence no special cleaning of the system before filling it with liquid metal was thought necessary.

It was recognized that the use of NaK would be an advantage in the early stages of commissioning and operation when liquid metal could be circulated under varying temperature conditions without freezing. It was decided to operate the reactor with the NaK alloy as the coolant.

The Na-30 K coolant enters the reactor at 392°F and exits at 662°F. Steam is generated at 200 psia and 525°F. Both hot and cold traps are used to maintain control of the oxide or hydride level in the coolant. Nitrogen was originally used as the primary gas blanket, but argon was used later.

1-4.5 *Enrico Fermi Atomic Power Plant*

The Enrico Fermi Atomic Power Plant (EFAPP) [7], located on the Michigan Shore of the western end of Lake Erie near Monroe, Mich., is the first full-scale industrial fast reactor power plant in the United States. The design and development work was carried out under the auspices of a group of electrical utility companies and industrial firms, incorporated as the Atomic Power Development Associates. A separate corporation, consisting of a slightly different group of electrical power companies and industrial firms, known as the Power Reactor Development Company, provided funds for the actual construction of the reactor plant and the sodium heat-transport systems. The Detroit Edison Company owns and operates the electricity- and steam-generating facilities of the plant.

Some features of the Fermi reactor are similar to those of the Experimental Breeder Reactor No.II (EBR-II). However, the EBR-II is of lower capacity [20 Mw(e)]. Although the Fermi reactor is developmental, it is designed for an ultimate capacity of 156 Mw(e) [430 Mw(t)], comparable to an average-sized conventionally fueled unit. The initial design net electrical output of the plant is 60.9 Mw with a reactor thermal power of 200 Mw.

The fuel for the Fermi reactor will be reprocessed off-site, in contrast with the EBR-II integrated-fuel concept. Considerable flexibility exists in the development of future fuel systems.

The Fermi is a fast neutron breeder. It is contained in a stainless-steel reactor vessel sealed at the top by a rotating shield plug, which supports the control mechanisms, the holddown mechanism, and the fuel-handling mechanism. A sweep mechanism, used to ensure proper axial positioning of core subassemblies, is also mounted on the plug. The entire vessel is in the lower compartment of the steel reactor building; the compartment is below grade and has a nitrogen atmosphere. The reactor operates at essentially atmospheric pressure.

The primary system (Fig. 1.10) is composed of three coolant loops that have a common point in the reactor vessel. Each loop contains a sodium pump, a check valve, a blanket throttle valve, and the shell side of an intermediate heat exchanger. Primary sodium flows up through the core and blanket into a large plenum and then by gravity from the upper reactor vessel through three 30-in. pipes to the shell side of an intermediate heat exchanger. The discharge of each intermediate heat exchanger is connected to the pump suction by a 30-in. line. The discharge of each pump supplies a 16-in. line, which, in turn, supplies a 6-in. and a 14-in. line. The three 14-in. lines deliver approximately 87% of the flow to the plenum serving the reactor core. The three 6-in. lines deliver approximately 13% flow to the plenum serving the radial blanket. Flowmeters are located in both the 6- and the 14-in. lines. The flow of coolant to the blanket plenum can be adjusted by a throttle valve in each of the 6-in. lines.

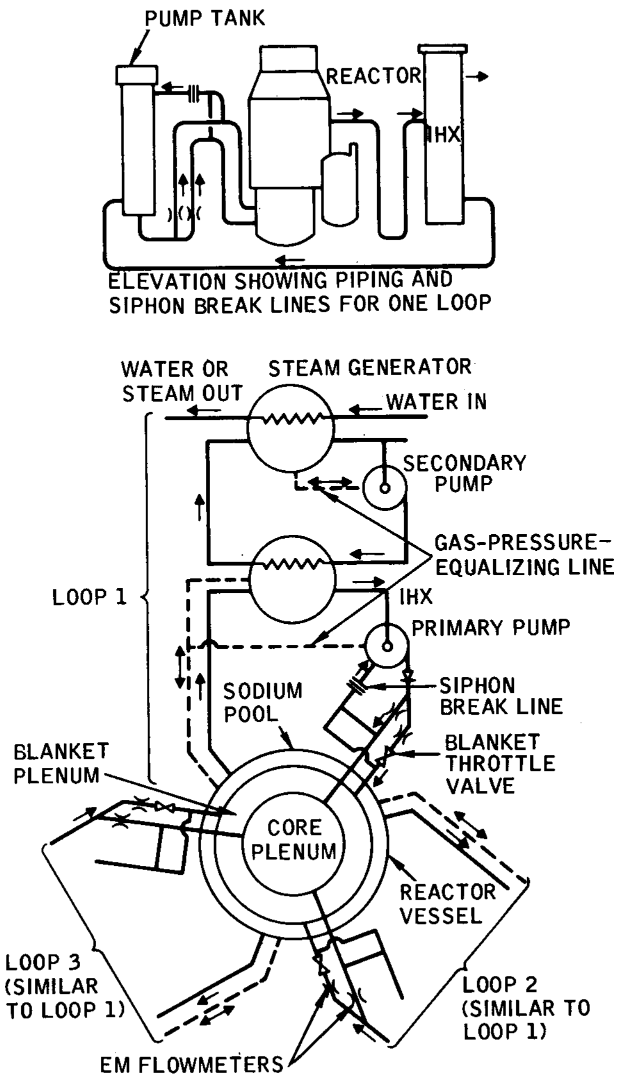


Fig. 1.10 Flow diagram of Fermi heat-transport system. (From J.G. Yevick (Ed.), *Fast Reactor Technology: Plant Design*, p. 132, The M.I.T. Press, Cambridge, Mass., 1967.)

The 30-, 16-, and 14-in. pipes are fabricated of 304 stainless-steel plate. The wall thickness for all three pipe sizes is 3/8 in. The 6-in. piping is Schedule 40 seamless 304 stainless steel. The 30-in. piping is cold sprung 100% for 900°F operation, and the pump-discharge piping is cold sprung 100% for 600°F operation.

Stainless steel is used throughout the primary system, and complete carbon-steel secondary containment is provided around this system. Auxiliary 5-hp motors on each of the primary and secondary sodium pumps furnish the power to circulate primary coolant to remove decay heat from the reactor after shutdown.

The primary piping is of double-wall construction to minimize the possibility of leakage. The steam generators are once-through vertical units with seamless single-wall heat-exchanger tubes.

Primary sodium enters the reactor at 550°F and exits at 800°F. Steam is generated at 560 psia and 760°F.

1-4.6 *Experimental Breeder Reactor No. II*

The Experimental Breeder Reactor No. II (EBR-II) [7], designed and operated by Argonne National Laboratory and located at the National Reactor Testing Station in Idaho, is a fast breeder reactor power plant integrated with a complete fuel-processing and fuel-fabrication facility. The plant is rated at 62.5 Mw(t) and 20 Mw(e) and is the nation's principal fast-flux irradiation facility. The major objective of the facility is to establish the feasibility of large-scale plutonium-fueled fast reactor systems. The reactor began power operation in 1964. The reactor facility was designed to be experimental in nature and to demonstrate the feasibility of operating such a power plant with integral closed fuel cycle provided by an on-site fuel-reprocessing and refabrication plant. As an irradiation facility it is proving very useful in irradiating candidate fuels and structural materials in the USAEC's Liquid Metal Fast Breeder Reactor program. Its high-temperature sodium and fast-neutron flux provide an ideal environment for this purpose. By the end of 1966, 340 capsules containing irradiation specimens and samples of interest had been or were being irradiated in the reactor core [81].

The engineering design of the EBR-II, started early in the 1950's, was predicated on maximizing the safety of the reactor plant. It was on this basis that selection was made of the pot-system arrangement. Costs of the pot approach were not compared against those of the more conventional loop arrangements. The arguments advanced to justify adoption of the submerged primary-system arrangement were as follows [82]:

1. The large bulk volume of sodium contributes significantly to the reliability and integrity of the primary coolant system. Since the entire system is flooded with coolant (to a level approximately 10 ft above the top of the reactor), loss of reactor coolant is virtually impossible. In addition, the system is ideally suited to natural-convection cooling, providing very reliable shutdown cooling in the event of loss of forced convection.
2. The large bulk volume of sodium also provides thermal inertia to the primary system, preventing rapid changes in load demand from being reflected as temperature changes in the coolant entering the reactor. The large heat capacity of the system also provides intrinsic emergency cooling in conjunction with natural convection if the heat-removal system (secondary sodium system) fails simultaneously with the loss of forced convection. Such circumstances might arise in the event of a total power failure, in which case the bulk sodium heats very slowly and considerable time is available to initiate standby cooling procedures.

3. Since the reactor is to demonstrate the method of operation to be employed in a central-station power plant, the fuel replacement must require only a short time. Shortly after reactor shutdown, the heat generation in the fuel element is high, and reliable cooling must be provided. Therefore the fuel elements are unloaded and transferred while submerged in sodium. They are cooled by natural convection of the sodium, and unloading can begin immediately after shutdown. The fuel elements are transferred to a fuel storage chamber within the primary tank where they continue to cool by natural convection of sodium until they are removed for processing.

4. A maximum of integrity is provided with regard to containment of radioactive sodium. The entire radioactive system is confined within the primary tank. A very high degree of integrity can be constructed into this vessel since it is of relatively simple design and contains no external connections below the liquid-sodium level. It is of double-wall construction as further insurance against failure.

5. The need for high integrity of the primary sodium piping is eliminated. Small amounts of leakage are permissible since the leakage is internal. A small amount of leakage actually does occur in the piping system at the connections between the pumps and the reactor and between the reactor and the heat exchanger. These connections are slip joints, which permit the pumps and heat exchanger to be removed from the system without cutting or disconnecting a tight piping system.

6. All the radioactivity in the plant is confined in the primary tank, and therefore only the primary tank requires shielding. Shielded equipment cells and piping galleries are eliminated.

7. Auxiliary heating of the primary-system sodium to prevent freezing is simplified since the entire system is heated as a unit. The individual components, pipes, etc., are in an "atmosphere" of sodium, and the entire system is at the same temperature.

Pertinent design and operating data on the EBR-II are presented in Table 1.2. The primary tank arrangement and major equipment locations and a simplified flow diagram are shown in Figs. 1.11 and 1.12, respectively.

The mechanical coolant pumps take in bulk sodium about 19 ft above the bottom of the primary tank; coolant flow from the pumps is downward to the connecting piping. The flow from each separates into two pipes; one enters the reactor high-pressure plenum, and the other, the reactor low-pressure plenum, with the smaller line supplying the low-pressure plenum through an orifice and a valve. In all regions of the reactor vessel, coolant flows upward through the fuel and blanket subassemblies and into an upper plenum chamber, which has a single 14-in. outlet located on the opposite side of the reactor vessel from the intermediate heat exchanger. The connecting pipe between these two components is designed to accommodate thermal expansion and contains an auxiliary pump. The coolant flows downward through the shell side of the heat exchanger and discharges into the bulk sodium in the primary tank. The heat-exchanger outlet, located approximately 7.5 ft above the center line of the reactor, provides natural-convection shutdown cooling.

Ball-seat pipe couplings are used in the lines between the main sodium pumps and the lower plenums of the reactor vessel so that the pump can be removed. The sodium line between the upper plenum of the reactor vessel and the heat-exchanger shell is

TABLE 1.2 - EBR-II Design and Operating Data

Heat output	62.5 Mw(t)
Gross electrical output	20 Mw(e)
Primary sodium temperature to reactor	700°F
Primary sodium temperature from reactor	883°F
Primary sodium flow rate through reactor	9000 gpm
Primary sodium maximum velocity in core	23.8 ft/sec
Primary-system sodium capacity	89,000 gal
Secondary sodium temperature to heat exchanger	588°F
Secondary sodium temperature from heat exchanger	866°F
Secondary sodium flow rate	5890 gpm
Steam generator	
Output	250,000 lb/hr
Steam temperature	837°F
Steam pressure	1300 psig
Feedwater temperature	550°F

permanently attached to the cover of the primary tank. The intermediate heat-exchanger tube bundle, the secondary sodium inlet and outlet nozzles, and the shield plug can be lifted out as a unit.

When the reactor is in operation, coolant is supplied by the two primary sodium mechanical pumps. Flow to the low-pressure plenum can be controlled by a valve in each circuit. During shutdown conditions, when the reactor power is 1% or less of the design value, sufficient coolant flow is established by thermal convection to remove fission-product decay energy without exceeding the established fuel-alloy temperature limitations. For more drastic emergency shutdown conditions, including the case of complete failure of all pumps accompanied by reactor scram, analysis indicates that the fuel will overheat, but not dangerously. The relative elevations of the heat exchanger and the reactor were established to ensure natural circulation of the primary sodium.

The primary purpose of the auxiliary pump (Fig. 1.12) is to augment thermal convection under certain conditions of reactor shutdown. These conditions can result from any system malfunctions which destroy the normal temperature distributions that promote thermal convection. An example would be the case of a rapid reactor shutdown followed, after several seconds, by failure of the pumps. During the interim the pumps would overcool the reactor and eliminate most of the temperature differential (and the thermal convection head) that would normally exist across the reactor. The auxiliary pump ensures continuity of flow under these conditions. Auxiliary-pump power is supplied from metallic rectifier units backed up by storage batteries. During normal operation these batteries float on the line and remain fully charged. In the event of a sustained power failure, the pump operates until the battery is discharged; the discharge results in a gradual decay of the flow rate and an ideal transition to thermal convection. Interlocks between the auxiliary pump and reactor controls prevent reactor start-up unless the pump is connected and operating with the batteries fully charged.

If rejection of heat to the secondary sodium is not possible, heat from

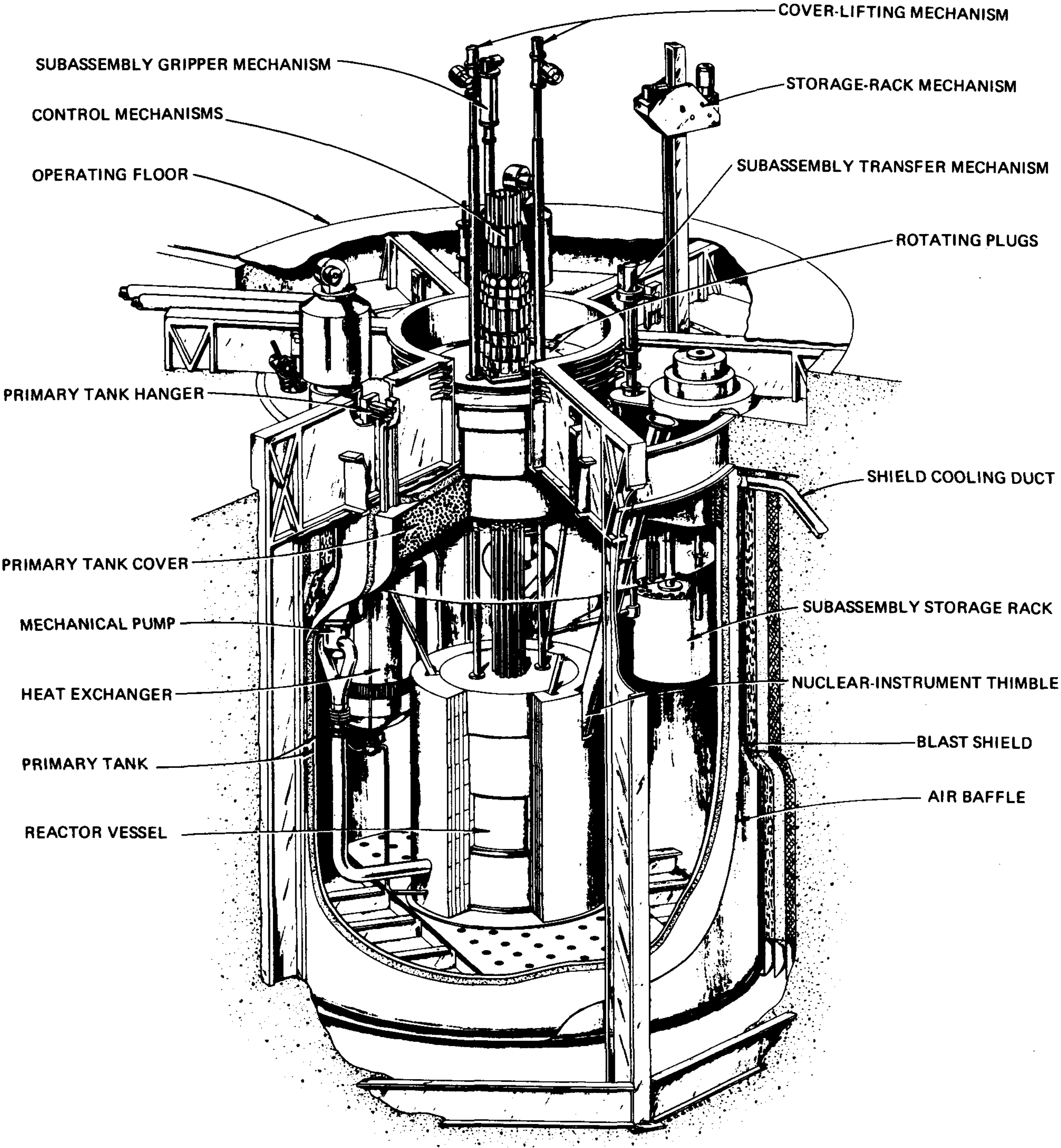


Fig. 1.11 Experimental Breeder Reactor No.II primary system. (From J.G. Yevick (Ed.), *Fast Reactor Technology: Plant Design*, p.161, The M.I.T Press, Cambridge, Mass., 1967.)

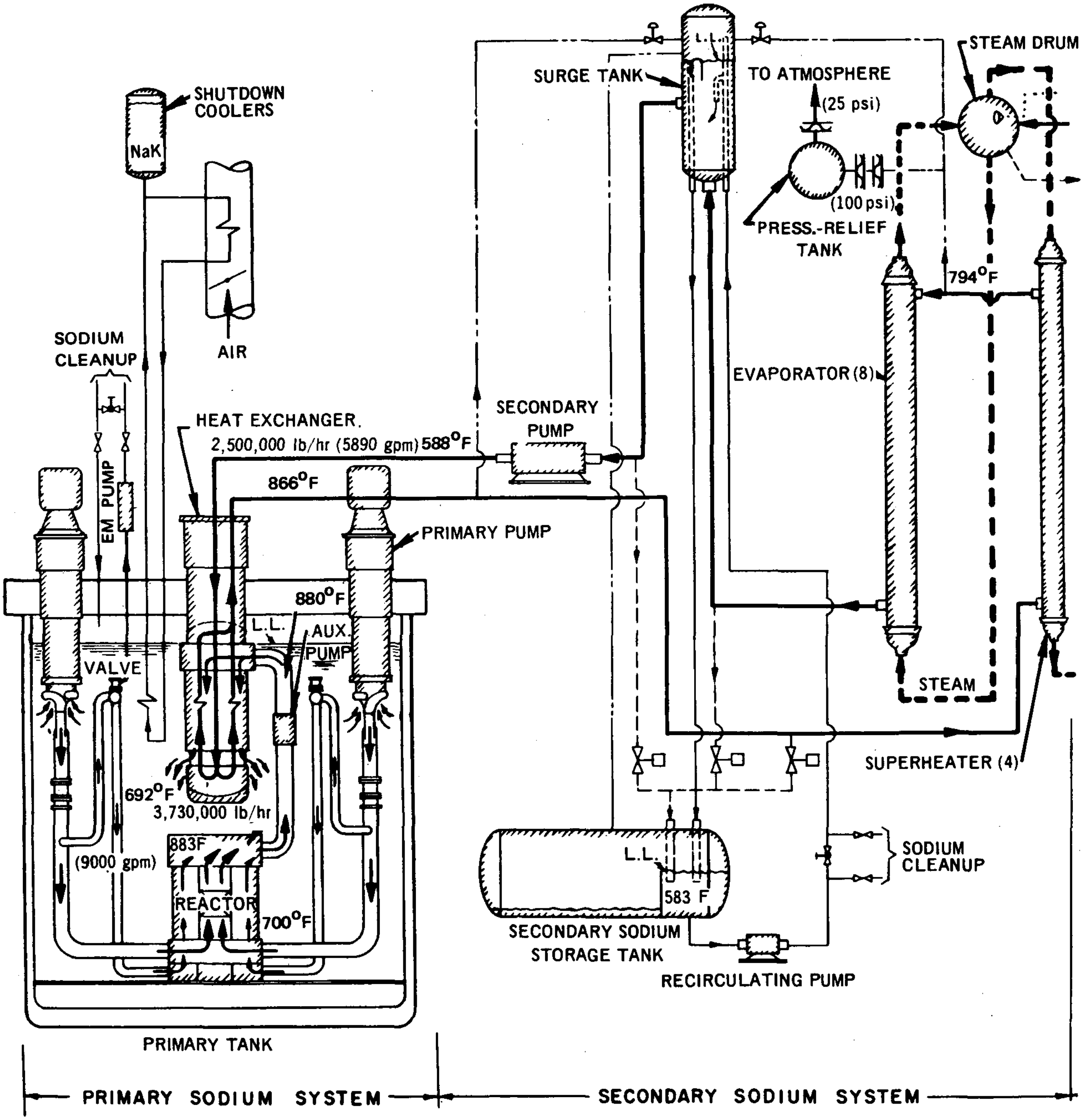


Fig. 1. 12 Experimental Breeder Reactor No. II simplified flow diagram.

the reactor core is discharged to the bulk sodium in the primary tank. The heat is then removed from the bulk sodium via two shutdown coolers with a design removal capacity of 500 Kw at 700°F. The shutdown coolers (see Fig. 1.13) are immersion-type natural-convection bayonet heat exchangers. Each cooler is positioned in a vertical thimble, which is immersed in bulk sodium of the primary tank; a thermal bond of sodium is provided in the space between the thimble and the bayonet heat exchanger. This type of construction has a dual purpose: (1) It provides a structural barrier between

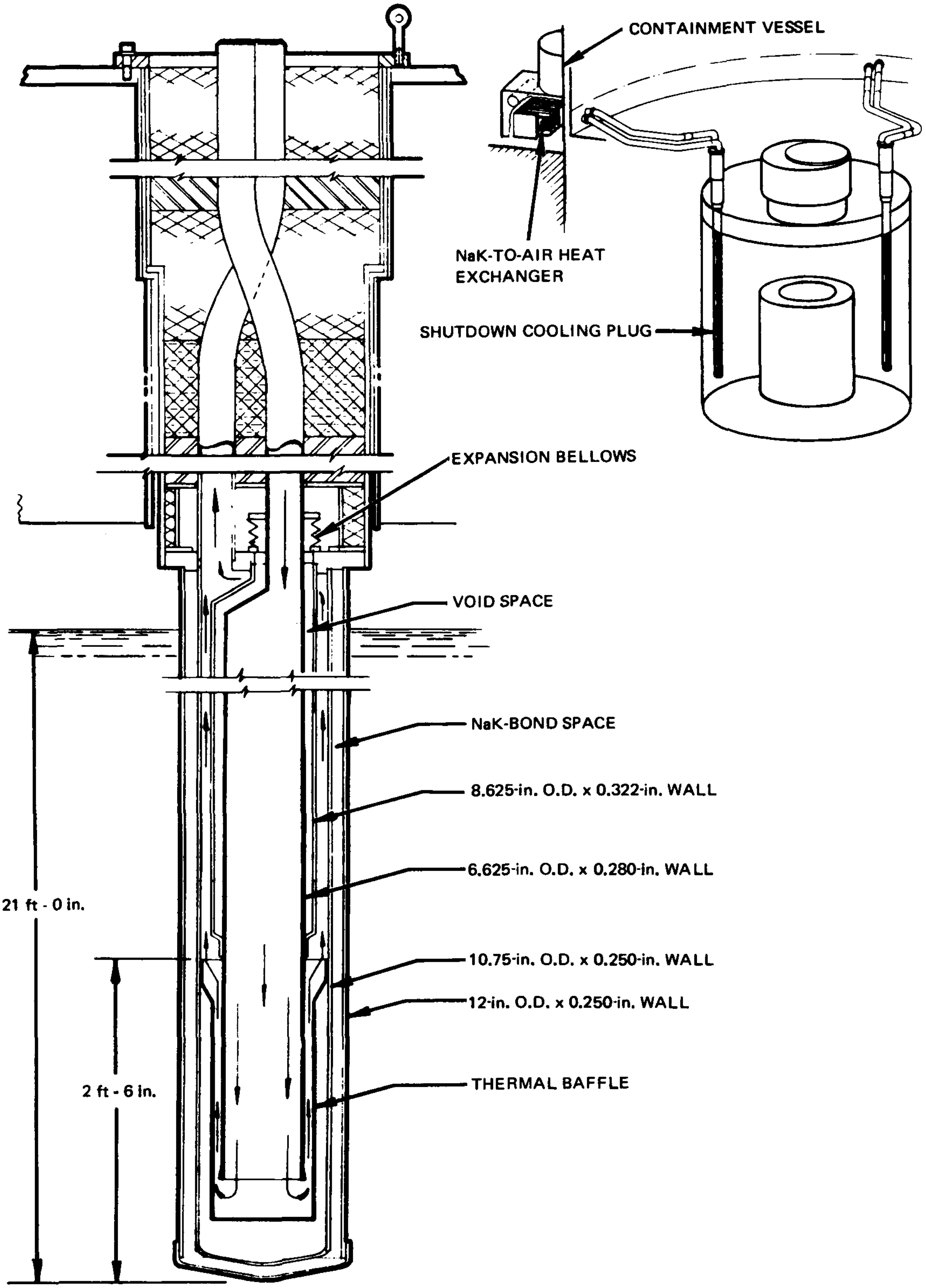


Fig. 1.13 Experimental Breeder Reactor No.II shutdown cooling system.

the primary tank sodium and the coolant in the bayonet cooler, the coolant being the eutectic alloy of sodium and potassium (NaK), and (2) it reduces the thermal stresses in the bayonet cooler.

NaK enters the inner pipe of the bayonet cooler at the top and flows downward to the bottom of the inner pipe, where it reverses direction and enters the annulus. The flow is then upward through the annulus, where heat transfer to the NaK occurs, to the top of the bayonet cooler. When the NaK leaves the bayonet cooler, it flows upward into a finned-tube air heat exchanger, which is located in a dampered air stack outside the reactor containment building. Here the heat is transferred to the atmosphere by natural convection of air. The cooled NaK then flows downward into the inlet of the bayonet cooler.

The rate of heat release from the system is controlled by the position of the stack dampers. Normally the dampers are actuated by automatic control; however, manual control is also incorporated in the event of failure of the automatic system. During reactor operation the dampers are normally closed, and a minimum flow of NaK occurs in the shutdown cooling system. This method of operation prevents the freezing of NaK in cold weather, provides for positive starting when the dampers are opened, and reduces thermal shock on the system. When the stack dampers are opened, the thermal head on both the NaK side and the air side is increased. This gives rise to increased flow of both fluids, which, in turn, increases heat removal from the bulk sodium.

The NaK cooling system, external to the bayonet cooler, is instrumented with thermocouples and an electromagnetic flowmeter. An alarm system is interlocked with these measuring devices to annunciate and indicate abnormal conditions of flow and temperature.

The system is designed for maximum reliability and simplicity. The bayonet coolers are designed for minimum internal stresses over large temperature ranges and minimum obstructions in the flow circuit. All-welded construction is used, and no valves are included in the system.

The sodium pumps circulate 8600 gal of sodium per minute in the primary system. The coolant enters the reactor at 700°F and exits at 883°F. Steam is generated at 1300 psig and 837°F.

1-4.7 *Rapsodie*

The Rapsodie reactor is an experimental sodium-cooled fast breeder reactor fueled with mixed plutonium-uranium oxide. The 20-Mw(t) reactor, located at the Cadarache Center in southeastern France, achieved rated power early in 1967. The secondary sodium system rejects its heat to air rather than a steam-raising system.

Although Rapsodie was originally intended as an experiment, the purpose has largely been redefined by the French Commissariat à l'Energie Atomique so that it will be utilized as a fuel and material test reactor in support of the Fast Neutron Project.

The heat released in the core and blankets of Rapsodie is removed by two parallel primary loops (Fig. 1.14 and Table 1.3), each with a capacity of 10 Mw(t). For initial operation, the sodium enters the reactor at 482°F and leaves at 644°F. However, the thermal equipment and the fixed part of the reactor are designed for temperatures of 360°F higher. The primary loops are symmetrically placed around the reactor, each in a separate room. One room has a tank for expansion of the sodium in the reactor vessel. From this tank the sodium passes through the purification loop and then to an upper level in the reactor vessel.

The two loops have a common return line to the reactor and a common storage tank. The joint to the return line is made just before it enters the

TABLE - 1.3 Rapsodie Primary Loop Data (Per Loop) [53]

Power	10 Mw(t)
Fluid	Sodium
Flow at average temp.	1543 gpm
Temperature entering reactor	482°F
Temperature leaving reactor	644°F
Volume of sodium	5400 gal
Piping	
Material	316 or 321 S.S.
Diameter (reactor to the pump)	11.8 in. inside diameter; 12.15 in. outside diameter
Diameter (pump to the reactor)	7.88 in. inside diameter; 8.19 in. outside diameter
Sodium velocity	
In the reactor (max.)	10.35 ft/sec
In the 11.8-in. pipe	4.5 ft/sec
Pressure drop	
In the reactor	49 psi
In the circuit	3.8 psi

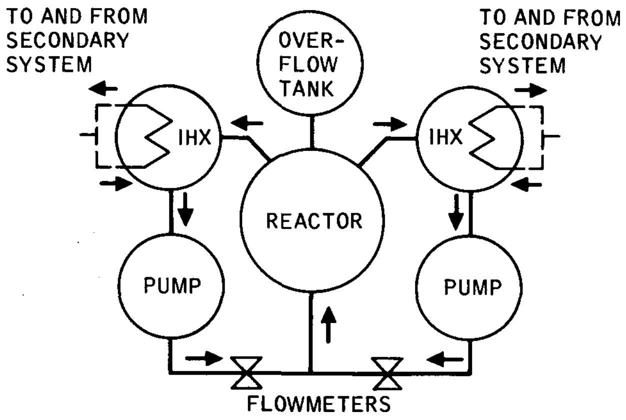


Fig. 1.14 Rapsodie primary sodium system. (From J.G. Yevick (Ed.), *Fast Reactor Technology*: *Plant Design*, p. 133, The M.I.T. Press, Cambridge, Mass., 1967.)

primary shielding tank. The storage tank is located in a room below the rooms containing the primary loops and is surrounded by sufficient shielding to allow access to either of the primary loops after the reactor is shut down and that particular loop is drained. All primary equipment that may require periodic cleaning or repair is accessible from the floor deck. Each piece of equipment has a removable shielding plug in the floor deck to facilitate removal for maintenance, which can be carried out when the reactor is shut down and the loop is drained. The reactor vessel can remain full of sodium.

The reactor, the intermediate heat exchanger, and the pump each have a free surface that permits maintenance. With a free surface the shield plug of each piece of equipment is in a neutral atmosphere, and all the leakproof closures are at the level of the deck where they are easily accessible. Closures are made with a torus seal except for the reactor vessel, which uses a tin-bismuth dip seal.

The fluid in the secondary system

TABLE 1.4 - Performance Data for PFFBR Coolant Systems [54]

Sodium flow per loop	8.3 × 10^6 lb/hr
Sodium flow per loop	20,200 gpm at 650°F
Pipe diameters	
Reactor to intermediate heat exchanger	20 in.
Intermediate heat exchanger to pump	24 in.
Pump to reactor	20 in.
Velocities in system	
Reactor to intermediate heat exchanger	22.4 ft/sec
Intermediate heat exchanger to pump	15.3 ft/sec
Pump to reactor	22.4 ft/sec
Design temperature (primary system)	1050°F
Operating temperatures	
Reactor outlet to intermediate heat exchanger (normal operation)	1000°F
Intermediate heat exchanger to pump to reactor (normal operation)	650°F
Shutdown and refueling	600°F
Design pressure (primary system)	125 psig
Material in primary system	304 S.S.
Pressure drop in system	223 ft Na
Intermediate-heat-exchanger loss	17
Piping (reactor outlet to intermediate heat exchanger)	16
Piping (intermediate heat exchanger to pump)	8
Piping pump discharge to reactor	17.5
Reactor entrance and exit loss	11.5
Fuel element	141
Pump entrance loss	1
Check valve	11
Total sodium volume	4500 cu ft
Total sodium weight	232,200 lb
Cycle time	33.4 sec

is sodium. During the first phase of reactor operation, the heat is dissipated to the atmosphere through sodium-to-air heat exchangers. In the second phase these exchangers can be replaced by steam generators, which could transmit the energy to a turbine generator.

1-4.8 *Plutonium-Fueled Fast Breeder Reactor*

The primary system of the Plutonium-Fueled Fast Breeder Reactor (PFFBR) is composed of three coolant loops having a common point in the reactor vessel. Each loop contains a sodium pump, a check valve, and the shell side of an intermediate heat exchanger (Table 1.4 and Figs. 1.15 and 1.16).

A ventilated space of 8 ft is provided adjacent to the reactor where the piping turns to go underneath the shield wall. There are no penetrations of the 11.5-ft-thick shield wall surrounding the reactor. The wall is laid out in a hexagonal pattern with the pump and intermediate-heat-exchanger tank centered on a line parallel with one of the exterior sides. Coolant piping is located in tunnels 6 ft below the bottom of the shield wall. A minimum of four bends are taken in each piping run, and a distance equal to three trench widths is maintained between turns to prevent neutron streaming. The space outside the shield wall allows access of the crane hook to the intermediate heat exchanger and pump tanks. Equipment storage tanks are located between the primary loops in the equipment compartment.

The primary piping is constructed of ASTM A-358 type 304 stainless steel. A 3/8-in. wall was selected for structural stability. The secondary containment is insulated and induction heated. Aerogel insulation is used in trenches and other close-clearance areas and

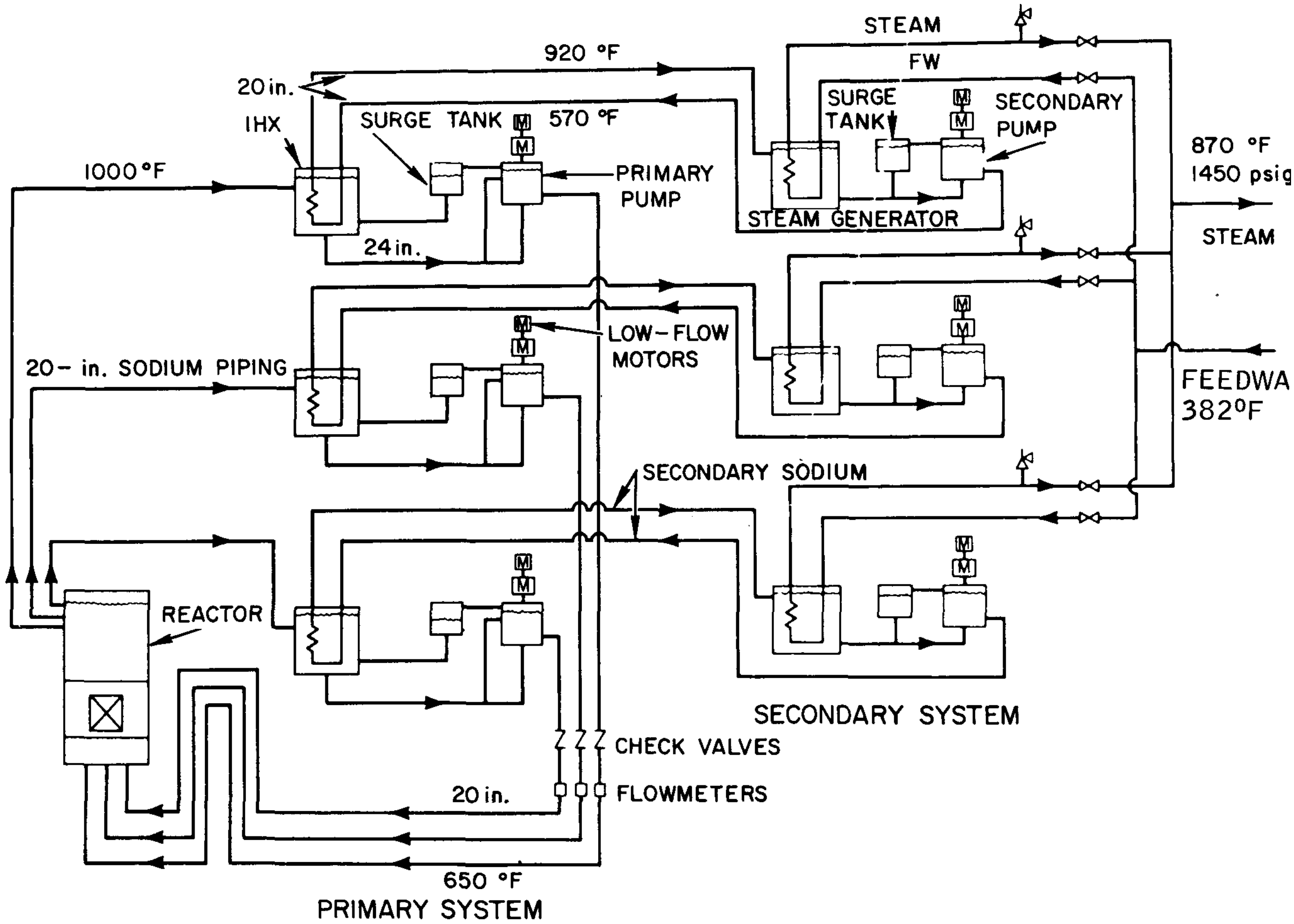


Fig. 1.15 Flow diagram of PFFBR heat-transport system.

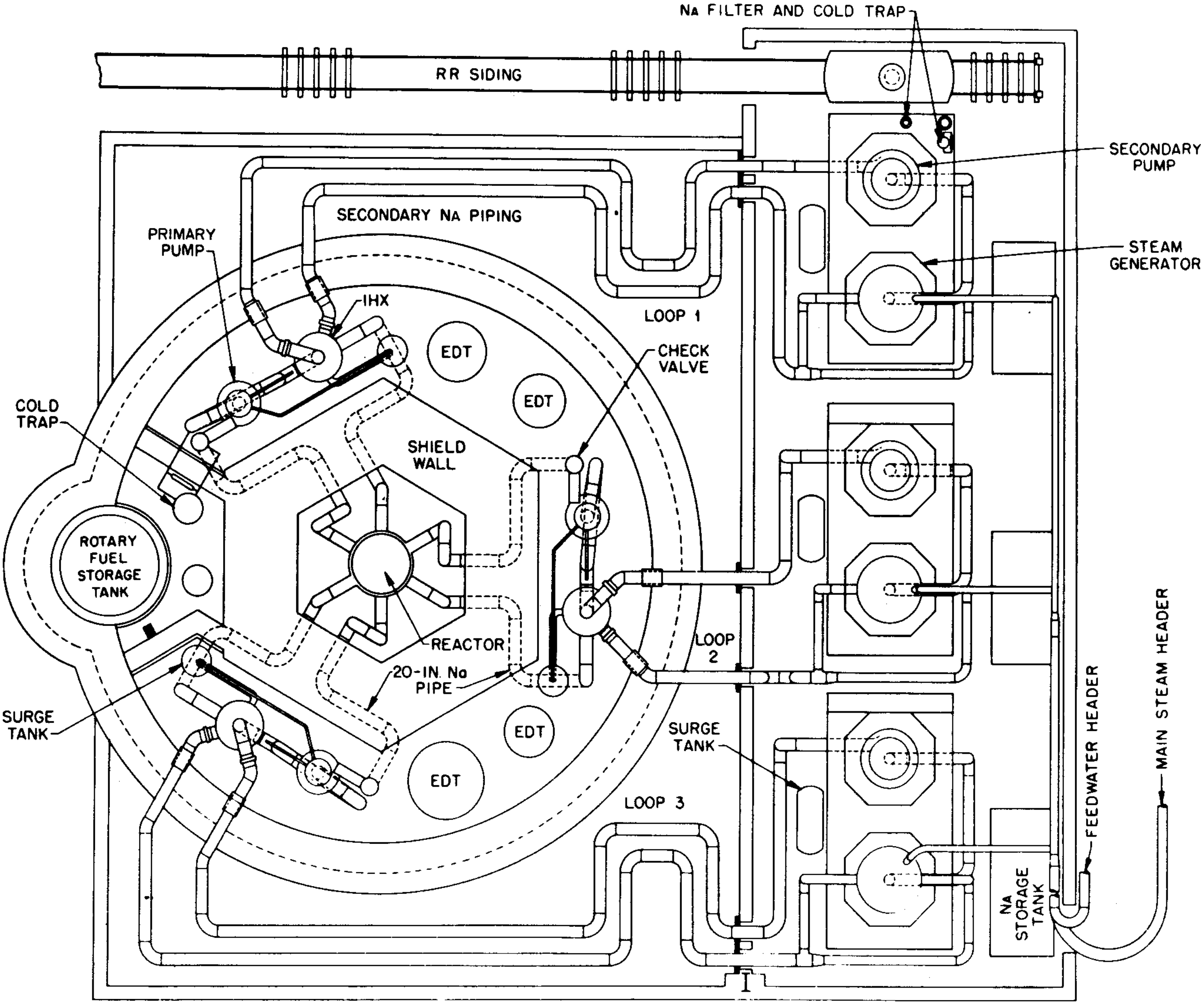


Fig. 1.16 Heat transport system of PFFBR, plan view (EDT represents equipment decay tank).

conventional insulation at all other locations.

1-4.9 *Los Alamos Molten Plutonium Reactor Experiment*

The Los Alamos Molten Plutonium Reactor Experiment (LAMPRE-1) [83, 84] was a 1-Mw(t) molten-plutonium-fueled reactor in which the fuel was contained in cylindrical capsules with the sodium coolant flowing outside. The LAMPRE-1, which was located at the Los Alamos Scientific Laboratory, was intended as a facility to test a variety of fuel and container-material combinations in conjunction with the development of a homogeneous molten-plutonium-fueled fast reactor concept. It achieved criticality in April 1961 and is now decommissioned.

The LAMPRE-1 sodium primary coolant system (Figs. 1.17 and 1.18) consisted of 2- and 3-in. Schedule 40 type 316 ELC stainless-steel piping. It employed two a-c electromagnetic pumps connected in parallel and a finned-

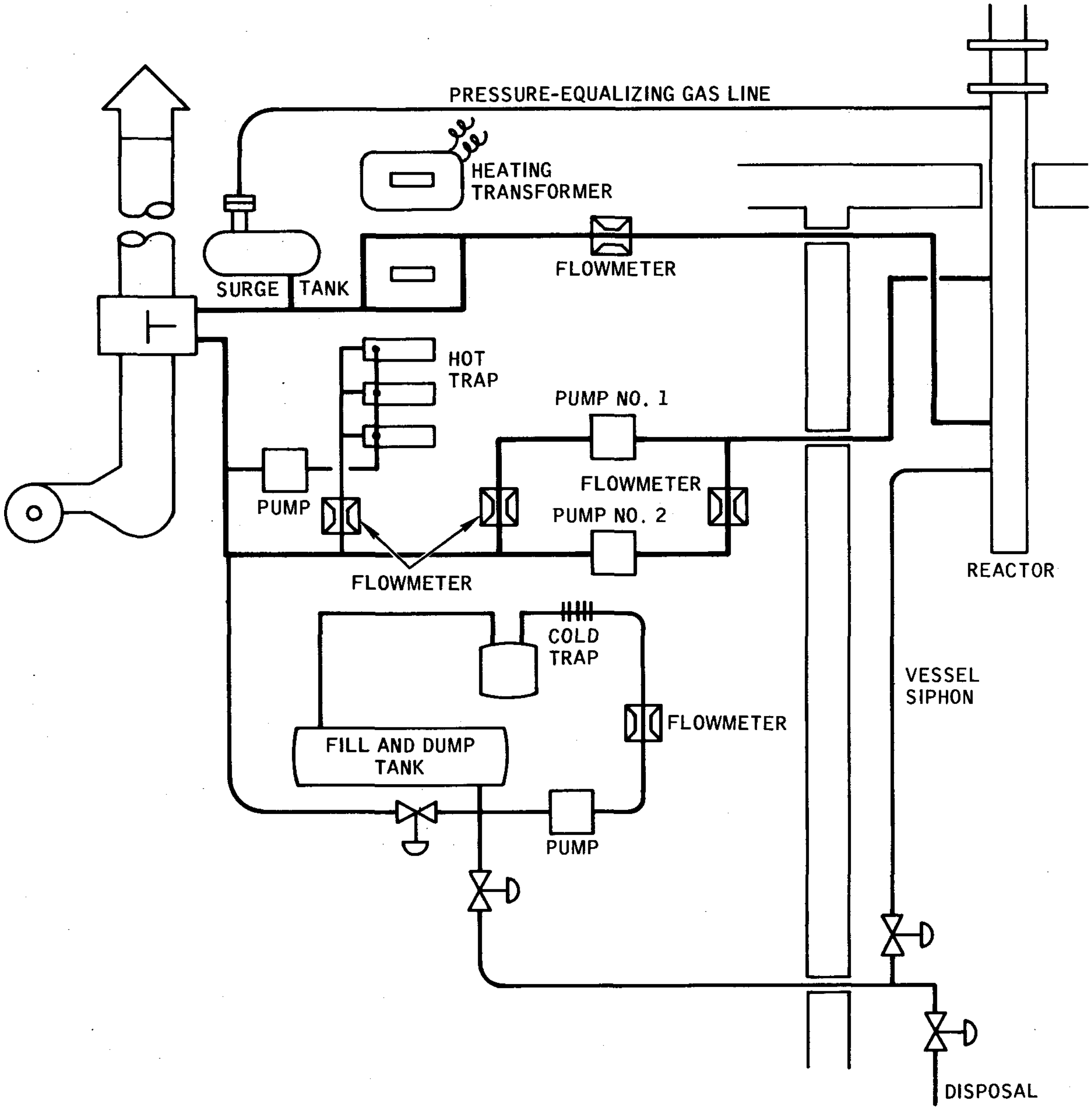


Fig. 1.17 Schematic of LAMPRE-1 coolant loop.

tube sodium-to-air heat exchanger. High-purity helium was used as a cover gas. Water vapor and oxygen were removed from the helium by a NaK bubbler before the helium entered the cover-gas volume.

Two methods were used to heat the coolant loop: (1) Piping and components were traced with electrical tubular resistance heaters for preheating the loop before sodium charging. (2) A transformer and part of the sodium loop designed to be a one-turn secondary on the transformer added about 40 kw of heat.

The sodium coolant loop was containe in a cell adjacent to the reactor vessel (Fig. 1.18). An air radiator-type heat exchanger removed the heat directly from the primary sodium which

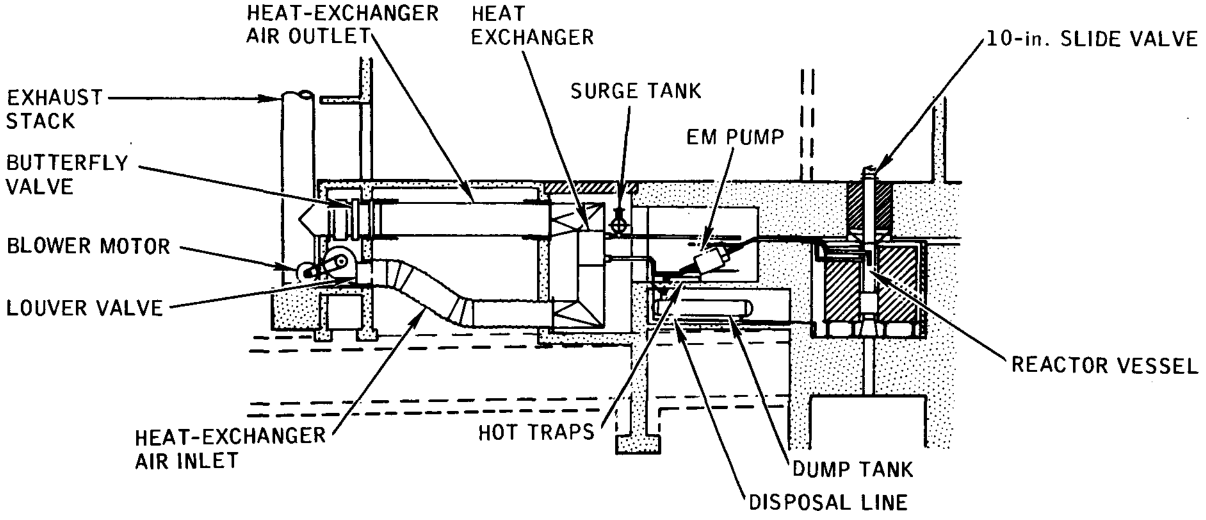


Fig. 1.18 Cross-sectional view of the LAMPRE-1 system.

cooled the reactor core.

The loop inlet and outlet coolant pipes were attached above the level of the core to prevent uncovering of the core should the primary system leak.

The sodium flow rate was 133 gpm with an average coolant inlet temperature of 450°C and an average coolant outlet temperature of 563°C. The LAMPRE-1 operated from March 1961 to June 1963 at power levels up to 1 Mw for an accumulated power history of 100 Mwd.

1-4.10 *Breeder Reactor-5*

The Breeder Reactor-5 (BR-5) [85, 86] is a 5-Mw(t) sodium-cooled fast reactor located at Obninsk near Moscow in the USSR. The reactor began power operation in 1959. Sodium is used as the coolant in the primary system, and NaK is used in the secondary system.

The primary system consists of two separate cooling loops, each with its own mechanical pump and cold trap. Heat in the primary loop is transferred to the secondary NaK loop by an intermediate heat exchanger. One of the secondary loops is air cooled, and the other loop is equipped with a double-wall steam-generating unit. Mercury is used as an intermediate-heat-exchanger medium in the steam-generating unit to prevent any possibility of sodium-water reactions.

The sodium enters the reactor at 806°F (430°C) and leaves at 932°F (500°C). The total sodium flow through both primary loops is about 300 gpm. Steam at 230 psig is produced in the steam generator. The BR-5 heat-transport-system design data are shown in Table 1.5.

1-4.11 *The BN-350 Nuclear Power Plant*

The BN-350 Nuclear Power Plant (BN-350) [43] is the first USSR full-scale sodium-cooled fast reactor central station. It is a dual-purpose electrical generating-water desalting plant designed to produce 150 Mw of electric power and 120,000 m^3 of fresh water per day (∿32 million gallons per day). Thermal rating of the reactor is 1000 Mw. Completion of the facility is scheduled for 1968-1969. The primary system (Fig. 1.19) consists of six parallel sodium coolant loops. Only five loops are in continuous operation; one is held in standby. Each loop contains a sodium-sodium intermediate

TABLE 1.5 - BR-5 Heat-Transport-System Design Data

Primary system	
Volume of sodium	70 cu ft 528 gal
Flow of sodium	∿230,000 lb/hr
Secondary system	
Pump-developed pressure	60 psi
Volume of NaK	120 cu ft 90 gal
Flow of NaK	∿271,000 lb/hr
IHX outlet temperature	880°F (470°C)
NaK-air heat-exchanger inlet temperature	700°F (370°C)
Steam system	
Steam flow	10,000 lb/hr
Steam pressure	∿230 psig
Steam temperature	752°F (400°C)
Thermal power generated in nickel reflector	220 kw
Air flow in reflector cooler	39 cu ft/sec

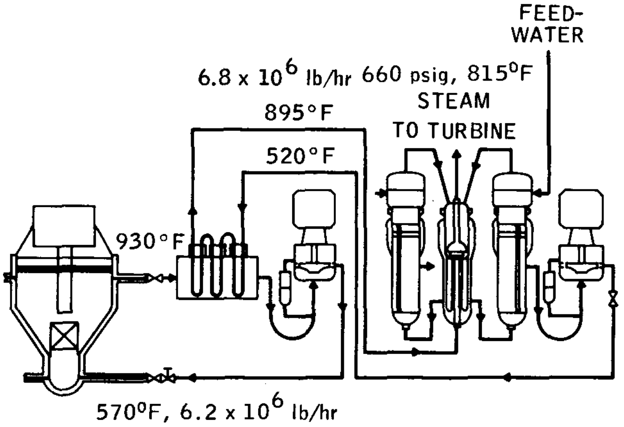


Fig. 1.19 BN-350 reactor process system.

heat exchanger and a vertically mounted mechanical centrifugal pump. Equipment of the primary loop is located within six hermetically sealed cells filled with nitrogen. Components are constructed such that the moving parts of the pump and gate valves can be raised for repair or replacement without cutting the piping in the radioactive primary loop. Sufficient shielding is provided to allow maintenance on the loop either when drained or when filled with sodium.

The reactor vessel and part of the primary loop piping system up to the gate valves have a secondary containment casing filled with an inert gas. Any vessel leakage will be contained within the annulus formed by the reactor vessel and the secondary containment.

An interlock deactivates the sodium pump in the secondary loop if the primary pump is turned off and vice versa. This protects the reactor vessel and sodium piping system from severe thermal shocks.

The primary loop piping system consists of 500- and 600-mm-diameter pipes. Each loop contains a check valve and blocking valves to isolate the loop from the reactor. NaK is used as coolant to freeze the seals of gate valves, pump junctions, and cold traps. Gas blankets above all unrestricted volumes are interconnected.

Sodium at 570°F (300°C) enters the reactor plenum chamber at the bottom of the vessel through six 500-mm-diameter pipes. It is heated up to 930°F (500°C) before it leaves the reactor through six 600-mm-diameter pipes located in the upper portion of the vessel. Sodium flow rate through the reactor is 14,100 tonnes/hr. The piping material is commercially available stainless steel X 18 H 9. Cold traps in both primary and secondary loops will maintain an oxygen content of $\leq$ 0.005%.

1-4.12 *Southwest Experimental Fast Oxide Reactor*

The Southwest Experimental Fast Oxide Reactor (SEFOR) [87] is a 20-Mw(t) sodium-cooled fast reactor with characteristics similar to the large, soft-spectrum fast breeder reactors fueled with mixed PuO_2-UO_2, for which studies indicate the potential for producing low-cost power. The SEFOR will be used to obtain physics and engineering data at fuel compositions, temperatures, and crystalline states characteristic of power-reactor operating conditions. The SEFOR is designed particularly for the systematic determination of the Doppler coefficient of reactivity at temperatures up to the vicinity of fuel melting.

The SEFOR project consists of two major parts: the design and construction of the reactor facility and the related research and development program. Funds for the design and construction of the facility are being provided by the Southwest Atomic Energy Associates (a group of 17 investor-owned utility companies located in the southern and southwestern parts of the United States), together with the Karlsruhe Laboratory of West Germany, Euratom, and the General Electric Company. The USAEC supports the research and development program.

The SEFOR plant facility is located near the center of a 620 acre site 18 miles southwest of Fayetteville, Ark. Principal plant structures are the reactor building, operations building, and fuel service building [88].

A simplified flow diagram of the SEFOR coolant system is shown in Fig. 1.20. The sodium coolant system consists of two parallel heat-transfer circuits and a main and an auxiliary coolant system. Each system consists of a primary loop, which transfers thermal energy from the reactor core to an intermediate heat exchanger, and a secondary loop, which transfers heat from the intermediate heat exchanger through an air-blast cooler to the atmosphere. Coolant-system design characteristics are summarized in Table 1.6.

The main coolant system can remove up to 20 Mw of heat, and the auxiliary system 1 Mw of heat. The auxiliary system serves as an operating standby facility to remove reactor decay heat if the main system is out of service. In addition to the main and auxiliary coolant systems, a pump-around loop maintains the reactor sodium level under normal operating conditions and provides makeup sodium to the reactor vessel and irradiated-fuel storage vessel in an emergency. The main coolant loops are designed for forced-circulation flows up to 5000 gpm and the auxiliary loops for up to 250 gpm. In addition, the main coolant system will provide a minimum of 250-gpm emergency flow by natural circulation for a heat-removal capacity of 1 Mw. The auxiliary coolant system can remove 100 kw at reactor outlet temperatures of 1000°F or less with the use of natural circulation.

At the 20-Mw power level, sodium enters the reactor vessel at 700°F and leaves at 804°F. The heat is transferred via an intermediate heat exchanger located within the concrete structure of the containment building and, in turn, is transferred to the atmosphere via a forced-air heat exchanger located adjacent to the operations building. Since the temperature rise of the sodium across the core is relatively low, the outlet sodium can be kept at less than 1100°F for the most severe transient tests [87].

The primary sodium loops, which

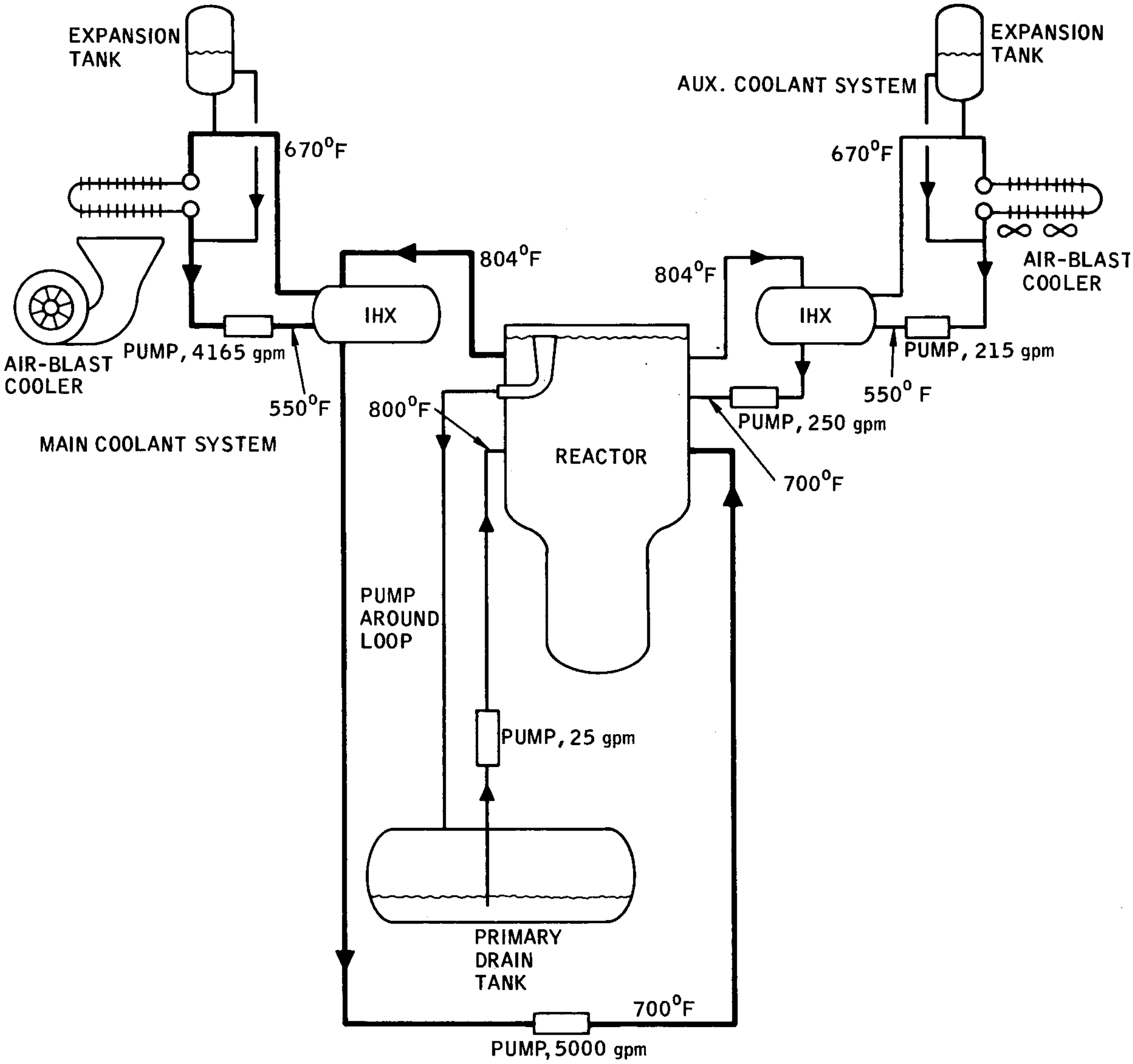


Fig. 1.20 Diagram of SEFOR sodium coolant system.

contain radioactive ^{24}Na, are located in concrete-shielded nitrogen-atmosphere cells in the reactor building. The main secondary sodium loops are located principally outside the reactor containment vessel in an air atmosphere in the operations building. The air-blast coolers are located outside the operations building.

The major components and systems throughout the SEFOR plant, with special emphasis on the sodium coolant system, are designed for earthquake loads (i.e., suddenly applied loads). The sodium coolant system is designed to withstand the thermal and flow transient conditions encountered during reactor testing or accidents. All materials in sodium service are 304 stainless steel.

Seismic snubbers are located throughout the piping systems to resist earthquake loads. These snubbers will not inhibit the relatively slower movements caused by temperature changes.

All sodium piping and vessels are traced with tubular electrical-resistance heaters underneath the thermal insulation to preheat the system before sodium filling. Piping and equipment within the reactor building have sodium leak detectors with alarms

TABLE 1.6 - SEFOR Sodium-Coolant-System Characteristics

	Main	Auxiliary
Reactor power, Mw(t)	20	1
Coolant	Sodium	Sodium
Coolant temperature, °F		
Reactor inlet	700	700
Reactor outlet	804	804
Pipe size		
Primary		
Pump suction	12 in. Sch. 20	4 in. Sch. 40
Pump discharge	10 in. Sch. 20	3 in. Sch. 40
Secondary	10 in. Sch. 20	3 in. Sch. 40
Design flow rate, gpm		
Primary		
Total	5000	250
Core bypass	700	
Pump capacity		
Flow, gpm at 700°F	5000	50/265
Developed head, psi	38	25/13
Intermediate heat exchanger		
Primary		
Inlet temperature, °F	804	804
Outlet temperature, °F	700	700
Secondary		
Inlet temperature, °F	550	550
Outlet temperature, °F	670	670
Heat-transfer coefficient, design, Btu/(hr)(sq ft)(°F)	1000	1060
Sodium-air heat exchanger		
Sodium		
Inlet temperature, °F	670	670
Outlet temperature, °F	550	550
Air		
Inlet temperature, °F	90	90
Outlet temperature, °F	493	403
Heat-transfer coefficient, design, Btu/(hr)(sq ft)(°F)	9.0	7.3
Design temperature, °F		
Primary system	1050	1050
Secondary		
Cold-leg piping	900	900
Pump	1050	1050
Balance of loop	1000	1000
Design pressure, psig		
Primary		
Pump discharge	100	100
Pump suction	50	50
Secondary	100	100

located in the control room. Instrumentation for temperature, pressure, flow, and level indication is provided for process control of the system, for monitoring equipment performance, and for safety trips.

Gas-vent pipes connected to the sodium system permit filling with sodium and regulating the gas pressure over the free sodium surfaces. The primary sodium drain tank serves as the principal expansion volume for the reactor and primary loops. The main and auxiliary secondary loops have expansion tanks in which the gas pressure is regulated to ensure a higher sodium pressure in the secondary system than in the primary. Thus, if a leak should develop between the two systems at either intermediate heat exchanger, the sodium would flow toward the radioactive primary side. The gas-vent lines contain vapor traps to condense any sodium vapor that might be transported into the gas-vent system.

1-4.13 *The Phenix Reactor* [89]

The Phenix reactor will be a 250-Mw(e) sodium-cooled prototype power reactor fueled with UO_2-PuO_2. Phenix will be the second French fast neutron reactor built and is intended to be the prototype of future large fast breeder power plants in France. Start of construction is scheduled for 1969.

Initially, two different primary-system configurations were studied and compared: one with external cooling circuits similar to the Rapsodie design concept (loop arrangement) and the other with integrated primary cooling circuits and the reactor immersed in a large sodium tank (pool arrangement) similar to EBR-II. The pool concept was finally chosen for further studies.

The reactor is immersed in a large sodium tank containing the pumps and the intermediate heat exchangers which ensure heat removal from the reactor. The core is completely surrounded by neutron shielding to avoid activation of the secondary sodium and the primary components. The fuel subassemblies are transferred from the core to an internal storage (around the core between the blanket and the shielding) by an eccentric rotating plug and a rigid rotating arm. The subassemblies are unloaded in sodium-filled casks which are removed through a shielded air lock located above the reactor on the side of the reactor uppe shielding.

The secondary circuits circulate the sodium to the steam generators, which consist of single-wall modular units designed to produce superheated steam at 2364 psia (1.63×10^{7} N/m^{2}) and 1004°F (540°C).

The Phenix reactor pool arrangement is shown in Figs. 1.21 and 1.22. A cylindrical primary tank (approximately 20 ft in diameter and in height) contains the core, the blankets, the neutron shielding, and the fuel subassemblies stored before unloading. The pumps and intermediate heat exchangers (three pumps and six exchangers) pass through an enlarged upper portion of the primary tank (approximately 36 ft in diameter and 6 1/2 ft in height). The primary tank opens freely into a large cylindrical tank called the main tank (about 37.5 ft in diameter and 39.5 ft in height). The sodium flows upward in the core and through the neutron shielding; it is then distributed into the intermediate heat exchange by the collector formed by the upper part of the primary tank. It flows dow into the heat exchangers, enters the main tank, then goes to the pumps, and back into the core supply collector.

The thermal characteristics for a primary sodium pressure drop of about 102 psi (7×10^{5} N/m^{2}) and superheated steam temperatures of 959°F (515°C) and 1004°F (540°C) are as follows:

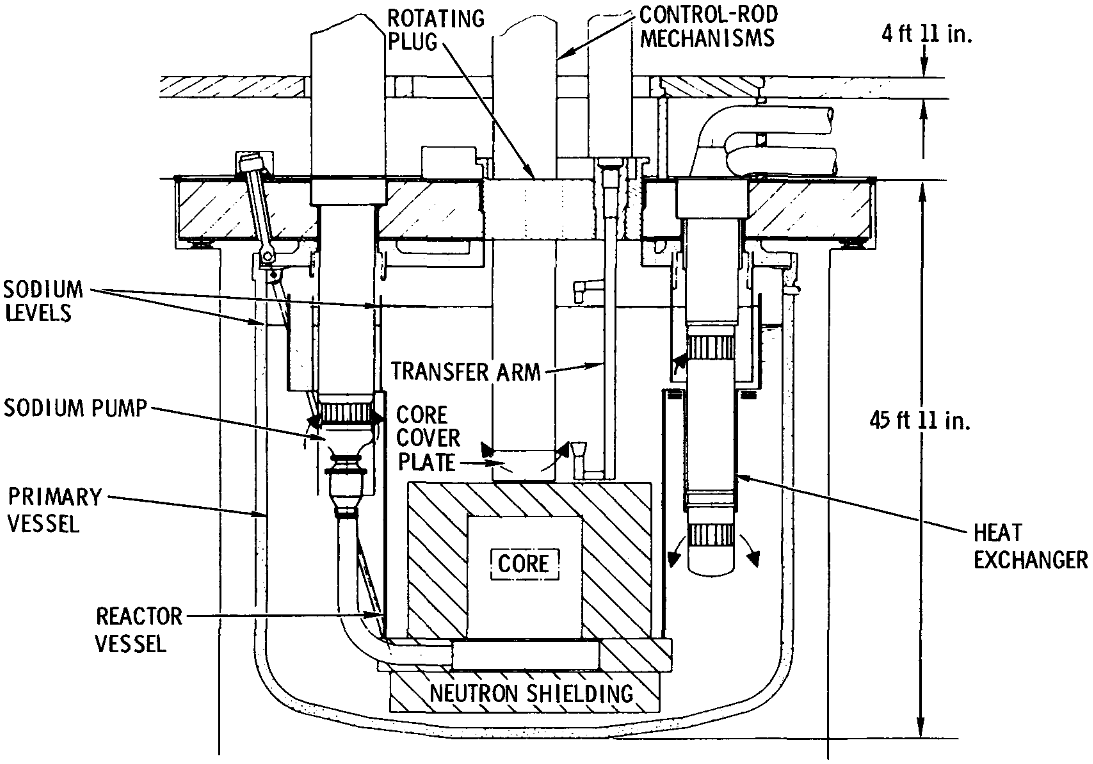


Fig. 1.21 Phenix reactor pool arrangement elevation.

	°F	°C	°F	°C
Superheated steam temperature	959	515	1004	540
Primary sodium temperatures				
Core outlet	1049	565	1058	570
Core inlet	761	405	788	420
Primary sodium ΔT	288	160	270	150
Secondary sodium temperatures				
Intermediate-heat-exchanger outlet	1018	548	1040	560
Intermediate-heat-exchanger inlet	676	358	680	360
Secondary sodium ΔT	342	190	360	200

1-4.14 *UKAEA Prototype Fast Reactor*

The Prototype Fast Reactor (PFR) [90] is the first commercial-size fast breeder reactor to be built by the UKAEA. The plant is to be a prototype and demonstration unit that will verify as far as possible the economic incentive for developing large LMFBR's. It is being constructed at Dounreay, Scotland, and was scheduled for completion in 1970 with full-load operation in 1971. The principal plant parameters are presented in Table 1.7.

The 250-Mw(e) power output of the

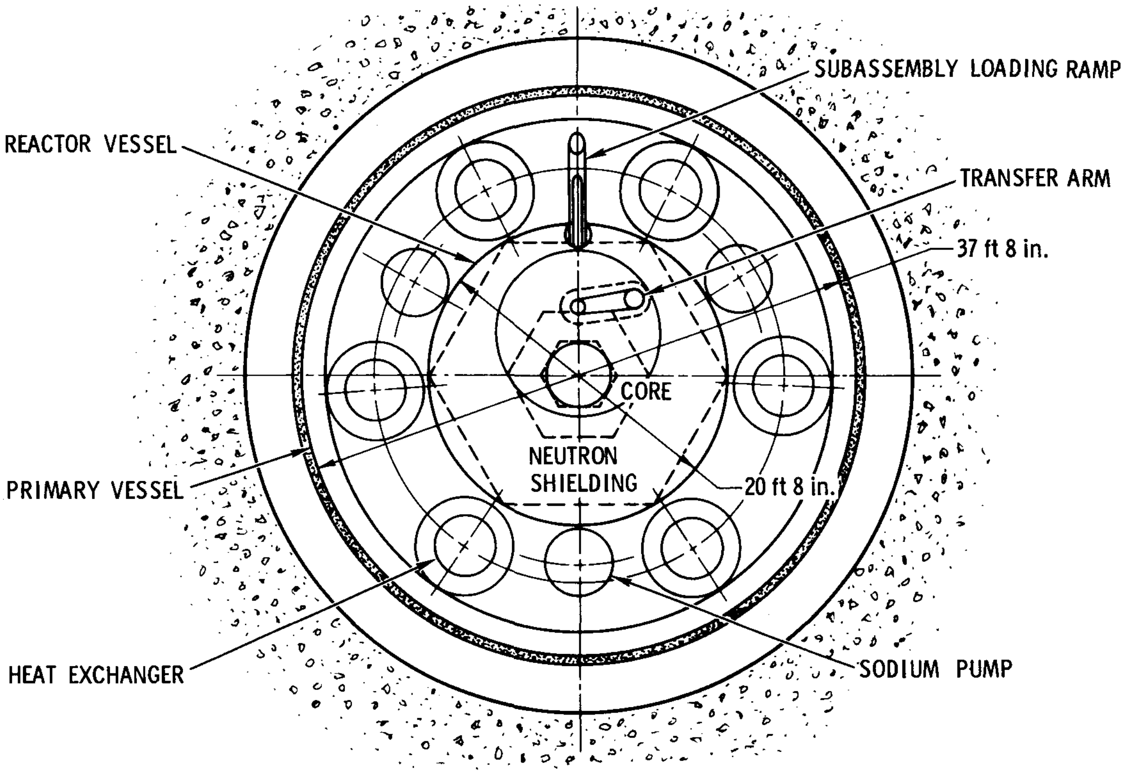


Fig. 1.22 Phenix reactor pool arrangement section.

TABLE 1.7 - Main UKAEA PFR Parameters

Thermal output	
Core	559 Mw(t)
Blanket	41 Mw(t)
Gross electrical output from generator	∿265 Mw(e)
Net electrical output from station	∿248 Mw(e)
Coolant temperature at core inlet	752 to 806°F
Coolant temperature at core outlet	1040 to 1110°F
Secondary sodium temperature at steam-generator inlet	986°F
Secondary sodium temperature at steam-generator outlet	698°F
Primary flow through core	23.2×10^6 lb/hr
Primary pump head	117 psi
Secondary coolant flow	23.2×10^6 lb/hr
Secondary pump head	45 psi
Diameter of primary vessel	40 ft
Weight of sodium in primary vessel	900 tonnes
Steam temperature at throttle valve	955 to 1050°F
Steam pressure at throttle valve	2315 psia
Reheat inlet pressure	495 psia
Feed temperature	550°F

PFR is based on the requirement that it should be the smallest reactor capable of providing, with confidence, the information necessary to install and operate commercial fast reactors in the United Kingdom in the later 1970's or early 1980's. After consideration of the fuel development, physics and safety aspects, and finally the engineering features of the reactor, it was concluded that a minimum power output of 600 Mw(t) was necessary.

The main features of the design are the ceramic fuel elements, the layout and containment of the single-tank primary circuit, the fuel-handling arrangements, the single-wall steam generators, and the adoption of temperatures that permit modern steam conditions of 2300 psig at 960 to 1050°F (162 kg/cm^2 at 516 to 566°C). A simplified flow diagram for the plant is shown in Fig. 1.23.

The primary system is preheated by a closed-loop circulating hot-argon system. Low-voltage radiant electric heaters installed between the leak jacket and the vault concrete reduce heat losses. The primary system is preheated to about 350°F at which point the hot-gas system is stopped and all temporary connections are broken. The electrical system is left energized during sodium transfer. The system is filled with 300°F sodium.

(a) *Secondary Circuits*

A secondary sodium system with three circuits in parallel is shown diagrammatically in Fig. 1.23. The three secondary loops are not interconnected in any way; thus leakage can result in the draining of one loop only.

The steam-generator units are shell-and-tube heat exchangers with provision for isolating the the effects of a sodium-water reaction and dumping the reacting fluids (see Vol. II, Chap. 4, for details).

The entire secondary loop outside the steam generator is fabricated of 321 stainless steel with full radiographed butt welding throughout. All pipework and vessels containing sodium are electrically trace heated.

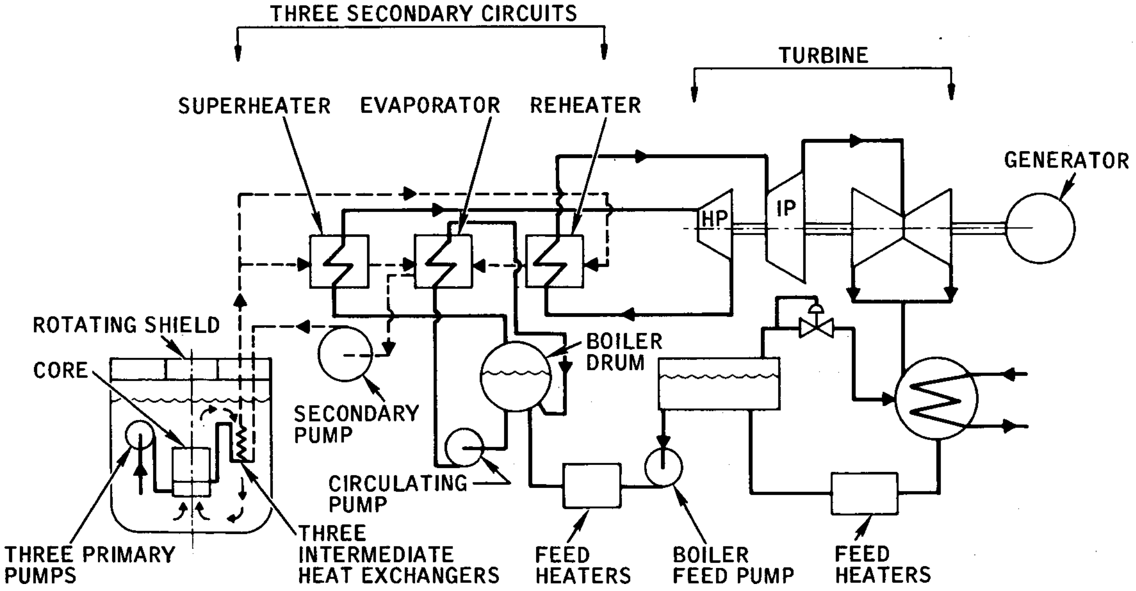


Fig. 1.23 Schematic flow diagram of Prototype Fast Reactor plant [90].

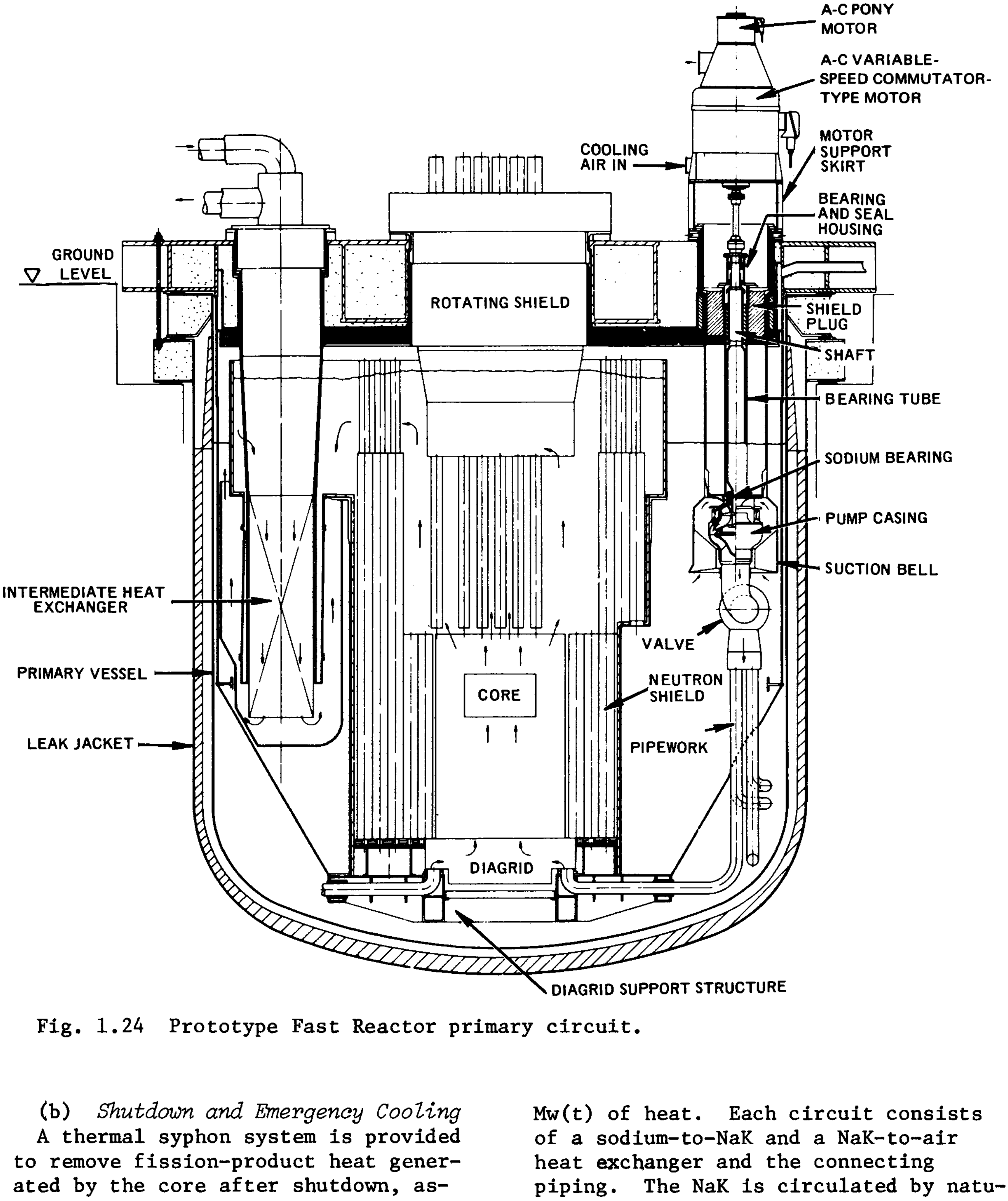


Fig. 1.24 Prototype Fast Reactor primary circuit.

(b) *Shutdown and Emergency Cooling*

A thermal syphon system is provided to remove fission-product heat generated by the core after shutdown, assuming complete power failure. The system consists of six independent circuits, and each can remove 0.75 Mw(t) of heat. Each circuit consists of a sodium-to-NaK and a NaK-to-air heat exchanger and the connecting piping. The NaK is circulated by natural convection between the two heat exchangers. Each circuit incorporates a thermal-expansion tank with an argon blanket over the NaK.

(c) *Primary Circuit* (*Fig.* 1.24)

It was considered that the prototype should give experience of operating multiple loops in parallel. Kinetic analysis showed that the failure of one pump in three gave an acceptable transient; so three primary loops were adopted. The size of a primary pump [approximately 18,000 gpm (82,000 liters/min)] represented a reasonable intermediate step between the experimental pump already under test and the larger pumps envisaged for later reactors. A comparison of mechanical and electromagnetic sodium pumps indicated that the mechanical pump had greater potential for extrapolation to large outputs as well as a clear advantage in efficiency. Mechanical pumps were therefore chosen for the PFR.

All primary circuit components are supported from the vault roof and can be withdrawn for maintenance. Sufficient internal shielding allows maintenance on components, such as pumps and heat exchangers, once adhering primary sodium has been removed.

Each sodium-to-NaK heat exchanger is an 18/8/1 stainless-steel coiled tube having an inside diameter of 4 in., a wall of 0.080 in., and an effective length of 70 ft. The coil is supported from the vault roof and is permanently installed in the high-temperature distribution tray. Sodium flows over and around the coils. The ends of the coil extend through the vault roof, where they are welded to pipes that lead to and from the NaK-to-air heat exchangers; the circuit is thus completed.

Each NaK-to-air heat exchanger consists of 13 stainless-steel finned U-tubes. Air flow across the tubes is by natural draft of outside air to the chimney stack, which is of mild steel and is 11 ft in diameter and 150 ft in height. Air flow across the six heat exchangers is controlled by louvers actuated by local or remote manual control. The louvers open automatically on power failure by loss of current to an electromagnetic holding device.

There are two types of "last ditch" cooling: (1) Outside air supplied to a sump below the reactor leak jacket circulates upward in the annulus between the leak jacket and the concrete vault. The upward-moving air extracts heat from the leak jacket and is then collected near the top for discharge to the outside through a stack. (2) Should the heat generation exceed the capacity of the air system, an ultimate system would flood the annulus with seawater and permit atmospheric-boiling heat transfer.

(d) *Fuel Handling*

Since the choice of the refueling system can have a marked effect on the reactor layout, availability, core instrumentation, and experimental facilities, requirements of a commercial reactor system were studied very carefully before the PFR arrangement was settled. There was a small economic incentive in favor of an on-load refueling system for a commercial fast reactor. The complexity of the mechanisms and problems of core design, however, were believed to decrease reliability of the system enough to reduce the calculated gain. Also, there were the problems of controlling reactivity and coolant flow during the refueling operation. For these reasons on-load refueling was rejected for the PFR.

The problems in transferring highly rated subassemblies from a sodium system shortly after shutdown made it necessary for the subassemblies to be transferred under sodium until the decay heat had fallen to such a level that reduced cooling could be accepted. The depth of the primary tank was affected considerably by this requirement.

(e) *Safety Principles*

The PFR safety principles are summarized as follows:

1. Loss of coolant from the core is discounted because all penetrations in the primary tank are in the roof and there is a completely separate leak jacket. The primary circuit and leak jacket are contained in a concrete vault below ground level.

2. Temperature transients due to coolant-flow failure are controlled by tripping the reactor (guaranteed by a multiplicity of trip parameters) and by sufficient pump inertia to restrict the maximum temperature to acceptable values. The large volume of sodium in the primary tank is directly cooled at all times by a number of independent natural-convection loops.

3. Reactivity transients are controlled by limiting the maximum rate of reactivity insertion, assuming all absorber is moved simultaneously to a value such that the transient can be terminated by reactivity trips without exceeding fuel-failure temperatures.

4. Propagation of certain subassembly faults cannot yet be ruled out, and therefore the inherent strength of the primary tank, leak jacket, and vault has been exploited to provide a containment system. A series of model tests has demonstrated the adequacy of this containment arrangement.

1-4.15 *Fast Flux Test Facility*

The FFTF [91] consisting of a fast test reactor and supporting auxiliaries is planned for construction at Richland, Wash., to serve as a primary irradiation test facility for the USAEC's LMFBR development program [92].

In 1964 the Pacific Northwest Laboratory (PNL), operated by Battelle Memorial Institute for the USAEC, began studies and preparatory designs for such a national fast-neutron-flux testing facility. Envisioned for at least five years prior to 1964, the FFTF is now being designed and built by the Hanford Engineering Development Laboratory, operated by the WADCO Corp.

The objective of the FFTF is to provide adequate and flexible testing space for the many LMFBR fuels and materials that will be developed for the demonstration and commercial fast breeders [93]. Its power level of about 400 Mw(t) will provide a fast-neutron-flux, temperature, and coolant environment similar to that of a commercial breeder. The successful achievement of high fuel burnup required for economic operation of the fast breeders will depend largely on the FFTF.

This brief description of the sodium coolant systems for the FFTF was obtained from Ref. 91, which describes the reference concept.

This concept was developed to fulfill the following objectives:

1. Providing an adequately controlled environment in fast neutron flux for highly instrumented fuels and materials irradiation tests with capabilities for fuels testing to failure in dynamic sodium and for testing specimens for short duration (minutes).

2. Providing facilities for preirradiation testing to characterize the experiments for safety and performance, for interim nondestructive examination, and for postirradiation examination.

3. Serving all U.S. fast flux needs consistent with the primary objectives of fuels and materials testing.

The Bechtel Corporation is the architect-engineer for the FFTF, and the Westinghouse Electric Corporation is the prime contractor for reactor design. The following description represents a preliminary conceptual design of the FFTF prepared by PNL.

The reactor heat transport system provides cooling for the reactor driver fuel and reactor-vessel internal parts other than closed-loop test fuels, which are cooled by separate systems.

The system transfers reactor thermal power to a circulating liquid-sodium coolant and waste heat from the sodium to an air-cooled heat dump. Figures 1.25 and 1.26 illustrate the process-flow arrangement.

The overall system is comprised of four independent, parallel cooling circuits of equal power-handling capability. Each of the four circuits is made up of a primary-system loop, a secondary-system loop, and an air heat dump.

The system can provide a nominal 400 Mw(t) when any three of the four cooling circuits are operating with a reactor outlet sodium temperature at 1100°F. For initial reactor operation, the system capability is 400 Mw(t) when all four of the cooling circuits are operating with a reactor outlet sodium temperature above approximately 865°F.

(a) *Primary Sodium System*

The primary sodium system cools the driver fuel, reactor vessel, and other internal parts of the reactor vessel. Sodium circulated through the four closed piping loops transports the reactor heat to intermediate sodium-to-sodium heat exchangers. The four loops have common flow paths through the reactor vessel but are otherwise independent in operation. Each loop includes one pump and one heat exchanger.

Heat is transferred from primary to secondary sodium systems within the intermediate heat exchangers. The heat-exchanger tube bundles isolate activated primary sodium from the secondary system, and thus they serve as barriers to prevent the transport of radioactive sodium and fission products out of the containment structure. This arrangement permits design flexibility for locating heat-dump equipment outside the containment structure in accessible unshielded areas.

Centrifugal-type sodium pumps are located downstream of the heat exchangers. Variable-speed pump drives adjust the sodium flow rate. The pumps are equipped with auxiliary pony motors to provide low-flow conditions required during reactor refueling and standby operation. Energized from the plant emergency electric-power supply, the pony motors provide backup cooling if the normal power supply fails.

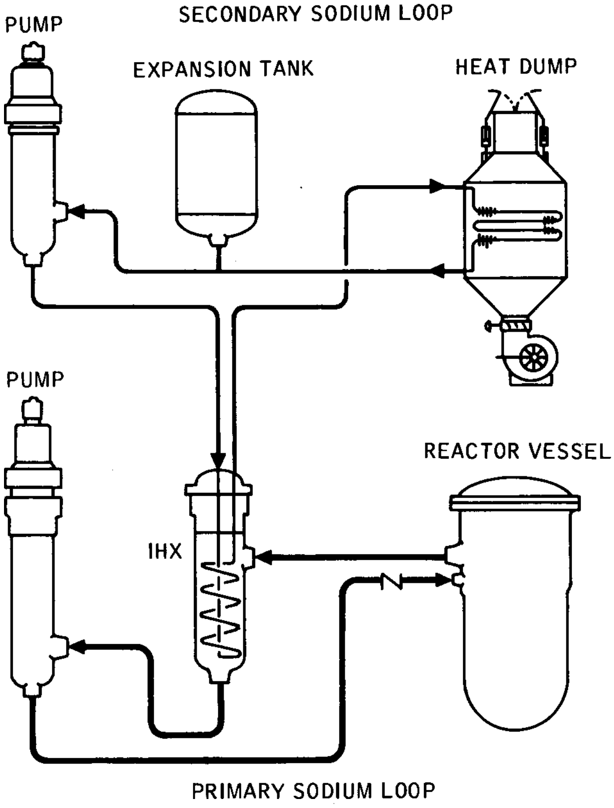


Fig. 1.25 Reactor heat-transport system.

Pressure control of inert cover gas above the free surfaces maintains system operating pressure at the reactor-vessel outlet. The sodium level within the reactor vessel is fixed by an overflow to a surge tank.

The relative elevation of reactor-core and heat-exchanger thermal centers establishes a driving head for natural-convective sodium flow adequate for reactor decay-heat cooling following an emergency reactor shutdown.

All reactor-vessel nozzles are

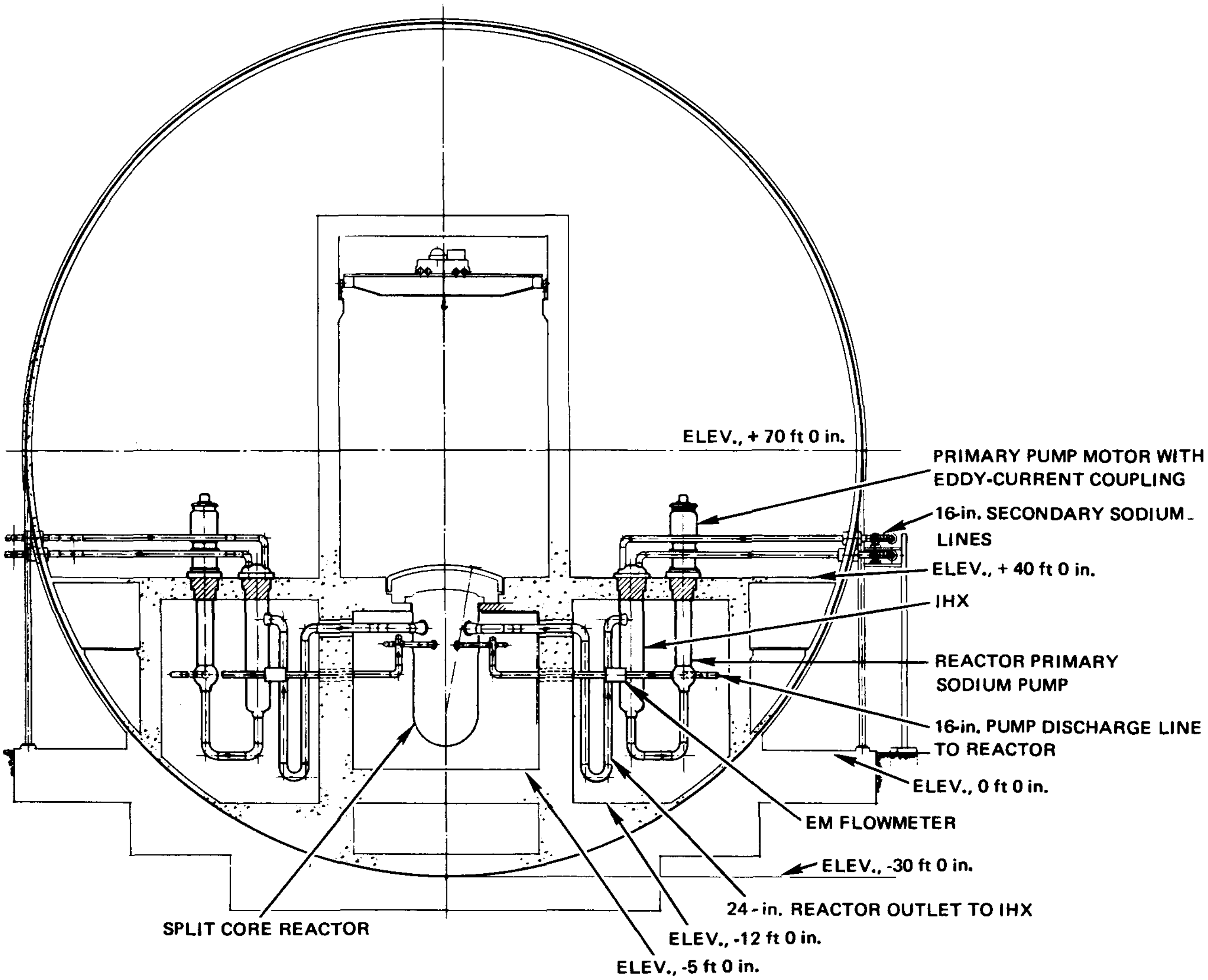


Fig. 1.26 Fast Flux Test Facility heat-transport-system arrangement.

located above the top of the core. Siphon breaks are installed to prevent the reactor sodium from draining below the vessel nozzles if a pipe leaks. Check valves in each pump discharge line prevent sodium backflow following a pump shutdown.

For minimum potential sodium leaks, permanently installed valves are not used for system gravity drain. Temporary dip tubes installed through openings located above normal reactor sodium level are used to drain the system.

Primary-system components, other than pump-drive motors, are installed in shielded vaults below the main operating floor and adjacent to the reactor vault. Shielding is provided between primary-system components and habitable building areas. An inert-gas atmosphere minimizes fire hazards in the primary equipment vault.

The major primary-system components are:

1. Primary sodium pumps and electric-motor-driven equipment.
2. Primary side of intermediate heat exchangers.
3. Check valves for pump discharge.
4. Piping.
5. Pipe and equipment supports.
6. Thermal insulation.
7. System preheat equipment.
8. Control and surveillance instrumentation.

(b) *Secondary Sodium System*

The secondary sodium system receives heat transferred from the primary side of the intermediate heat exchangers and transports the heat to the air heat dumps. There are no sodium interconnections between the four secondary system loops, and thus individual loops can be selectively operated. Centrifugal pumps located in the system cold-leg piping circulate the sodium coolant.

Expansion tanks accommodate sodium thermal expansion and establish the required pump net positive suction head for secondary pumps. System operating pressure is maintained by control of inert-gas makeup and vent to the expansion tanks. Sodium pressure at the intermediate heat exchangers is maintained above the primary-system pressure to avoid radioactive contamination of secondary sodium if a heat-exchanger tube leaks.

The physical arrangement of secondary-system components promotes natural-convective sodium flow adequate for reactor decay-heat removal following a reactor shutdown.

Other than the secondary sides of the intermediate heat exchangers and piping connections at the heat exchangers, secondary-system components are located in accessible, unshielded building areas outside the reactor-system containment vessel. Piping runs to the heat dumps are located outdoors and above ground level.

The major secondary-system components are:

1. Secondary sodium pumps and electric-motor-driven equipment.
2. Secondary side of intermediate heat exchangers.
3. Expansion tanks.
4. Valves as required for heat-dump module isolation, sodium drain, and vent.
5. Piping.
6. Pipe and equipment supports.
7. Thermal insulation.
8. System preheat equipment.
9. Control and surveillance instrumentation.

(c) *Heat-Dump System*

The heat-dump system transfers heat from secondary-system sodium to ambient air. The heat dumps are the forced-draft type, using motor-driven blowers and fin-tube heat-exchanger coils. The cooling rate is modulated over the reactor-power range by controlling air flow. Heated air is discharged through exhaust stacks. Stack heights are designed to promote natural draft adequate for removing reactor decay heat.

The heat-dump exchangers are located in an outdoor area adjacent to reactor-plant buildings.

The heat-dump components are:

1. Heat-exchanger fin-tube coil sections.
2. Cooling air blowers and electric-motor drives.
3. Coil casings, ductwork, breeching, and exhaust air stacks.
4. Structural supports.
5. Thermal insulation.
6. Preheat equipment.
7. Control and surveillance instrumentation.

(d) *Inert-Gas Service System*

Three inert gases are used in the FFTF: argon, nitrogen, and helium. Argon is used as a cover gas for low-temperature liquid-metal systems, as an atmosphere for irradiated-fuel-handling cells, and as an alternate cover gas for closed-loop primaries and the fuel-handling machine. Nitrogen is used as an atmosphere in radioactive-sodium equipment rooms, and helium is used as a cover gas for high-temperature liquid-metal systems.

(e) *System Process Conditions*

Table 1.8 lists the general system design and performance conditions which typify the design for operation using advanced driver fuels. Operation with three of the four available cooling

TABLE 1.8 - Process Conditions for Ultimate Operation Using Three Cooling Circuits [91] (Data given are for one of the three operating circuits)

Power-handling capability	133 Mw(t)/loop
Sodium temperatures	
Reactor-vessel outlet (IHX primary inlet)	1100°F
Reactor-vessel inlet (IHX primary outlet)	800°F
Heat-dump inlet (IHX secondary outlet)	975°F
Heat-dump outlet (IHX secondary inlet)	675°F
Air temperatures	
Heat-dump inlet	100°F
Heat-dump outlet	500°F
Flow rate	
Primary sodium	5.02×10^6 lb/hr/loop
Secondary sodium	4.98×10^6 lb/hr/loop
Heat-dump air	4.42×10^6 lb/hr/loop
Reactor-vessel cover-gas pressure	< 10 in. H_2O
Primary-system pressure loss	
Reactor vessel	120 psi
Intermediate heat exchanger (shell side)	3 psi
Piping system	20 psi
Total pressure loss	143 psi
Secondary-system pressure loss	
Dump heat exchanger	16 psi
Intermediate heat exchanger (tube side)	2 psi
Piping system	66 psi
Total pressure loss	84 psi
Nominal pipe diameters (OD)	
Primary	
Reactor outlet to pump suction	24 in.
Pump discharge to reactor inlet	16 in.
Secondary	16 in.
Maximum pipe velocities	
24 in. (primary)	9.3 ft/sec
16 in. (primary)	20.6 ft/sec
16 in. (secondary)	21.1 ft/sec

circuits and 400-Mw(t) total reactor power generation is assumed.

1-4.16 *Design Studies of 1000-Mw(e) Sodium-Cooled Fast Reactors*

Five independent design studies [94-100] have been made on a 1000-Mw(e) ceramic-fueled fast breeder reactor cooled with liquid sodium. These studies were focused on the reactor and primary heat-removal systems and represent the first phase in the

USAEC's program to develop basic fast breeder concepts for large commercial power stations. The objectives in the studies were to develop designs that optimized fuel-cycle costs, obtained attractive fuel-doubling times, and permitted high-temperature steam conditions at the turbine consistent with safety requirements in fast reactors. The studies thus included core physics and thermal-hydraulic analysis, mechanical design features, fuel-handling concepts, and fuel-cycle economics.

Some of the design parameters of each of the five designs are given in Table 1.9. Also included are the characteristics of Argonne National Laboratory (ANL) 1000-Mw(e) design study [101] and the Karlsruhe 1000-Mw(e) study [102].

The design studies [103] are being continued for the USAEC to obtain information for reference designs of 1000-Mw(e) plants; they will identify the research and development programs required for the creation of such plants. The design will be based on estimates of the state of technology by 1980, the effects of fuel costs, the installed generating capacity and growth rate of the power industry at the time, efficient use of natural resources, and public safety.

In addition to these USAEC-funded studies, a number of utilities are participating with reactor manufacturers in privately funded design studies for LMFBR demonstration plants. These studies are based on current technology for plants in the range of 300 to 500 Mw(e) for operation in the 1970's.

1-4.17 *10,000-Mw(t) Very Large Fast Breeder Reactor (VLFBR) - Conceptual Design*

As part of the USAEC's desalting program, a conceptual design study [104] was performed by Argonne National Laboratory with the aid of Westinghouse Electric Corporation as a subcontractor to determine the feasibility of a nuclear stream supply system utilizing a very large sodium-cooled fast breeder reactor. The design was concluded to be feasible. Sodium-cooled fast breeder reactor plants of 10,000 Mw(t) size should be considered as being evolutionary from nominal 2500-Mw(t) commercial fast reactor designs.

Some salient features of the design studied include an annular-type reactor with carbide fuel in the core, a reactor outlet temperature of 1050°F, and steam conditions of 2400 psia and 900°F with live-steam reheat to 660°F. Some of the plant data are given in Table 1.10.

The design of the primary coolant circuit is based on the loop concept, in which all primary circuit equipment is in individual complete loops. Six primary and six secondary loops, with the steam generators paired to each of three turbine generators, were selected for the conceptual design.

The primary system has been designed with the following safety provisions:

1. The entire radioactive primary sodium system is housed in a spherical steel containment building 240 ft in diameter and 1 1/2 in. in thickness.
2. The primary sodium heat-transport system has been designed so that it is impossible to syphon the reactor vessel and thus uncover the core. Syphon breakers are placed in the reactor-vessel sodium-inlet annulus and all reactor-vessel nozzles are brought in at an elevation higher than the core. Also, there are no drains in the reactor vessel.
3. The reactor vessel is surrounded by a second vessel to contain sodium in the unlikely event of a sodium leak in the reactor-vessel proper.
4. Reactor decay heat can be removed by natural-convection flow of sodium in the six main loops or by a separate auxiliary sodium loop powered by electromagnetic pumps or by both.

TABLE 1.9 - Heat-Transport-System Design Parameters from 1000-Mw(e) Fast Reactor

Parameter	Allis-Chalmers [95]	Atomics International [99]	Combustion Engineering [96]
Electrical output, Mw(e)	1000	1000	1000
Reactor thermal power, Mw(t)	2500	2500	2500
Reactor outlet temp., °F	1200	1075	1100
Reactor inlet temp., °F	950	750	850
Reactor flow (total), lb/hr	1.14×10^8	0.87×10^8	1.136×10^8
No. of primary loops	6	5	6
No. of primary pumps	6	5	6
Primary pump flow rate, gpm	50,000	36,300	50,000
Primary pipe size (s), in.	36 and 30	32 and 30	36 and 30
Pipe material	316 S.S.	304 S.S.	316 S.S.
Secondary outlet temp., °F	1140	985	1050
Secondary inlet temp., °F	650	635	750
Secondary flow rate, lb/hr	0.58×10^8	0.86×10^8	0.942×10^8
No. of secondary loops	6	5	6
No. of secondary pumps	6	5	6
Secondary pump flow rate, gpm		36,300	40,000
Secondary pipe size (s) in.	30	32 and 30	28

The auxiliary loop is placed lower than the main sodium loops and is double contained so that loss of sodium in the auxiliary loop and core is virtually impossible.

Each primary-system loop has one heat exchanger and one pump connected by 4-ft-diameter piping. The loops are connected symmetrically around the reactor vessel; the inlet nozzles are staggered and are at a lower elevation than the outlet nozzles. A seventh piping loop (the auxiliary loop) is to remove reactor decay heat in emergency situations. Check valves in each main loop and in the auxiliary loop prevent flow reversal during pump outages. A simplified flow diagram is

Design Studies			
General Electric [97]	Westinghouse [98]	Argonne National Laboratory [101]	Karlsruhe [102]
1000	1000	1000	1000
2500	2500	2510	2500
1100	1200	1000	1076
800	979	720	806
0.954×10^8	1.28×10^8	1.01×10^8	1.04×10^8
6	2	6	2
6	4	6	4
37,500	80,000		3296 kg/sec
∿ 30 and 22	68-53 coaxial	30 and 24	67-75-87.7 coaxial
304 S.S.	300 series		
1050		960	1040
720		665	680
0.86×10^8		0.978×10^8	0.781×10^8
6	2	6	2
6			

shown in Fig. 1.27. Figures 1.28 and 1.29 depict primary-system layout and design.

Primary sodium flows around the circuit in the following manner. From the outlet plenum in the reactor vessel directly above the core, sodium flows by gravity to the pump inlets and is then pumped through the shell side of the intermediate heat exchangers to the reactor vessel. Flow in the reactor vessel leaves the inlet nozzles, passes down the annulus bounded by the reactor vessel and core barrel, and enters the high-pressure and intermediate-pressure plenums between the core-support grid plates. The circuit is completed as the

TABLE 1.10 - Reference VLFBR Plant Data

General data	
Gross reactor power	10,000 Mw(t)
Core power	8200 Mw(t)
Net plant output	3880 Mw(e)
Sodium reactor inlet temperature	720°F
Sodium reactor outlet temperature	1050°F
Steam pressure at turbine throttle	2400 psia
Steam temperature at turbine throttle	900°F
Net plant heat rate	8800 Btu/kw-hr
Number of primary loops	6
Number of steam generators	6
Number of turbine generators	3
Primary and secondary sodium systems	
Primary	
Sodium flow	3.4×10^{8} lb/hr
Sodium temperature rise	330°F
Number of pumps	6
Flow per pump	143,000 gpm at 1050°F
Design total head	289 ft
Nominal motor power	10,000 hp
Pumping power	6.1 Mw(e)
Intermediate heat exchanger	
Number	6
Material	316 S.S.
Area per exchanger	54,000 sq ft
Primary inlet temperature	1050°F
Primary outlet temperature	720°F
Secondary inlet temperature	620°F
Secondary outlet temperature	1000°F
Type	Vertical shell and tube
Diameter	14 ft
Height	42 ft
Secondary	
Sodium flow	3.0×10^{8} lb/hr
Sodium temperature rise	380°F
Number of pumps	6
Flow per pump	113,000 gpm at 620°F
Design total head	105 ft
Nominal motor power	3200 hp
Steam generator	
Number	6
Tube material	Incoloy 800
Area per exchanger	75,000 sq ft
Steam flow	3.7×10^{7} lb/hr
Feedwater temperature	480°F
Feedwater pressure	2600 psia
Steam outlet temperature	900°F
Steam outlet pressure	2450 psia
Type	Once through, steam in tube
Diameter	14 ft
Length	50 ft

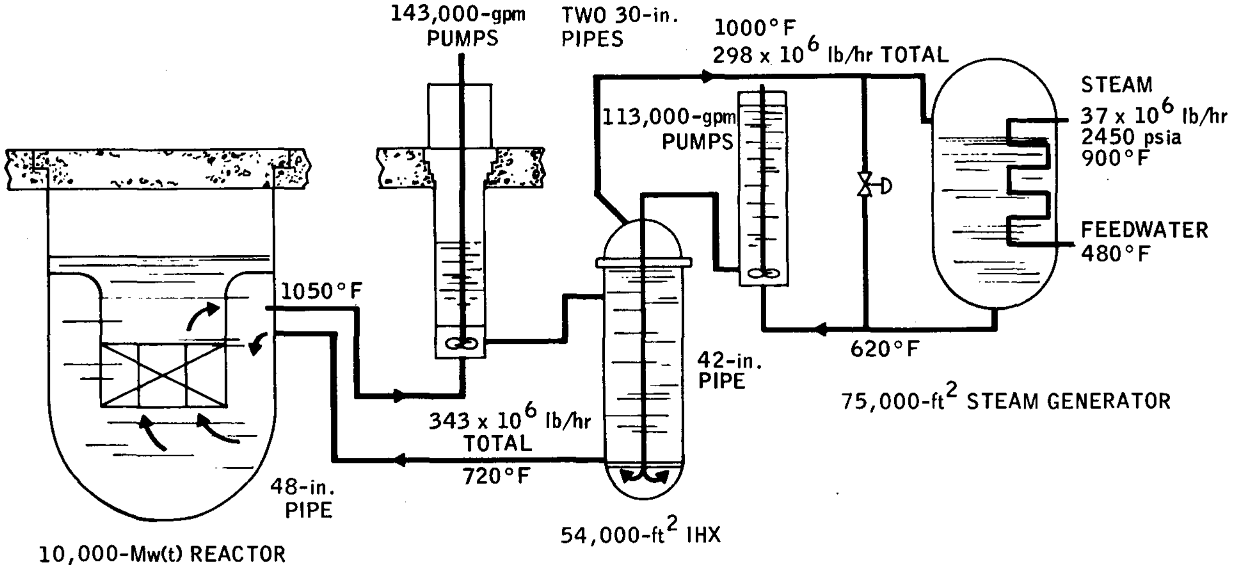


Fig. 1.27 Simplified flow diagram for 10,000-Mw(t) sodium-cooled fast breeder reactor. One loop is shown. The system has six primary loops and six secondary loops.

sodium flows up through the core, blanket, and reflector subassemblies into the outlet plenum.

Free sodium surfaces exist in the reactor vessel, the primary pump tanks, and the reactor overflow tank. Gas equalizer piping is connected between all inert cover-gas volumes to maintain equal gas pressures throughout the the system. The inert cover-gas pressure is to be maintained slightly below that of the containment-building atmosphere to prevent radioactive contamination of the primary-system containment atmosphere.

Primary piping is 304 stainless steel with a 4-ft outside diameter and 1/2-in. wall thickness. The intermediate heat exchangers and primary pumps are fixed so that thermal expansions are absorbed by the pipe loops. No gate or globe valves are specified for the 4-ft-diameter main piping.

All piping and equipment containing sodium are provided with electric heating to preheat the systems before sodium charging, to keep the sodium molten, and to maintain a specified temperature level during reactor-refueling periods. Tubular electric resistance heaters, strapped to piping and equipment surfaces, can raise and maintain the systems at a temperature corresponding to the steam-generator saturation temperature of 660°F. This minimizes downtime between standby and start-up.

The six main primary sodium pumps are electric-motor-driven, vertical-shaft, centrifugal-type, free-surface pumps with an oil-lubricated mechanical-shaft seal. Lubricating sodium flows up through the hydrostatic bearing and into the upper pump tank, where it is drained off by an overflow line that terminates at the reactor vessel. The pump casing is welded in and becomes part of the piping system.

The intermediate heat exchangers are shell-and-tube units closed at the top by tube sheets and semitoroidal heads. This type of closure has several advantages over the gasket-closure shielding-plug head: The possibility of leaking secondary sodium to the primary system is reduced by elimination of the gasket, the unit is simpler, and the shell side

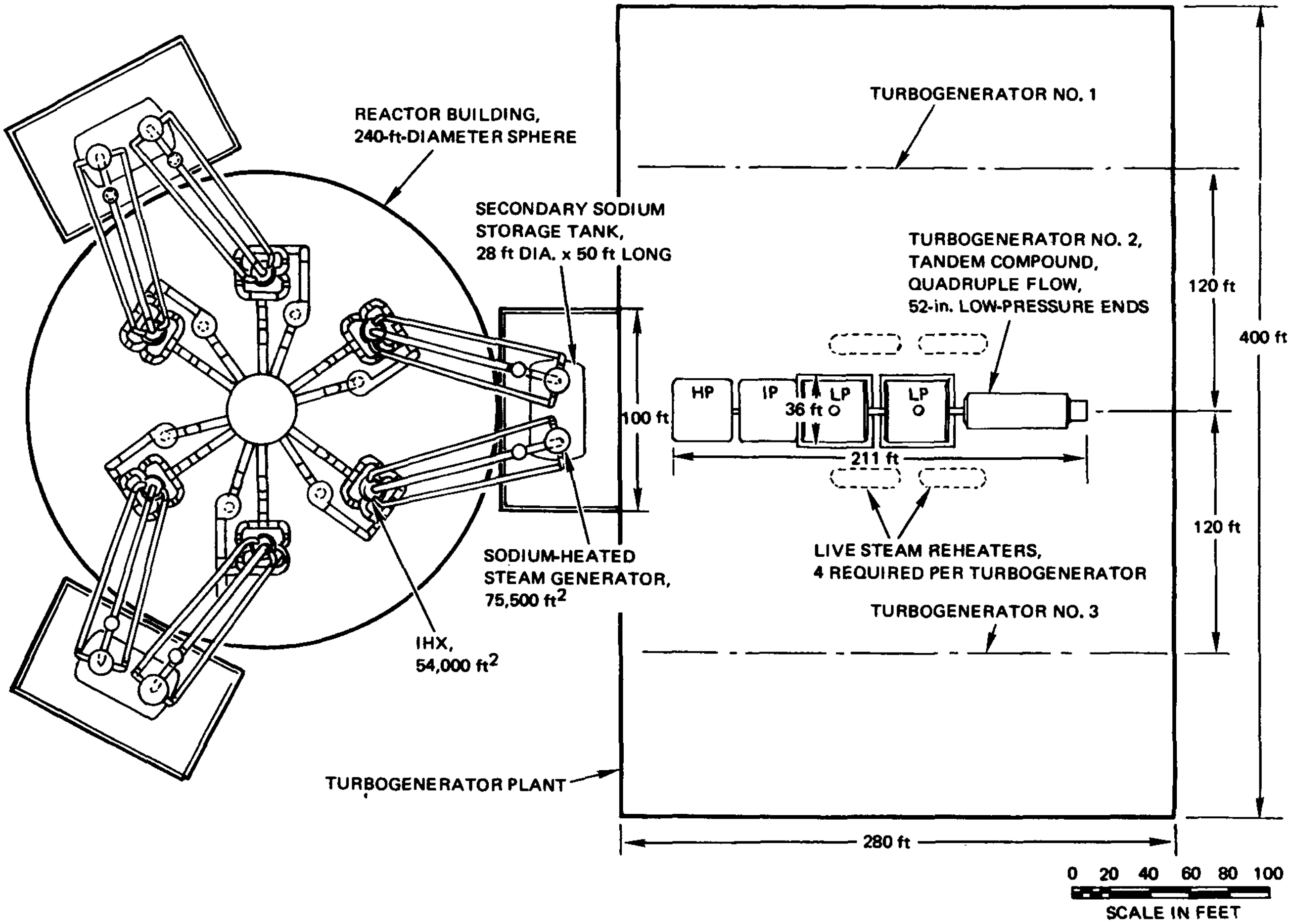


Fig. 1.28 Plan view of very large fast breeder reactor plant.

can be operated full of sodium so that level control is not required.

The cover-gas system provides an inert atmosphere over all sodium and sodium-potassium surfaces to prevent sodium oxidation. Argon gas was chosen for the cover-gas atmosphere because it is chemically inert to sodium, readily available, and heavier than air.

1-4.18 *Compact Reactor Primary Systems*

The high heat-removal capability of sodium and NaK, combined with their relatively low vapor pressure in the temperature range of interest, makes these liquid metals suitable heat-transfer media for compact nuclear reactors for such applications as space-vehicle power. Because of the low sink temperature of space and consequent coolant freezing considerations, the low melting point of NaK (12°F for the eutectic) makes this alloy preferable to pure sodium in space power systems.

(a) *SNAP-10A*

SNAP-10A is a nuclear power unit designed to produce a minimum of 500 watts of electric power for a period of at least one year in a space environment. Figure 1.30 shows the system thermodynamic cycle. Hot NaK leaves the reactor at 1040°F. A d-c Faraday conduction-type pump, composed of a permanent magnet and an integral thermoelectric power supply, causes the NaK to flow through 40 parallel stainless-steel tubes that compose the hot side of the combination radiator converter. Power is generated when heat passes through silicon-germanium

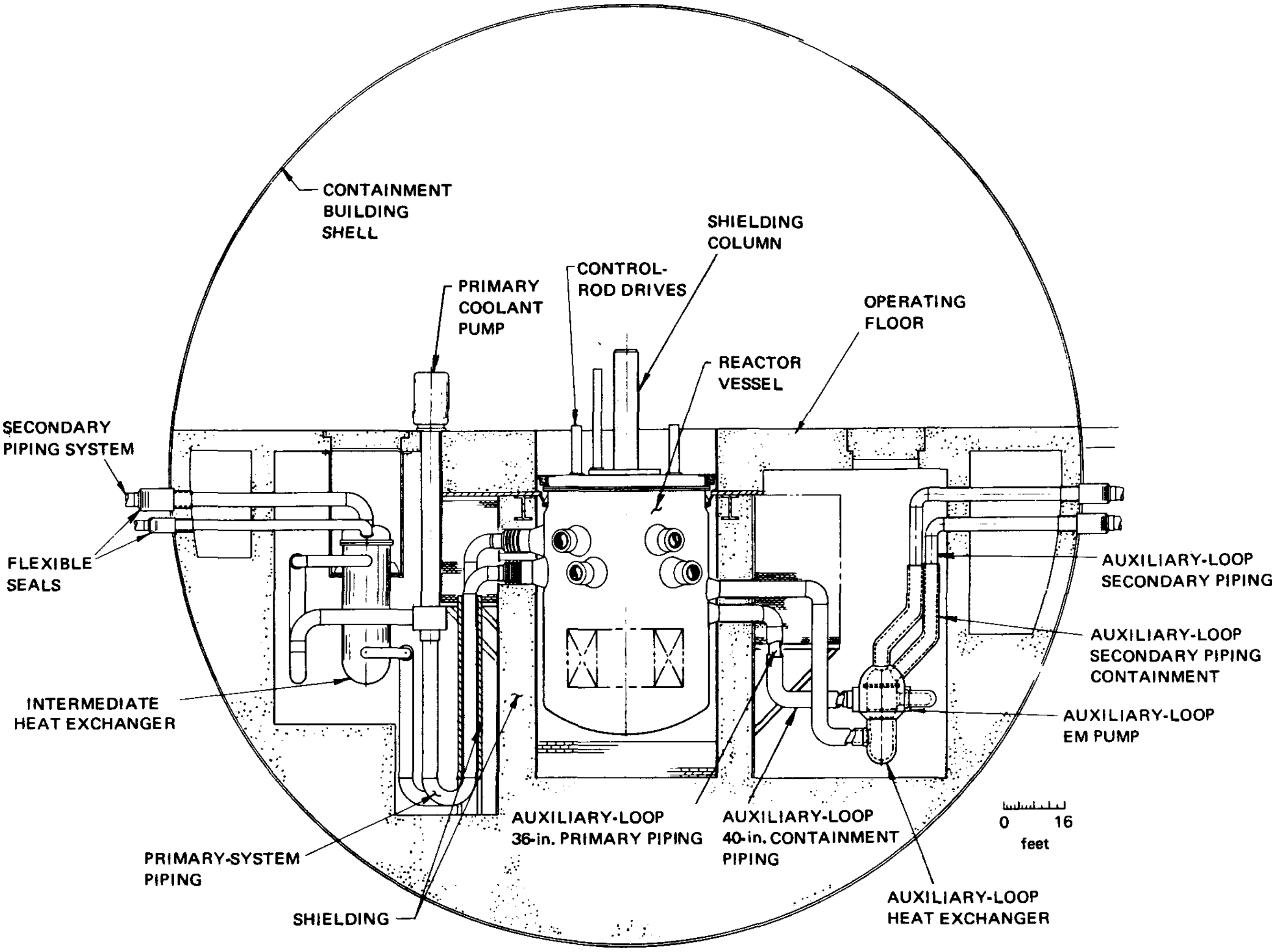


Fig. 1.29 Very large fast breeder reactor plant layout.

thermoelectric elements mounted between the NaK tubes and an aluminum radiator that dissipates the waste heat to space. The NaK reenters the reactor at 910°F.

The SNAP-10A system is reliable partly because it has no moving parts during operation. The pump and the power-conversion equipment are static systems. The reactor control drums are required to operate only while the reactor is being brought to power and until equilibrium operating conditions are established. Thereafter the reactor power is controlled statically through consumption of burnable poisons with no movement of the control elements.

Figure 1.31 presents a cutaway view of the SNAP-10A configuration. Table 1.11 lists the operating performance of two SNAP-10A systems, the ground-test system FS-3 and the flight-test system FS-4.

The SNAP-10A reactor vessel is manufactured of 316 stainless steel. The thickness of the vessel shell ranges from 0.032 in. in the side walls in the core region to 0.125 in. in the top-head and lower-plenum regions.

Bellows-type expansion compensators allow for density changes of the NaK in the closed loop. The spring constant of the bellows plus an external

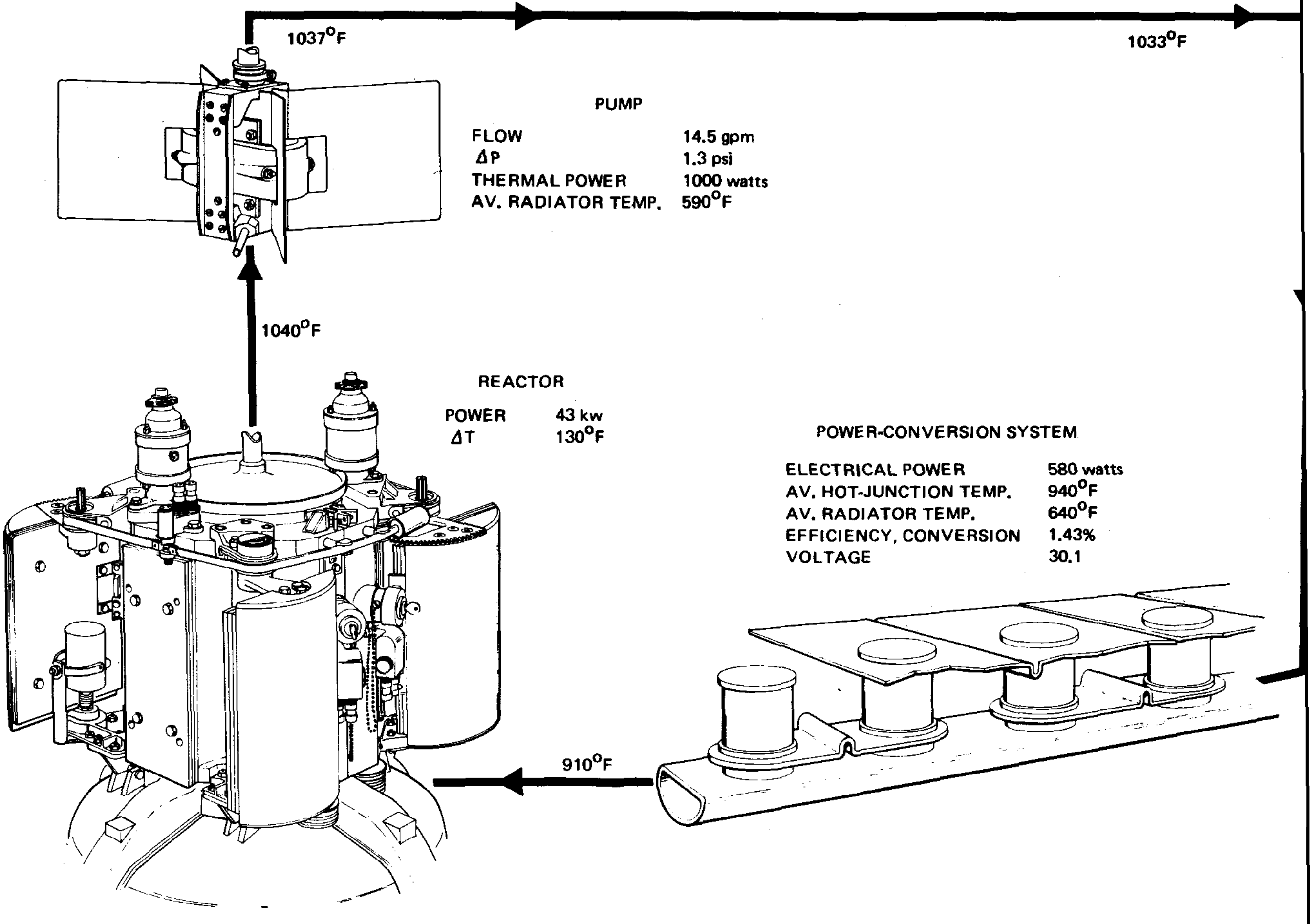


Fig. 1.30 Thermodynamic cycle of SNAP-10A.

spring mounted on the compensator provide a system pressure high enough to prevent cavitation in the pump.

(b) *SNAP-8*

The SNAP-8 reactor is a larger, more powerful, and more sophisticated version of the SNAP-10A reactor. Figure 1.32 shows the flow and temperature conditions in the SNAP-8 system. The primary loop circulates NaK-78 at 49,000 lb/hr; the coolant temperature at the reactor exit is approximately 1300°F.

The SNAP-8 is a turboelectric nuclear space power system using a mercury Rankine cycle. It is being developed jointly by the National Aeronautics and Space Administration and the USAEC to produce a minimum of 35 kw of electric power, to have high reliability, and to be capable of unattended full power operation for 10,000 hr. NaK is used as the heat-transfer medium in the reactor primary loop as well as in the heat-rejection loop, which transfers waste heat from the mercury condenser to the radiators for dissipation by thermal radiation to the space environment.

The SNAP-8 reactor core vessel is a 9.4-in.-diameter cylinder of 316 stainless steel. Hastelloy alloy C is used for the lower grid plate in the core, and stainless steel is used for the upper grid plate. The selection of grid-plate materials was based on considerations of the effect of thermal expansion on the delayed and prompt negative temperature coefficients of

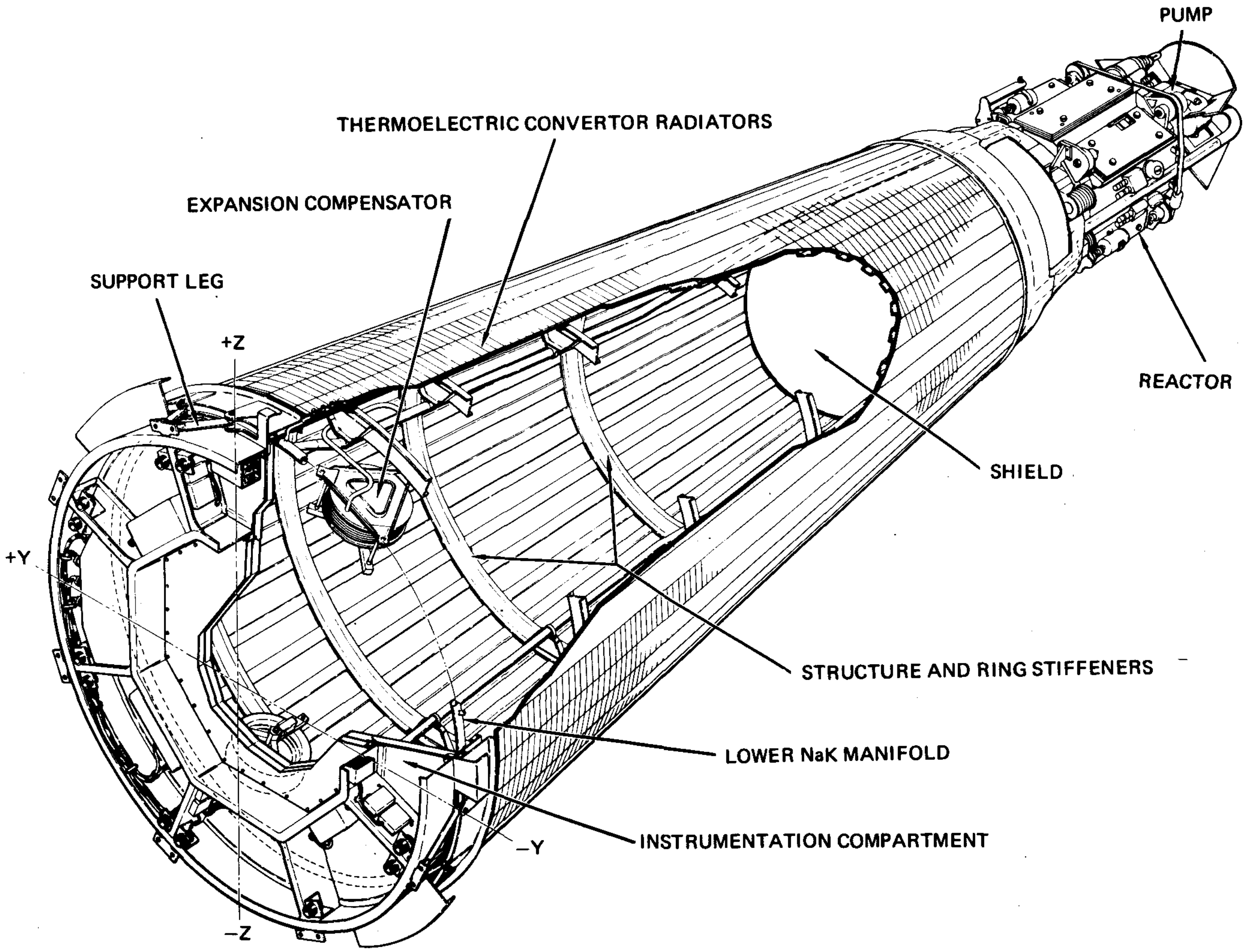


Fig. 1.31 SNAP-10A configuration.

reactivity.

The SNAP-8 reactor operating parameters are listed in Table 1.12.

Reliable NaK containment is achieved by (1) a design that minimizes weld footage, permits no core-vessel penetrations for thermocouples, and is analyzed for both static and dynamic stress loads; (2) careful welding and thorough inspection techniques covering fabrication and procurement of piping; and (3) reactor acceptance testing, which includes low-level shock and vibration, long-term circulation of hot NaK, and thermal cycles.

The SNAP-8 system contains two NaK pump-motor assemblies, one in the reactor loop and the other in the heat-rejection loop. The pump-motor assemblies are self-contained hermetically sealed units incorporating on a single shaft a centrifugal pump, a hermetically sealed drive motor, an internal coolant-lubricant circulating pump, and NaK-lubricated bearings. The NaK coolant-lubricant circuit for the pump-motor assemblies has its own filtering and heat-exchanger (to organic fluid) circuit, independent of the process pumping circuit [107].

TABLE 1.11 - SNAP-10A Actual Performance [105]

System	FS-3	FS-4
Type of operation	Ground-test simulated space environment	Earth orbit
Date initially operated	Jan. 22, 1965	Apr. 3, 1965
Launch environment	Ground-qualification-level tests	Atlas-Agena
Remote start-up	Via ground test console	Via spacecraft telemetry on ground command
Initial stabilized power	634 watts*	590 watts
Date of termination of operation	Mar. 15, 1966	May 16, 1965
Cause of termination	Successful completion of scheduled 10,000-hr test program	Believed to be failure of voltage regulator in spacecraft
Elapsed operating time	417 days	43 days
Power before termination	537 watts†	530 watts

*Corrected for space conditions.

†After reactor temperature adjustment to compensate for hydrogen leakage from fuel elements.

TABLE 1.12 - SNAP-8 Reactor Operating Parameters [106]

Thermal power, kw	600
Coolant outlet temperature, °F	1300
Coolant inlet temperature, °F	1100
Coolant flow rate, lb/sec	13.6
Coolant pressure, psia	$\sim$ 45
Coolant pressure drop, psi	$\sim$ 4

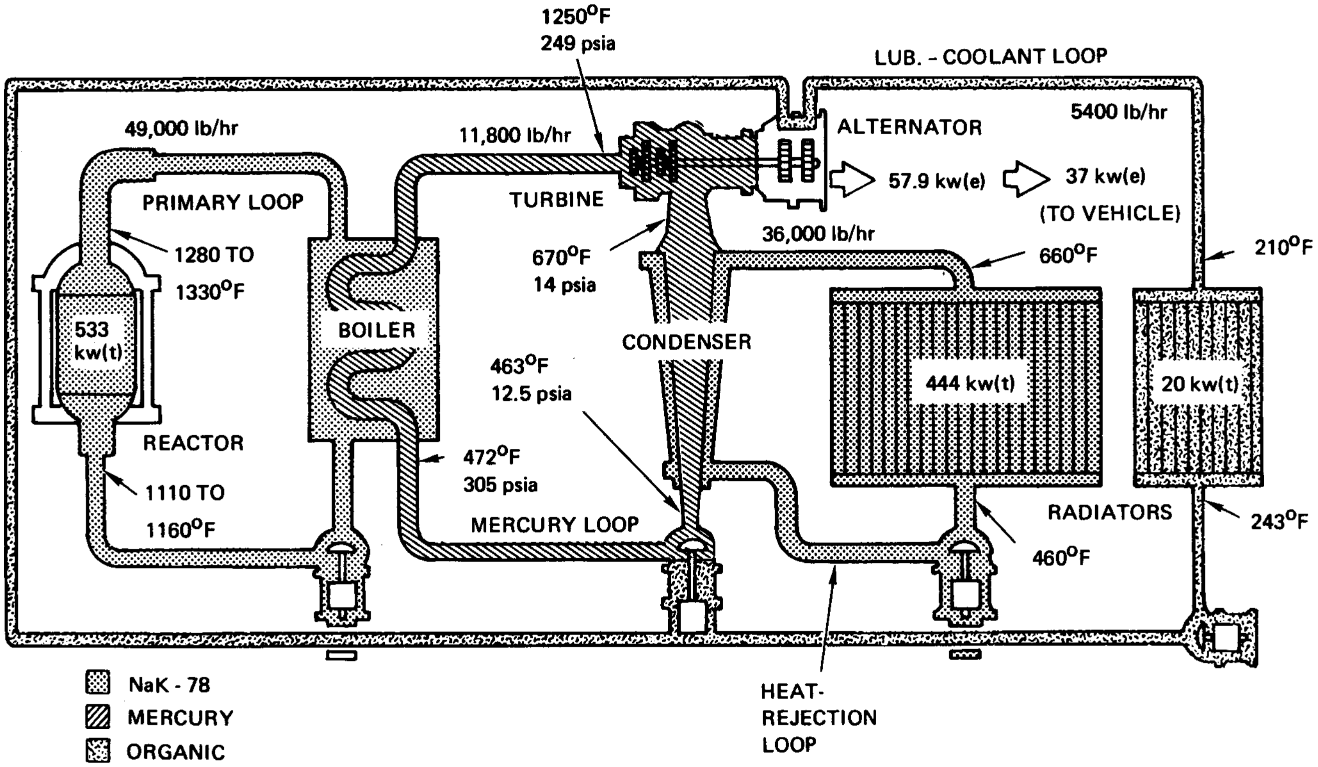


Fig. 1.32 SNAP-8 electric generating system

1-5 EXPERIMENTAL SODIUM LOOPS

The development of heat-transport systems utilizing sodium requires extensive testing and development in such areas as heat transfer, effects on materials, and component evaluation. Numerous loops have been built for investigating heat and mass transfer; a few very large loops have been and are being built for testing and developing pumps, heat exchangers, and steam generators for large sodium-cooled reactor systems.

1-5.1 *Sodium Technology Facilities in the United States*

Tables 1.13 to 1.27 represent a compilation of sodium technology facilities in the United States as of 1968. A majority of these tables were prepared by the LMFBR program office at Argonne National Laboratory and include facilities that are in operation, in standby, under construction, under design, or mothballed (i.e., partly disassembled but with main components intact). Some facilities that could be converted to use with sodium are included even though they were not specifically designed for sodium.

1-5.2 *Component Test Loops*

A number of facilities have been used for developing and testing sodium pumps, heat exchangers, and steam generators. Facilities that are designed to test components for projected large sodium-cooled fast reactor systems are themselves multimegawatt installations. Four of these facilities are described in a paper by Morabito and Savage [108], which is quoted extensively in the following text.

The four facilities discussed in this paper are: (1) the 10-Mw(t) test loop at Cadarache, France; (2) the 5-Mw(t) Grand Quevilly Station near

(Text continues on page 98.)

TABLE 1.13 - Sodium Technology Facilities at Aerojet-General Corporation

Facility designation	Construction material	Power level, kw	Temp., °F	Pressure, psig	Flow, lb/hr	Instrumentation and/or special features	Remarks
Power Conversion System Loop 1 (PCS-1)	Primarily 316 S.S.	720	To 1425	Primary NaK:50	Primary NaK: 50,000	Cold trap, plugging meters; manual and automatic flow and power control; extensive data acquisition system	Three-fluid four-loop facility for Rankine cycle system and component testing
Liquid NaK Loop 3 (LNL-3)	Primarily 316 S.S.	27	1320	100	60,000 (NaK)	Cold trap, plugging meters; fail-safe automatic shutdown system	Endurance test facility for NaK component development
Liquid Mercury Loop 5 (LML-5)	316 S.S.	7	600	500	15,000 (Hg)	Fail-safe automatic shutdown system; can simulate space vacuum conditions	Used for testing components of SNAP-8 Hg system
Mercury Corrosion Loops (CL-1 through CL-4)	CL-1 and -2, Haynes 25; CL-3, 9 Cr-1 Mo						Boiling-Hg corrosion studies
Seventh-Scale Loop			1300		1,650(Hg); 6,800 (NaK)		1/7-scale SNAP-8 system loop to study Hg boiler heat-transfer effects

TABLE 1.14 - Sodium Technology Facilities at Argonne National Laboratory

Facility designation	Construction material	Na temp., °F	Pressure	Na flow	Instrumentation and/or special features	Remarks
FARET Simulation Loop (4 and 5 in.)	304 S.S.	1200 (isothermal)	100 psig	380 gpm	Temperature, flow and ΔP indicators	For fuel-subassembly hydraulic-stability tests
Loop (2 in.)	304 S.S.	1200 to 1700	5 psig	25 gpm	Temperature, flow, and ΔP indicators	For plugging-meter and metallurgical-sample tests at high temperature
Quality control	304 S.S.	900	15 psig	15 gpm	Blake meter, United Nuclear Corp. oxygen meter, and distillation sampler	Used for comparative studies on oxygen-analysis devices
EBR-II	304 S.S.	560 to 900				
EBR-II Sodium Storage Tank	Carbon steel internally lined with 1/4-in. 304 S.S.	650 to 900	5 psig		Cold traps and quality-control loop mounted on tank	5000-gal capacity
Components Test Loop (4 in.)	304 S.S.	1200 (isothermal)	100 psig	150 gpm	Na surge tank, EM pump, Freeze-seal valve, cold trap, Calrod heater; modulator construction permits installation of instruments and components	Test section, 4 by 48 in. long; sufficient size and flexibility for many experiments
Two-Phase Heat-Transfer Standby Loop (3/16 in. diameter)	304 S.S.	1600	8 psia	5 ft/sec	Temperature, flow and ΔP indicators fitted with γ-scanner and test section for measuring two-phase composition	For flow studies with boiling sodium, 10^6 Btu/(hr)(sq ft)
Loop	Nb-1% Zr	2100	Vacuum		Electron bombardment heater	For boiling-heat transfer studies
Small TREAT Na Closed Loop (5/8 in.)	304 S.S.	2900 (max.)		$\sim$26 ft/sec	4-in.-square test section holds up to seven EBR-2 fuel pins; maximum flux, $\sim 10^{16}$ neutrons/cm^2/sec	Used in fuel-meltdown studies; could possibly be used in fission-product distribution
Large TREAT Na Loop (3 in.)	304 S.S.	935 (steady-state, electrical heating) 2900 (max.)	50 psig	150 gpm	Cold trap, by-pass flow, two level tanks recirculating and through flow, and gas scrubber train	Designed for safety studies; could possibly be used in fission-product-distribution studies
Autoclave with Small Pump Loop (1 in.)	304 S.S.	> 1200	Ambient	2 gpm	Removable dry box over test section, (40 ppm oxygen)	
Electromagnetic Flowmeter Calibration Facility Operation (1/4 to 4 in.)	304 S.S.	1200	50 psig	300 gpm	Temperature and level indicators and forced-circulation pump	For flow measurement
Tantalum Still	Tantalum					For Na distillation to purify it of metallic impurities, followed by Zr gettering
Falex Wear-Test Devices in Sodium Pots	304 and 316 S.S.	900 to 1200	Ambient		Permits all electrical readout of wear, wear rates, torque, etc.	For wear testing of reactor materials
Sodium Analytical Loop	304 S.S.	600			Resistance meter United Nuclear Corp. oxygen meter	Three 1/2-in. loops connected to common Na supply; for evaluation of in-line instruments and sampling techniques
Boiling Sodium Test Facility	Nb-1% Zr	2100	$\sim$ 100		Thermal radiation-heated boiler, radiating coil condenser, EM helical induction pump and EM flowmeter	Boiling Na studies, heat flux to 10^6 Btu/(hr)(sq ft)
Component and Materials Evaluation Loop (CAMEL)	304 S.S.	1200		184 gpm	O_2 and H_2O monitors, cold trap, plugging meter, Falex wear tester and Na distillation sampler	For testing of materials and components

TABLE 1.15 - Sodium Technology Facilities at Atomic Power Development Associates

Facility designation	Construction material	Power level, kw	Na temp., °F	Pressure, psig	Na flow	Instrumentation and/or special features	Remarks
High-temperature Sodium-Uranium Paste Flow Loop (1/2 in. diameter)	S.S.		1100	50	10 gpm	EM pump, 58 by 2-in.-diameter paste-flow test section, 3 pressure transducers, 2 temp. recorders, Fe-constantin thermocouples, 11 magnetic flowmeters, level indicators, rhometers, 5 micrometallic filters; Na vapor trap, cold trap, Zr hot-trap plugging meter, hydroclones and radiation gauge	To test two-phase ΔP's, particle mobility and attrition, and to compare performance in connection with mobile fuel (paste) programs; consists of a Na loop and a paste loop
Sodium Endurance Loop (4 in.)	S.S.	50	1000	147	300 gpm	Cold trap and in-place vacuum distillation for removal of sodium from components	Can accommodate 2 complete Fermi-sized subassemblies, about 96 in. long, in an 8-in.-diameter test section; primarily a component-endurance test loop
Sodium Technology Loop	304 S.S.		1000 max.		7.5 gpm	1- and 4-in. interconnected loops, plugging meter, 3 resistivity meters, United Nuclear Corp. meter with 4 cells, 2 sampling stations and hydroclone	To investigate Na systems, including development and evaluation of in-line instruments
Sodium Purification System	304 S.S.		Ambient to 750 (operating) to 1000 (max.)	Slightly >15 to high vacuum 1 1/2 hr (product)		Filter cascade; unit consists of 3 tanks, 2 condensers, and a filter (5-μ micrometallic)	To remove total impurities to the 1- to 10-ppm range
Hydrogen Detector Loop						Will employ analytical instrumentation	**To investigate** continuous H_2 detection
Sodium-Water Leak Facility	Test materials: 2 1/4 Cr-1 Mo 5 Cr-1 Mo 316 S.S. 304 S.S.		600°F (reaction water temp.)		1.5 to 3.0 ft/sec	Test unit 3 ft in diameter by 16 ft long: water leak rate, 4 cm^3/min to 75 cm^3/sec	Consists of 5 main systems: 1. Sodium 2. Circulating water 3. Reaction water 4. Reaction products 5. Nitrogen cover gas

TABLE 1.16 - Sodium Technology Facilities at Atomics International (Including Liquid Metal Engineering Center)

Facility designation	Construction material	Power level	Na temp., °F	Na flow	Instrumentation and/or special features	Remarks
Ultrapure Na Preparation	304 S.S. except for tantalum reflux condenser		500 (isothermal)		Gettered	Consists of Ta still, reflux condenser, S.S. extruder, and vacuum handling equipment
Sodium Test Loop	304 and 316 S.S.	1.5 by 10^6 Btu/(hr)(sq ft)	1200 (isothermal); 1400 (potential)	(∿ 20 ft/sec)	Plugging meter and cold trap	High-heat-flux loop
Large Component Test Loop (LCTL)	6-in. loop, 2 1/4 Cr-1 Mo; 3-in. loop, 304 S.S.	275 kw	1000 (6 in.) (isothermal); 1200 (3 in.) (isothermal)	1200 (6 in.); 2000 (3 in.); 130 (3 in.)	Cold trap and plugging meter	Contains 15,000 gal of sodium
Systems Quality Sodium Loop (1 in.)	304 S.S.		600 (isothermal)	10 gpm	Cold trap, plugging meter, United Nuclear Corp. meter, and hot trap (S.S.)	
Sodium Component Test Installation (SCTI) (10 in.)	304 S.S.	35 Mw(t) (furnace) 30 Mw (IHX)	900 to 1300 (primary) 1175 (max.) (secondary); 1100 (max.) (generator steam at 2400 psi)	3600 gpm	Cold trap, plugging meter, and sampling station	Consists of gas-fired furnace, IHX (900 to 1200°F), steam generator, primary and secondary Na loops, and feedwater/steam loop
Sodium Pump Test Facility (SPTF)			1250 (max.)			Either 30-or 42-in. pipe to have capacity for two 60,000-gpm loops
Sodium Reactor Experiment (SRE)	S.S.	30 Mw(t)	1200	1500 gpm (primary)	Carbon-removal hot traps, sodium-oxide-removal cold traps, and plugging meter	If put into operation, Na is in such condition that effect of carbon on materials could be determined
Pump Test Loop	304 S.S.		1000 (max.)	2200 gpm	Contains two 12-in. loops	For testing 12-to 14-in. Na pumps under nonradioactive operating conditions

TABLE 1.17 - Sodium Technology Facilities at Babcock and Wilcox Company

Facility designation	Construction material	Power level	Na temp., °F	Na flow	Instrumentation and/or special features	Remarks
Na-Heated Steam Generator Mock-up (1 1/4 in.)	Evaporator, 2 1/4 Cr-1 Mo; Superheater, 316 S.S.	140 kw	Enter superheater at 1140; enter evaporator at 750 (max. temp., to 1200)	25 gpm	Zr hot trap, cold trap, plugging meter, and Na sampler	Single-tube, once-through heat-transfer and fluid-flow mock-up; H_2O enters evaporator at 530°F; H_2O enters superheater at 1015°F; steam produced, 1050°F, 2450 psi
Natural Circulation Loop (3/4 in.)	2 1/4 Cr-1 Mo; 316 S.S.	10 kw	1200 (design)	0.25 gpm	Cold trap, plugging indicator, and Na sampler	Designed to study the effects of velocity on carbon transfer
Large Size Loop	304 S.S.		1350	15 to 40 ft/sec	To be designed for full flow	For fuel-element and drive-line (control-rod system) testing

TABLE 1.18 - Sodium Technology Facilities at Brookhaven National Laboratory

Facility designation	Construction material	Power level	Na temp., °F	Na flow, gpm	Instrumentation and/or special features	Remarks
13 Thermal Circulation Loops	1 V-20 Ti; six 316 S.S.; five 321 S.S.; 1 Haynes 25		1400 (max.); 910 (min.)		Hot or cold traps	To be used in fast-reactor-materials corrosion program
2 Pumped Corrosion Loops (1 in.)	321 S.S.	40 kw	1500 (max.)	6	Hot trap, cold trap, oxide meter, plugging meter, and bypass and bucket for analysis by distillation and Hg amalgamation-I^2R heating of test section, dry box attached to loop	Figure "8" design with regenerative heat; to test corrosion of refractory metal and cobalt alloys; ΔT, 500°F
High Heat Flux Loop (1 in.)	304 S.S. (tentative)	20 to 40 kw, 1 × 10^6 Btu/(hr)(sq ft) (electron-beam-heated specimens)	1500 (max.) surface temp.; 1200 bulk Na temp.	12	Same as for corrosion loops	To test corrosion of refractory metal and cobalt alloys under high heat flux
Analytical Loop (1/2 in.)	304 S.S. or 316 S.S.		1200 (isothermal)		Bypass, bucket, distillation, etc.; dry box	Develop sampling procedure; oxide meter, Na sample source
Sodium Heat Transfer Loop	316 S.S.	40 kw	1600 (max.)	40	Hot trap, cold trap, oxide meter, plugging meter, and bypass sampler	Forced convection, forced-convection boiling inception, natural-convection boiling inception, and steady boiling modes available

TABLE 1.19 - Sodium Technology Facilities at

Loop No.	Title	Construction material	Power level, kw	Na temp. (max.), °F
1	High Flux Heaters	316 S.S.	25	1470
2	Mass Transfer	316 S.S.; 2-1/4 Cr-1 Mo	25	1300
3	Mass Transfer	Hot leg, 316 S.S. cold leg, 2-1/4 Cr-1 Mo	25	1300
4	Stress Rupture	316 and 304 S.S.	25	1300
5R	Stress Rupture	316 and 304 S.S	25	1300
6R	Cyclic Stress	316 and 304 S.S.	25	1300
7	Multipurpose Tests	304 S.S.	10	1200
8	Mass Transfer	316 and 304 S.S.	100	1300
9	Corrosion Mock-Up Large Reactor System	316 and 304 S.S.	100	1300

General Electric Advanced Products Operation

Na flow, gpm	Pressure, psi	Special equipment	Remarks
3	60	Corrosion sample holders, plugging indicator, cold trap, and induction heaters	Test of heaters for 10^6 Btu/(hr)(sq ft) service
3	80	Plugging indicator, cold trap, and 25-kw cooler	Operated 30,000 hr in replicate corrosion program
3	80	Plugging indicator, cold trap, and 25-kw cooler	Operated 30,000 hr in replicate corrosion program
10	50	Plugging indicator, cold trap, and 6000-psi argon system	Long-term creep tests
10	50	Plugging indicator, cold trap, Na sampler, economizer, and 500°F ΔT	Sealed pressurized capsules operated at different pressure for stress-rupture data
10	50	Plugging indicator, cold trap, economizer, and 500°F ΔT	Pressure cycling between 3000 and 6000 psi by argon system; cover gas, helium
10	10	Cold trap, plugging indicator, valve manifold, visual sodium test pot, static pot mechanism test, and vessel-cover seal test	Useful for various tests or simultaneously
6	60	Plugging compound collector, plugging indicator, cold trap, 1300-cm^3 sampler, and 100-kw air cooler	450 corrosion samples in parameter study (velocity, length-to-diameter ratio, gpm)
6	60	Plugging indicator, cold trap, and 100-kw air cooler	Design for modification in progress to add 1400°F test section at 10^6 Btu/(hr)(sq ft)

(Table continues on next page.)

TABLE 1.19 - (Continued)

Loop No.	Title	Construction material	Power level, kw	Na temp. (max.), °F
10	Main Sodium Service and Supply System	304 S.S.	50	1000
11	Heat Transfer and Fluid Flow Loop	304 S.S.; 2-1/4 Cr-1 Mo	200	1300
12	Thermal Shock Loop	304 and 316 S.S.	15	1400
13	Sodium-Water Reaction System	316 S.S.	60	1200 Na; 550 H_2O
14	Sodium Disposal and Cleaning Station	Steel and concrete		
15	SEFOR Refueling Cell Mock-Up	Various		

TABLE 1.19 - (Continued)

Na flow, gpm	Pressure, psi	Special equipment	Remarks
10	10	4-ft-diameter reactor mock-up vessel, 750-gal storage tank, micrometallic filter, plugging indicator, cold trap, valve manifold and distribution system	Supplies sodium to several loops and SEFOR refueling cell
80	30	100-kw air cooler and two test sections for flow or heat transfer, 10 ft tall	Used for full-scale SEFOR fuel-assembly flow test and heat-transfer test
100-gpm transient	50	Timed gas pressurization and oscillograph	Can produce 500°F ΔT thermal transient in less than 1 sec in a 6-in.-diameter test section
10	10 Na; 3000 H_2O	Deionizer, feed pump, accumulator, and steam-generator reaction assembly	To be used in investigation of small leaks
		100-cfm water centrifugal fume scrubber, and remote nozzles for water stream, water spray, and steam	General-purpose cleaning and disposal work
		Crane, viewing windows, 8000-cu ft argon cell recirculating argon system, and master-slave manipulator	Full-scale refueling system for SEFOR

TABLE 1.20 - Sodium Technology Facilities at General Electric Nuclear Systems Programs Department

Facility disignation	Construction material	Fluid	Purity control	Temp., °F	Flow, gpm	Types of test	Remarks
50-kw Condensing Heat Transfer Facility	316 S.S.	Primary: K Secondary: Na	Cold trap and O_2 hot trap	1600	10	Heat transfer and components	K condensing experiments with heat flux to 300,000 Btu/(hr)(sq ft)
100-kw Boiling K Heat Transfer Facility	Nb-1 Zr	Primary: Na Secondary: K	Cold trap	2100	10	Heat transfer and components	Boiling experiments with heat flux up to 225,000 Btu/(hr)(sq ft)
300-kw Two-fluid Heat Transfer Facility	Haynes 25 alloy	Primary: Na Secondary: K	Cold trap and hot trap	Primary: 1850 Secondary: 1500	500	Heat transfer and components	Converted to NaK-Hg for SNAP-8 testing
3000-kw K Turbine Test Facility	316 S.S.	K	Hot trap	1600	50	Components	Single closed-loop Rankine cycle system
Two-Phase Corrosion Loop	Nb-1 Zr	Primary: Na Secondary: K	Cold trap and hot trap	Primary: 2150 Secondary: 2000	10	Corrosion, instruments, coolant purity, and components	
Advanced Material Test Loop	T-111*	Primary: Li or Na; Secondary: K		2150	10	Corrosion, instruments, coolant purity, and components	
Electromagnetic Pump Test Loop	316 and 321 S.S.	Na, K, NaK	Hot trap	1500	50	Components	
Bearing and Seal Test Loop	316 S.S.	K, Na	Hot trap	1400	10	Components and materials	
Bearing Friction and Wear Test Loop	316 S.S., Nb-1 Zr liner	K, Na	Hot trap	1600	10	Materials	
Boiler Development Loop	T-111* and 321 S.S.	Li, Na, K, NaK	Hot trap and cold trap		500	Two-phase heat transfer and components	
2600°K Lithium Loop	T-111*	Li, Na			10	Materials	
Valve Test Loop	T-111* and Nb-1 Zr	Li, Na			10	Components	

*Tantalum alloy.

TABLE 1.21 - Sodium Technology Facilities at Geoscience Limited Laboratory

Facility designation	Construction material	Temp., °F	Na flow		Pressure, psig	Instrumentation and/or special features	Remarks
			gph	ft/sec			
Forced-circulation boiling potassium system No. 1	Haynes 25 alloy	1750	6.0	25	250	System is completely mobile for safety purposes	Single or multiple tube, I^2R heated system for precise heat-transfer-conductance measurements
Forced-circulation boiling potassium and mercury	Haynes 25 alloy and 316 S.S.	1750	60.0	200	250	Optical port available for boiling-mercury-droplet distribution photography	Single tube, I^2R heated system for known vapor qualities
Liquid-metal-droplet vaporization research system	Any metal can be used	3000+			to 100	Interchangeable test surfaces, environmental gas control, vapor pressure and temperature control, and surface physics and chemistry control	Droplet vaporization lifetime measureable as a function of all important environmental parameters

TABLE 1.22 - Sodium Technology Facilities at Los Alamos Scientific Laboratory

Title	Construction material	Power level, kw	Na temp. (max.), °F	Na flow, gpm	Pressure, psig	Special equipment	Remarks
10 Thermal Convection Compatibility Test Loops (4 in.)	321 S.S.	1.5	1380	(Thermal convection, low)	6	Hot trap	Test of materials in hot-trapped sodium; 2 gal Na; ΔT, $\sim$ 10°F or less
Hot Trap Evaluation Loop (1/2 in.)	316 S.S.; some 321 S.S.	5	1300	1	5	Plugging indicator, distillation sampler, hot trap, and cold trap	To test hot-trap materials; 15 gal Na; ΔT, 360°F in test section and 900°F in system
Steam Generator Trap (1 in.)	Carbon steel storage tank; piping, 304 S.S.	$\sim$20	615	8	10	Rhometer, vacuum distillation, oxygen sampler, oxygen-meter housing, and cold trap	Originally to give Na supply, now used for oxygen-meter tests, rhometer test, isothermal in main flow, 600 gal Na
Fission Product Loop (1/2 in.-1 1/2 in.)	316 and 321 S.S.	1	1200	0.7	15	Hot trap, cold trap, carbon bed, S.S. and Ni surface collectors, and dip sampling	Study fission-product behavior, distribution, and trapping; 0.5 gal Na; ΔT, 810°F maximum, isothermal in test section
Open Capsule Loop (1/2 in.-1 1/2 in.)	316 and 321 S.S.	1.5	1300	0.7	15	Hot trap-2 fuel-test legs; 1 material-test leg	Out-of-pile fuel-venting experiment, isothermal, 0.5 gal Na
Cold Trap Experimental Loop (1 in.-1/2 in.)	304 S.S.	15	615 opt. 1100 max.	1	15	Plugging indicator, NaK coolant circuit, O_2 meter, distillation sampler, impurity addition system, and cold trap	Cold-trap design studies; ΔT, 360°F or more; 60 gal Na
Forced Convection Na Loops (4 in.)	321 S.S.	3	1380	1-2	6	Distillation sampler and Zr hot trap	Materials-compatibility studies in (Pu,U) C program; 4 gal Na, isothermal
Analytical Loop No. 1 (3/4 in.)	304 and 316 S.S.	6	840	2.5	3	Distillation sampler, cold trap, plugging valve, and chromatograph	To determine solubility of O_2 in Na. Evaluate analytical techniques; ΔT, 270°F; 8 gal Na
Analytical Loop No. 2 (3/4 in.)	304 and 316 S.S.	10	1020	5	3	Cold trap, hot trap, emf cell, distillation sampler, resistivity cell, and chromatograph	Evaluate analytical techniques, system gettering, hot trapping, and cold trapping; ΔT, 270°F; 50 gal Na
Forced Convection Temp. Gradient Loop (3 in.)	304 S.S.	14	1380	2	1 to 2	Zr hot trap, distillation sampler and sample-removal equipment	Compatibility testing of materials that will contain carbide fuels; ΔT, 630°F in 18 in.; 3 gal Na
Na Supply Loop (3/4 in.-5 in.)	304 S.S.	5	1200 to 1300	0.2	15	Inert glove box, distillation sampler, capsule loader, and Zr hot trap	Supply of Na at 8 ± 3 O, < 15C; < 10H; < 3N (ppm); ΔT, 540°F; 3 gal Na

TABLE 1.23 - Sodium Technology Facilities at MSA Research Corporation

Facility designation	Construction material	Power level or heat flux, kw	Na temp., °F	Pressure, psig	Na flow, gpm	Instrumentation and/or special features	Remarks
Heat Transfer System (3 in.)	316 S.S.	3000	1200 at 3 Mw; 1500 at 1 Mw; 1600 at 0.8 Mw		225	Primary NaK loop, secondary Na loop, and water-steam loop	Used to test prototype steam generators
2 Mechanical Property Test Systems (1 in.)	316 S.S.		1200 (isothermal) to be raised to 1400		∿25(71 ft/sec)	Cold trap and plugging meter	Contain seven test stations
Mechanical Property Test System (1 1/2 in.)	316 S.S.		1400		∿100 (15 to 30 ft/sec across test specimen)	Cold trap, plugging meter, Zr-Ti hot trap, in-stream sampler, and bypass sampler	ΔT, 50 to 150°F, will contain provision for 10 creep or creep-rupture test units
Pump Development Test Loop (4 in.)	316 S.S.		1600	60	500 to 1000	EM flowmeter, Venturi meter, throttling valve, and cold trap	
Pump Development Test Loop (2 in.)	316 S.S.		1600	100	200	EM flowmeter	

TABLE 1.24 - Sodium Technology Facilities at Oak Ridge National Laboratory

Facility designation	Construction material	Power level, kw	Liquid-metal temp., °F
Boiling potassium natural-circulation loop facility (1/2 and 4 in.)	313 S.S.	3 4 1/2	1600
Boiling Potassium Natural-Circulation Loop Facility No. 1 (3/8 and 1/2 in.)	Nb-1 Zr	6.1	2200
Lithium Thermal Convention Loop Facility (7/8 in.)	Nb and Ta alloys	2	2000 to 2400
Molecular-Distillation still		16 (max.)	
Intermediate Potassium System	304 and 316 S.S.	360	1540
Small Potassium System No. 1	304 and 316 S.S.	35	1540
Small Potassium System No. 2	316 S.S.	35	1540
Vacuum test facility (General Electric)	D-43	15	2200
Vacuum test facility (Stokes)	Cb-1 Zr	10	2000

TABLE 1.24 (Continued)

Liquid-metal flow, gpm	Instrumentation and/or special features	Remarks
180 (max.)	Vacuum chamber, 36 in. in diameter by 50 in. in height; pump, 500 liters/sec Ti sublimation pump; chamber pressure, 1×10^{-11} torr (cold and empty)	Used to provide a vacuum environment for high-temperature natural-circulation test loops of liquid or boiling alkali metals
0.06	Vacuum chamber, 2 by 2 by 4 ft; pumps, two 280 liters/sec getter ion; chamber pressure, 2×10^{-8} torr	Used for refractory-metal, boiling-loop corrosion
0.3	Vacuum chamber, 18 in. in diameter by 34 in. in height; pump, 400 liters/sec ion; chamber pressure, 10^{-8} to 10^{-10} torr	Used for loop and capsule studies of refractory metals in contact with alkali metals. Temp., 200 to 250°F
	Condenser, 12 by 24 in.; environment, 10^{-5} torr, xylene-cooled	To permit purification of alkalis by molecular vacuum distillation; estimated capacity, 225 g/min (max.)
8 1/2 gpm condensate flow	Variable electric power supply and air-cooled heat sink	Available. Conveniently modifiable for tests of simulated reactor cores, heat exchangers, and for topping cycle tests
144 lb/hr condensate flow	Variable electric power supply and air-cooled heat sink	Being used to measure burnout heat flux with boiling potassium. Scheduled for improvement tests for once-through potassium boilers. Available.
144 lb/hr condensate flow	Same as No. 1 except test loop contained in an electrically heated oven	Presently on endurance test of liquid-metal system and components. Available.
40 lb/hr condensate flow	Chamber, 4 ft in diameter by 10 ft in height; two 1500 liters/sec ion and four 5000 liters/sec sublimation pumps rated 5×10^{-12} torr cold	Scheduled for two tests of 3000-hr duration. Available.
40 lb/hr condensate flow	Chamber, 4 ft in diameter by 10 ft in height; two diffusion and one mechanical pump and a large liquid N_2 trap achieved 5×10^{-8} torr during hot test	Has completed 2000 hr of a 3000-hr compatibility test. Scheduled for use filling LiF capsules next. Available.

(Table continues on pages 92-93.)

TABLE 1.24 (Continued)

Facility designation	Construction material	Power level, kw	Liquid-metal temp., °F
Forced Circulation Boiling Potassium System	316 S.S.	7.5	1600 (max.)
NaK Corrosion Facility	316 S.S.; Hastelloy N; Croloy-9M	15	1450
Test Facility for United Nuclear Electrochemical Oxygen Meter	304 S.S.		600 for meter; 1300 elsewhere in system
Electromagnetic Pump Test Facility	316 S.S.		1300
Liquid-Metal Flowmeter Calibration Facility	304 S.S.		1500
Liquid-Metal Jet Pump Facility	304 S.S.		1500

TABLE 1.24 (Continued)

Liquid-metal flow, gpm	Instrumentation and/or special features	Remarks
40 lb/hr condensate flow	Has capability for small loop tests of material compatibility in sodium	Has completed 7000 hr of 10,000-hr metallurgical endurance test. Available.
2	Facility can handle simultaneously five small-loop compatibility tests	Available. Development and endurance tests of liquid metal instrumentation and purification systems.
2	Five flow-through sampling stations. Capability for impurity additions and variation of surface-to-volume ratio	Available, along with five meters.
0.5	Volume tank provides for calibration of low-flow electromagnetic flowmeters up to 0.5 gpm	Available. Suitable for obtaining both performance and cavitation inception characteristics of electromagnetic pumps for low-flow boiler feed duty.
40	Calibrated Venturi and differential-pressure-sensing systems provide for calibration of electromagnetic flowmeters up to 30 gpm	Available. Can also be used to obtain both performance and cavitation characteristics of electromagnetic pumps up to 40 gpm.
14.5 (max.)	Designed to measure the effects of cavitation on jet pump performance under both liquid and two-phase suction conditions	Available. Can be used to test a new theory designed to correlate the cavitation performance of jet pumps.

TABLE 1.25 - Sodium Technology Facilities at Pacific Northwest Laboratory

Facility designation	Construction material	Na temp., °F	Na flow	Pressure, psig	Instrumentation and/or special features	Remarks
Radioisotope Transport and Deposition Loop	304H S.S.	1400	2 gpm (40 ft/sec)	120	Hot traps, cold traps, plugging meter, and sampler	ΔT, 500°F at 2 gpm; loop will be in N_2-atmosphere glove box for Pu work
Sodium Loop	316 S.S.	1500 (design); 1200 (50-hr operational); isothermal	28 to 30 gpm		Cold trap	For fuel-reuse tests (will take a PRTR subassembly)
Mechanical Property Study Loop (1 in.)	304 S.S.	1600	25 gpm		Cold trap and plugging meter	Provision for seven test stations
Heat Transfer System	304 S.S.	1500	∿25 gpm			ΔT, ∿225°F
Static Sodium Facility	304 S.S.	1200	Static	to 250		Four "pots" for instrument testing

TABLE 1.26 - Sodium Technology Facilities at United Nuclear Corporation

Facility designation	Construction material	Power level, kw	Na temp. (max.), °F	Pressure, psig	Na flow, gpm	Maximum activity capability, curies	Instrumentation and/or special features	Designated use
FCL-1, FCL-2	316 S.S.	25	1600 (1750 with special refractory test section)	100	5	20	Hot trap, cold trap, argon cover gas, sodium samples, and provision for insertion and removal of corrosion samples	Designed to withstand large transients and thermal shocks; components are easily replaceable; corrosion and purity control tests
FCL-3	304 S.S.	25	1300	50	5	0	Cold trap, oxygen meters, plugging indicator, sodium sampler, impurity injector, and carbon-meter	Oxygen-meter and carbon-meter development
FCL-4	304 S.S.	6	1200	100	5	0	Oxygen meters, impurity injectors, impurity getters, and sampler	Oxygen-meter calibration
Thermal Convection Loops	304 S.S. or 316 S.S.	3	1200 to 1600		0.1	20		Designed so that harps can be easily removed as desired
NASA LM Heat Transfer	316 S.S., Nb-1 Zr	500	2240 (hot supply system); 1940 (heat-rejection system)					Maximum flux in test section 10^6 Btu/(hr)(sq ft) max.; active in other programs

TABLE 1.27 - Sodium Technology Facilities at Westinghouse

Facility designation	Construction material	Na temp., °F	Na Flow	Pressure, psig	Instrumentation and/or special features	Remarks
Thermal Convection Loop (1 in.)	304 S.S. (318, Inconel previously)	Heated leg, 1400 to 1500; cold leg, 950 to 1100	0.5 (6.24 cm/sec)		No trapping in system, and cold thermocouples	For testing corrosion of vanadium samples, atmosphere control during loading < 1 ppm O, < 0.5 ppm H_2O
Fission Product Loop, 1/2 in. pipe (FPL-1)	316 S.S. (isothermal)	900 (isothermal)	10	20	Cold-trap gamma scanner	For fission-product studies (now using ^{137}Cs)
General Purpose Test Loop (GPL-1)	304 S.S.	1200 (max.)	200			For heat-transfer tests, mechanical testing of small components, and three-tube steam-generator test to produce steam at 2400 psi
Mass Transfer Loops (1 in.)	316 S.S.	1350 (max.)	50			For testing fuel-cladding and steam-generator materials
Fission Product Loop (FPL-2)			20 to 30		To mock-up cold trap	For studies of fission-product management
General Purpose Loop (GPL-2)			600 to 1200			For testing full-size fuel assemblies
"Frosting" Study Loop						To study vapor deposition of sodium in inert atmosphere
Bench Scale Loops (Thermal and Forced Convection)						To study effect of impurities in Na bonds on heat transfer
Vanadium Test Loops (VTL-1 and VTL-2)	316 S.S.	1470	5 to 20 ft/sec		EM pumps and cold trap	To study Na corrosion of vanadium alloys

TABLE 1.28 - Development Facility Design Characteristics

	SCTI	Grand Quevilly	Interatom	Cadarache
Country	United States	France	Germany	France
Heat source				
Size, Mw(t)	35	5	5	10
Type	Gas	Oil	Oil	Oil
Primary coolant	Na	Na	Na	Na
Material	316 S.S.	321 S.S.	2 1/4 Cr-1 Mo-Nb	321 S.S.
Flow, lb/hr	1.14×10^6	0.13×10^6	0.21×10^6	0.70×10^6
Heater outlet temp., °F	1200	1112	1040	1004
Heater inlet temp., °F	900	662	770	842
Secondary coolant	Na	NaK-56	Na	NaK-56
Material	316 S.S.	321 S.S.	2 1/4 Cr-1 Mo-Nb	321 S.S.
Flow, lb/hr	8.55×10^5	0.16×10^6	0.13×10^6	0.85×10^6
IHX outlet temp., °F	1175	1075	995	968
IHX inlet temp., °F	777	635	554	788
Steam circuit				
Material	2 1/4 Croloy	321 S.S. + C.S.	2 1/4 Cr-1 Mo-Nb	Air heat dump
Pressure, psig	2400	1800	2400	
Steam temp., °F	1050	1013	1004	
Feedwater temp., °F	600	428	582	
Flow, lb/hr	1.16×10^5	0.16×10^5	0.20×10^5	

Rouen, France; (3) the 5-Mw(t) Interatom loop at Bensberg, Germany; and (4) the 35-Mw(t) SCTI at the Liquid Metal Engineering Center, Santa Susana, Calif.

Each of these installations includes a fossil-fueled heat source, primary and secondary sodium (or NaK) loops, and purification equipment. All except the Cadarache 10-Mw(t) loop include steam- and water-handling equipment. The Cadarache facility utilizes an air heat dissipating system. The development of heat exchangers and steam generators is a primary purpose, but each test facility can be used for developing and testing other sodium-system components. Final modifications of the Rapsodie fast reactor pumps were made as a result of tests conducted in the Cadarache facility.

Pumps for future sodium reactors will generally be of larger capacity than the flow capabilities of these four installations; nevertheless, these installations can be used in the development of prototype pumps. Facilities for testing pumps of 35,000- to 100,000-gpm size are planned by the USAEC and are being considered by France and Germany.

The design conditions for each of the four installations are listed in Table 1.28. In addition to these, each installation is capable of imposing transient operating situations such as may be encountered in a reactor-system application.

(a) *10-Mw(t) Cadarache Facility*

The 10-Mw(t) Cadarache loop started up in August 1962. The Cadarache loop and another rated at 1 Mw have been operated at several steady-state levels up to 100% of full power. Transient conditions studied during forced convection have included imposing up to 30% steps in primary sodium flow, 25% steps in secondary sodium flow, and up to 50% power steps in the sodium heater. During natural-convection regimes, the airflow to the system heat dump has been subjected to 30% changes. Transients that result in a change from forced to natural convection have been studied. These transient have been imposed by shutting off the primary pump, shutting off (at low powe both primary and secondary pumps, and b simulating reactor scram (loss of heate power) at 1 Mw.

In general, loop operation has been satisfactory, and the overall design of the installations proved correct. As a result, Rapsodie was upgraded to include two 10-Mw loops instead of one. The French report [44]:

> Experience with the loop led to modifications of the purification circuits, preheating system, mechanical pumps, and sodium-to-air heat exchangers. It also led to important modifications in the layout of the piping, both in the main circuits and in purification circuit and auxiliary pipe work. Furthermore, operation of the prototype circuits led to the choice of sodium for the secondary fluid instead of NaK as originally intended; it was found that the necessary preheating did not constitute a serious handicap in a circuit of large dimensions which was in continuous operation. Moreover, with the use of sodium, dismantling is faster and safer, leading to a correspondingly large reduction in the investment involved.

(b) *5-Mw(t) Grand Quevilly Station, France* [109]

The Grand Quevilly Station was commissioned May 25, 1964, and started up on June 25. Steam design conditions were achieved Dec. 22, 1964. It comprises an oil-fired sodium heater; a 4-in.-ID sodium primary loop for heating the shell side of an intermediate heat exchanger; a 4-in.-ID secondary NaK loop for heating the shell side of a bank of six parallel tube-in-tube double-wall steam generators; and steam circuitry. Type 321 stainless

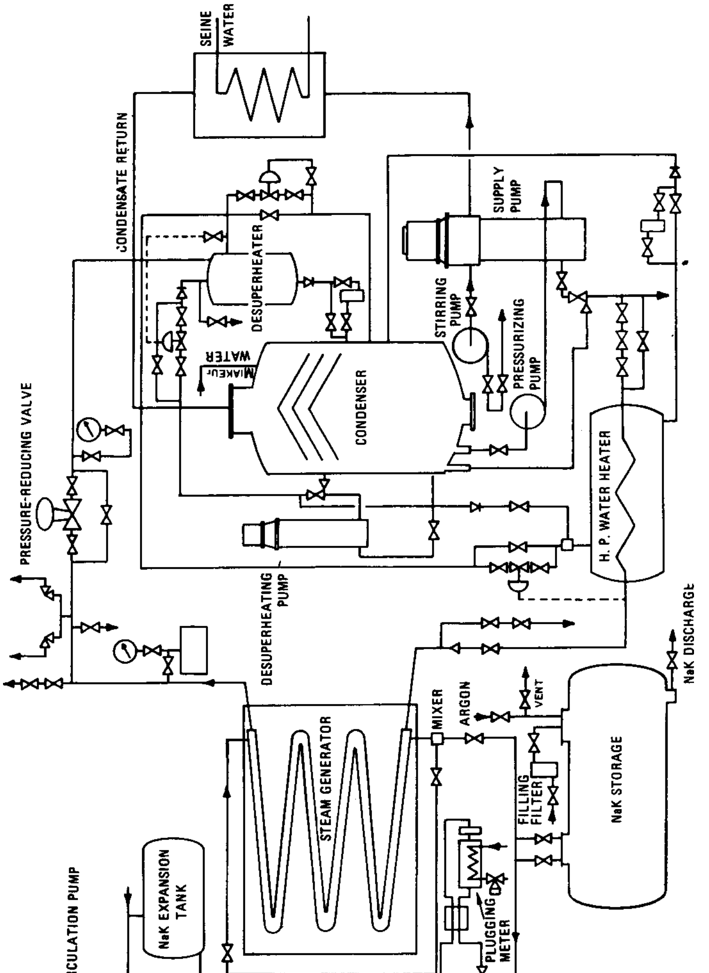


Fig. 1.33 Grand Quevilly 5-Mw(t) installation.

steel is utilized in the sodium and NaK systems, type 321 and 2 1/4 Cr-1 Mo steel are used for the steam system, and carbon steel is used in the water systems. A flow diagram of the Grand Quevilly Station is shown in Fig. 1.33.

In addition to steady-state performance, the control and regulation system will permit simulation of load-following characteristics, either by varying sodium heater power with steam demand or by dumping excess steam at essentially constant sodium heater power. Provisions were not originally included for testing heat exchangers and steam generators separately.

The loop has been used to evaluate the steady-state heat-transfer coefficients of the intermediate heat exchanger and the steam generator. Transient conditions were scheduled to be studied.

Steam generators of different designs, including single-wall and different geometric configurations, will be tested in connection with choosing economical types for Phenix, the next French fast reactor. Among concepts under consideration are the single-wall modular type, one with straight tubes and shell, another with bellows in the shell, and a third having hairpin-shaped tubes.

(c) *5-Mw(t) Interatom Facility* [110]

A 5-Mw(t) facility for testing sodium heat exchangers, steam generators, pumps, and other components and subsystems has been built by Interatom at its Bensberg, Germany, site. The immediate objectives of the facility are to develop components for the 58-Mw(t) KNK reactor to be built at Karlsruhe and to develop 2 1/4 Cr-1 Mo-Nb ferritic steel as a basic structural material compatible with both sodium and water. The modified Croloy includes niobium to approximately ten times normal carbon content to overcome decarburization properties of 2 1/4 Croloy in sodium and includes other proprietary constituents to improve its strength. Another basic objective of the development program is to achieve sodium components and systems economically competitive with other coolants.

The Interatom facility accommodates two steam generators and two intermediate heat exchangers simultaneously. The piping, however, permits testing of only one pair of units at a time. Either of the units can be bypassed to permit testing of either the heat exchanger or the steam generator by itself. For heat-exchanger tests, a sodium-to-air heat dump is used, and the heat exchanger is operated regeneratively.

The control system for the facility permits the study of transient conditions and load-following capability. The desired capability is expressed in terms of percent of load change as follows:

Maximum Permissible Load Changes

Load before change, %	Step change of load, %	Rate of change of load per minute, %
100	-10	1.3
75	±13	2
50	±20	2.5
25	±40	5

Main test objects are primarily plant components that either are or can be permanently installed in the facility. Included are the two sodium circulating pumps, the sodium blocking and control valves, two intermediate heat-exchanger models, and two steam-generator models. Thermal-shock and reactor-components test sections permit additional tests.

In the thermal-shock test section, plant areas or components that are difficult to assess by theoretical stress analyses can be tested. Such tests are to be conducted under temperature-shock conditions, which may, in certain cases, lead to failure. Countermeasures of a design nature are to be investigated when failure occurs. This test section is arranged parallel to the sodium-heater outlet pipe in such a manner that thermal shocks up to the temperature rise in the heater can be produced by sudden injection of lower temperature sodium from a line bypassing the heater.

The reactor-components test section consists of a reactor tank model arranged vertically in parallel to the expansion tank. The model permits testing under actual operating conditions, though initially without simulation of the temperature rise and naturally without the presence of radiation, of all essential reactor components (such as control-rod devices, fuel-element mock-ups, adjustable orifices, sodium-immersed grapples, and reactor cover locking systems). If this test section is included in the circuit using either of the first two valving arrangements described previously, such components can also be subjected to thermal shocks up to the maximum temperature rise in the sodium heater. The test section can be operated completely independently of the main loop via the secondary sodium pump.

A large number of transient tests of the complete facility are visualized with time rates of temperature change up to 50°F/sec and up to a maximum range of 212°F. In special test sections, transient experiments involving temperature changes up to 572°F and at rates up to 76°F/sec can be conducted.

(d) *35-Mw(t) Sodium Component Test Installation*

The SCTI is the most ambitious, largest, and perhaps the most flexible of the facilities for developing sodium heat-transfer equipment. It is located at the Liquid Metal Engineering Center, Santa Susana, Calif. Intermediate heat exchangers and steam generators can be tested at a variety of steady-state and transient conditions consistent with the design

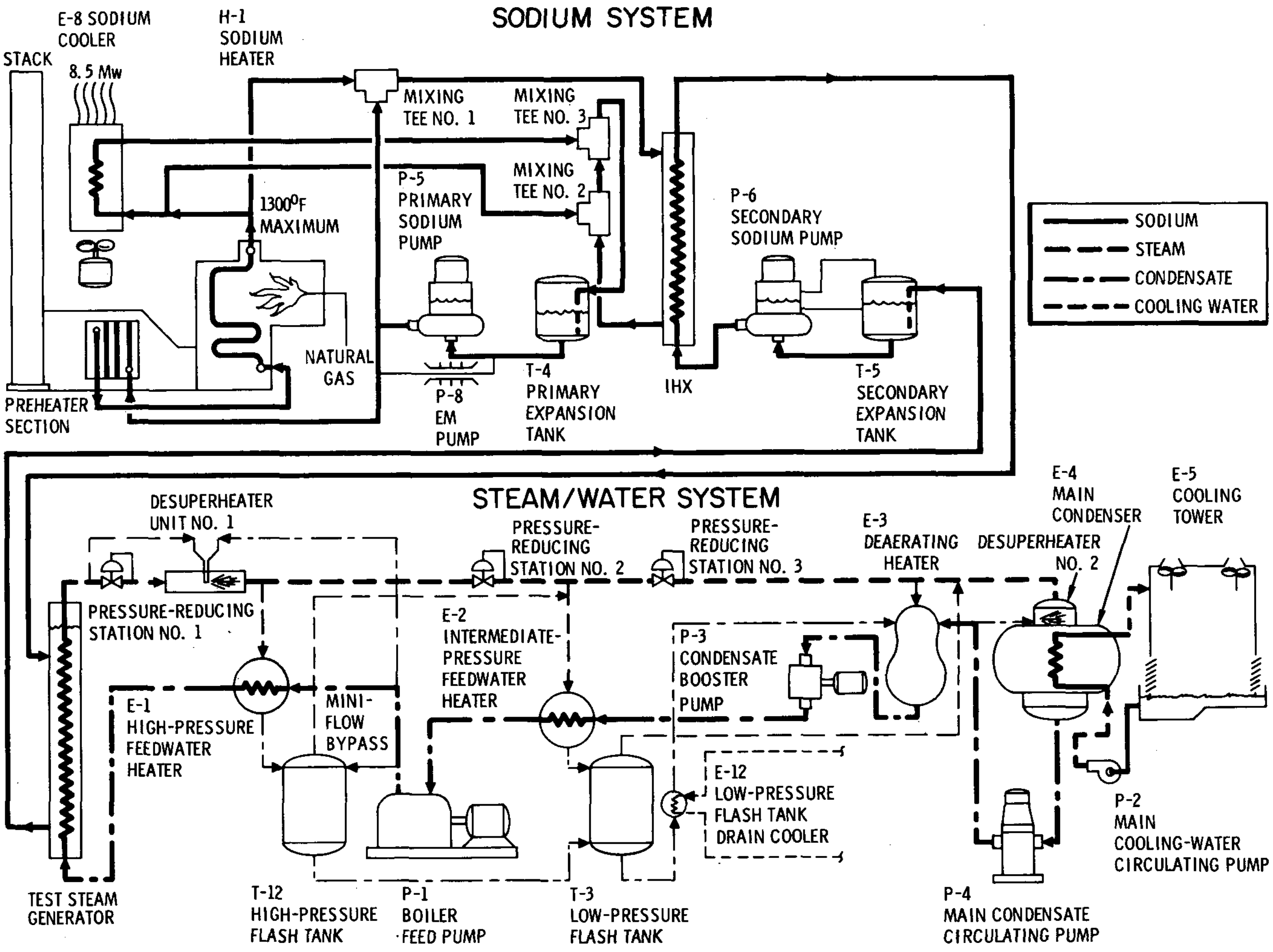


Fig. 1.34 Schematic flow diagram of SCTI.

specifications of the equipment and the design approaches used to make the equipment capable of sustaining mechanical and thermal loadings. The power level was made as high as could be readily achieved at the time to enable prototypes for testing to be acceptable scale models of equipment in the 100- to 1000-Mw(t) range. In all cases thus far, full-scale equipment has been designed first, and each prototype to be tested has been designed on the basis of a careful scale-down analysis so that it is in effect a segment or module of a much larger device typical of needs for future sodium-cooled reactors.

A schematic flow diagram of the SCTI is shown in Fig. 1.34. The primary sodium circuit includes a gas fired sodium heater, an auxiliary cooler, the shell side of a test intermediate heat exchanger, and piping for mixing hot and cold sodium in a variety of ways. The secondary sodium circuit includes the tube side of the intermediate heat exchanger and the shell side of the steam generator. The system is designed for sodium temperatures and flows as high as 1300°F and 5000 gpm, respectively, and will produce 1050°F, 2500-psig steam with condensation at 4 in. Hg absolute.

In addition to steady-state 30-Mw

design conditions outlined in Table 1.20, the components can be tested at part loads down to 10% of rated capacity or to the full heat capacity, 35 Mw(t), of the system. The maximum heating capability of the primary loop is 1×10^6 lb/hr of sodium heated from 900 to 1300°F. The SCTI control system [111] has the following capabilities for operating transients:

1. At a constant sodium flow rate of 1.14×10^6 lb/hr, the sodium temperature into the primary side of the intermediate heat exchanger can be reduced at the rate of -35°F/sec for 10 sec.
2. At a constant sodium temperature of 1200°F, the sodium flow rate into the primary side of the intermediate heat exchanger can be reduced from 100% (10^6 lb/hr) to 10% in 12 sec.
3. At a constant primary sodium flow rate of 10^6 lb/hr, the sodium temperature into the primary side of the intermediate heat exchanger can be increased from 1200°F to 1300°F at the rate of + 11°F/sec for 9 sec.
4. At a constant sodium inlet condition into the primary side of the intermediate heat exchanger of 0.6×10^6 lb/hr and 1200°F, the secondary loop flow can be reduced from approximately 0.46×10^6 lb/hr to zero in 10 sec. This rate corresponds to loss of the secondary pump.

Analog simulation and analysis of transient and steady-state operations and performance have been made. The following transient conditions can be achieved in the SCTI:

Cold shock	35°F/sec for 10 sec
Hot shock	11°F/sec for 9 sec
Primary flow ramp	Decrease from 100% to 10% in 12 sec
Secondary flow ramp	Decrease from 100% to 10% in 12 sec
Steam demand	± 25% step change
Steam load change	± 10%/min ramp between 20 and 100% load

With this system and its components, performance characteristics and the capabilities of the components to match design specifications can be determined for various normal and off-design conditions in a sodium-cooled reactor system. These include such normal operating conditions as system start-up, shutdown, load-following characteristics, and ability to withstand the normal series of reactor or plant shutdown operations for maintenance, repair, or refueling. Transient conditions include off-design situations or accidental, minor or severe, perturbations such as plant power failures, loss of primary or secondary flow, steam flow, turbine power demand, or reactor power; or a sudden reactor-power excursion.

(e) *Large Component Test Loop*

Another test facility at the Liquid Metal Engineering Center, operated by AI for the USAEC at the Santa Susana site, is the Large Component Test Loop (LCTL), shown in Fig. 1.35 [112, 113]. This is a nonradioactive liquid-metal test installation containing over 15,000 gal of sodium. The installation is 80 ft high and covers an area of 27,600 sq ft. It consists of a covered component test area, a test tower, a drain pit, and a control room. The component test area is a 4000-sq ft concrete pad covered by a 25-ft-high metal canopy. The test tower and drain pit contain the core tank, supply tank, 3- and 6-in. circulating loops, and the drain tank. The control room houses all loop controls and instrumentation plus data-readout equipment for test instrumentation.

A vertically mounted core tank, 8 ft in diameter and 31 ft high, allows ample room to insert full-size sodium-cooled reactor components. The horizontally mounted supply tank, located in the test tower adjacent to the core tank, is 8 1/2 ft in diameter and 22 1/2 ft long. The drain tank, horizontally mounted in the pit below the test tower, is 8 1/2 ft in diameter

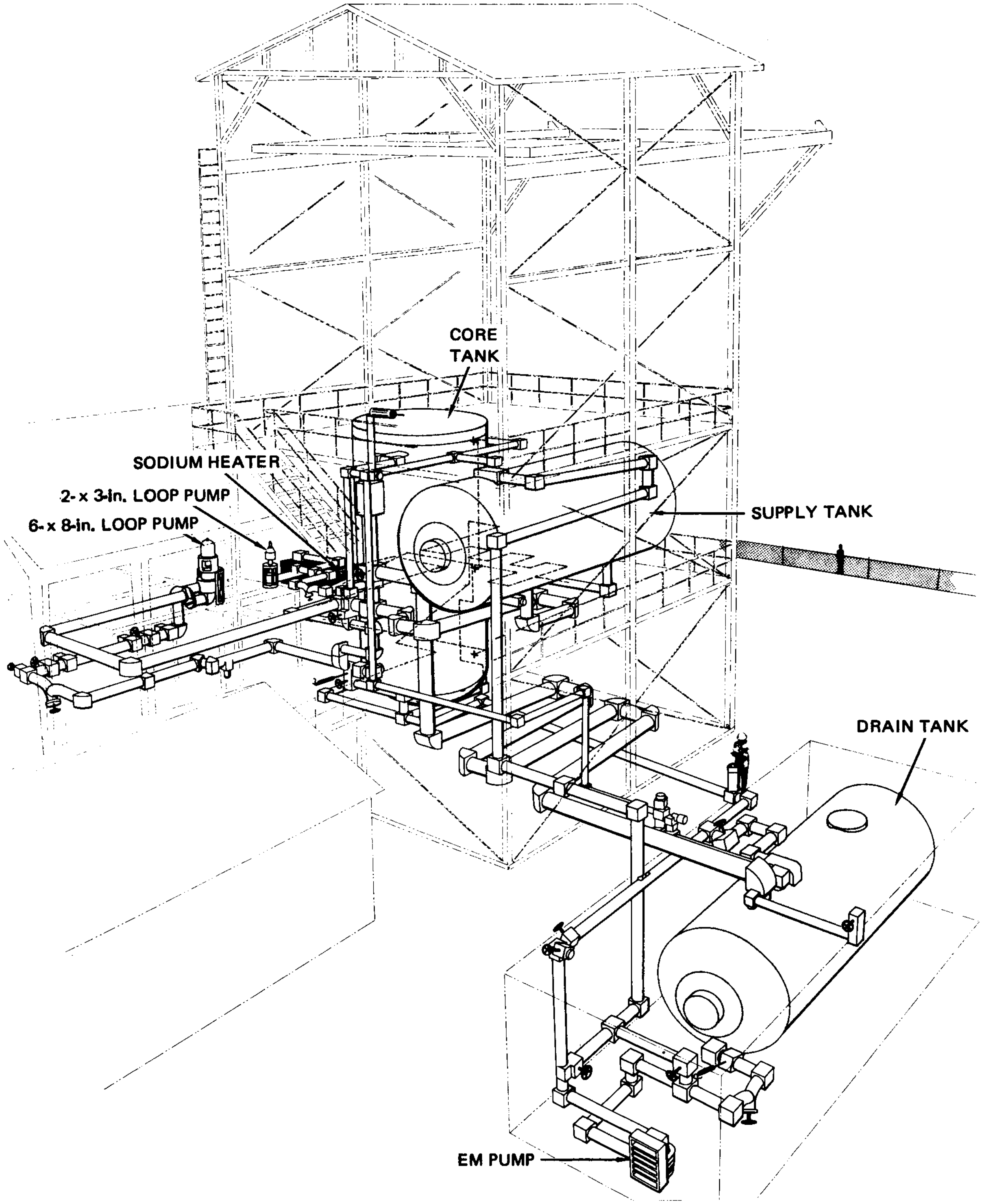


Fig. 1.35 Large Component Test Loop.

and 28 ft long. The 6- and 3-in. loops are both designed to circulate sodium (1) through the core tank, with the core tank used as the expansion tank, and (2) in a closed loop, valved off from the core tank, with the supply tank used as the expansion tank.

Sodium can be circulated for extended periods in the 6-in. loop at variable flow rates up to 2000 gpm at temperatures from 350 to 1000°F. The 3-in. loop is designed to circulate sodium for extended periods at variable flow rates up to 130 gpm at temperatures from 360 to 1200°F. An additional 8-in. shock line allows a piece of equipment to be alternately subjected to hot and cold sodium, permitting circulation and temperature to be maintained in one loop while another portion of the equipment is subjected to thermal shock by means of the shock line in the other loop. Most of the system, with the exception of the 6-in. loop, is designed to withstand a maximum sodium temperature of 1200°F and a maximum thermal-shock temperature difference of 500°F. Tanks and pumps have been sized so that the hot (or cold) sodium in the core tank can be displaced with cold (or hot) sodium in a minimum time of 7 min. The drain tank will hold the entire charge of the sodium displaced from the core tank during thermal transient tests.

The LCTL can handle core components up to a weight limit of 5 tons, which is the capacity of the component-handling equipment installed in the test tower. Heavier components can be installed by using higher capacity mobile crane equipment.

(f) *Sodium Pump Test Facility*

The Sodium Pump Test Facility (SPTF) [114], being designed to develop and proof-test large sodium pumps, will also be located at the Liquid Metal Engineering Center at Santa Susana, Calif. The SPTF design concept as of 1967 is discussed here.

The specific purpose of the SPTF is to proof-test prototype sodium pumps in sizes up to 120,000 gpm and at temperatures to 1200°F. In addition, the SPTF will be capable of carrying out acceptance testing of large-production sodium pumps. The facility will be used to determine (1) pump characteristics, (2) speed-flow control response, (3) thermal-shock resistance, and (4) performance under extended operational tests, both in steady-state and in cyclic-flow conditions. The SPTF will also be used to test instruments, large valves, and other components and equipment of sodium systems.

The facility is designed to test two pumps with rated capacities from 20,000 to 60,000 gpm, simultaneously and independently, in sodium environments simulating their intended service conditions. Future modifications will be possible so that a single pump with a rated capacity of 120,000 gmp can be tested.

The SPTF has two independent main flow loops. Each loop consists of a 30-in.-diameter closed piping circuit for recirculating sodium through the test pump, control valves for flow-rate regulation, and instrumentation for measuring test parameters. The pump is connected to the loop with pipe spools and is supported in the building structure on a special mounting adapter.

Sodium cooler-heaters are provided to control the temperature of the sodium in the loops in the range of 400 to 1200°F. A surge tank is connected to each loop to permit sodium volume changes with temperature and to compensate for changes of sodium level within the pump. During steady-state operation the pump-suction pressure is controlled between 4 and 50 psig by regulation of the cover-gas pressure in the surge tank.

Controlled thermal transient tests can be performed in each loop by injecting either hot or cold sodium into the loop from a feed tank while withdrawing sodium from the loop into a drain tank. Each main flow loop has both a feed tank and a drain tank for this purpose, with the necessary piping and control valves. During a transient test, pressures within the feed tanks are controlled to minimize the variations of pump-suction pressure. The drain tanks also serve as reservoirs for draining the main flow loops under both normal and emergency conditions.

Argon gas, which is used to control the pressure and to maintain an inert atmosphere in all sodium systems, is supplied from a liquid-argon storage station. Argon cover gas is used in the test pump for maintaining an inert atmosphere or for sodium-free surface-level control. If helium cover gas is required in the test pump, it can be supplied from bottle storage.

All systems containing sodium or sodium vapor have electrical-resistance surface heaters to prevent uncontrolled freezing or cold trapping. Electrical-resistance immersion heaters are used in the feed tanks to heat sodium for thermal transient tests.

Test pumps and other sodium-system components can be removed from the loop and transported to the cleaning-facility area by an overhead crane. The cleaning facility has a large tank in which the sodium-contaminated items are cleaned under controlled environmental conditions. The contaminated item is immersed in isopropyl alcohol by slowly raising the level in the cleaning tank. The alcohol reacts with sodium to form hydrogen and a soluble sodium alkylate. This reaction is slow enough so that the heat of reaction does not cause local hot spots and damage to the items being cleaned. After the sodium-alcohol reaction has been completed, the items are rinsed in low-chloride water and are then air dried.

A purification system reduces impurities in the sodium to a level that will minimize sodium plugging, particulate formation, and deterioration of materials of construction. Carbon hot traps, cold traps, and mechanical filters are included in the system. A material surveillance station monitors the condition of piping materials.

The design criteria for the sodium system are:

Design temp., °F	1210
Design pressure, psig	225
Design flow, gpm	60,000
Start-ups and shutdowns	250
Thermal transients	± 35°F/sec for 6 sec ± 4°F/sec for 120 sec

Figure 1.36 is a schematic flow diagram of a two-loop SPTF system.

(g) *United Kingdom Mechanical Pump Rig* [115]

The United Kingdom has sodium component test facilities in the Reactor Engineering Laboratory (REL) at Warrington and at the Experimental Reactor Establishment at Dounreay.

The British decided at an early stage to use mechanical pumps in the projected fast reactors and to obtain first-hand experience of the design and operation of this vital fast reactor component.

The pump chosen for study is of the centrifugal type with a vertical shaft supported by an upper oil-lubricated roller bearing and a lower sodium-lubricated journal bearing. The size chosen for study was 6000 gpm with a pressure rise of 75 psi. This pump will give enough technological and operational information to extrapolate to larger sizes of the order of 15,000 gpm.

The pump is being tested in a specially designed loop (Fig. 1.37). The loop consists of a stainless-steel vessel housing the pump and a reentrant loop of 12-in. diameter containing suitable instrumentation for flow measurement. The loop is

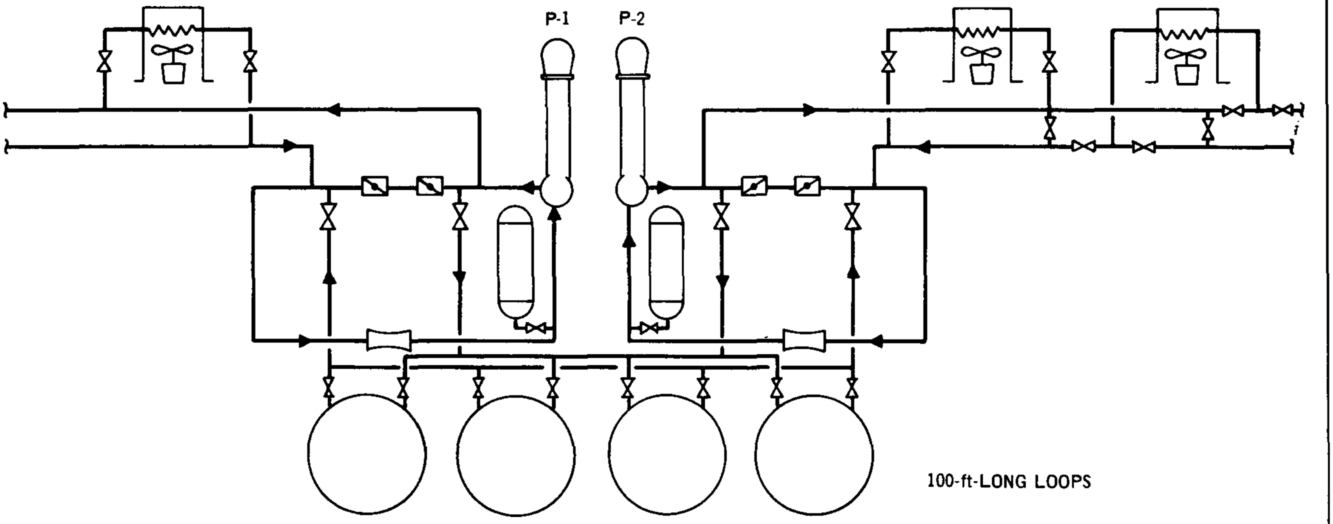


Fig. 1.36 Two-loop SPTF concept.

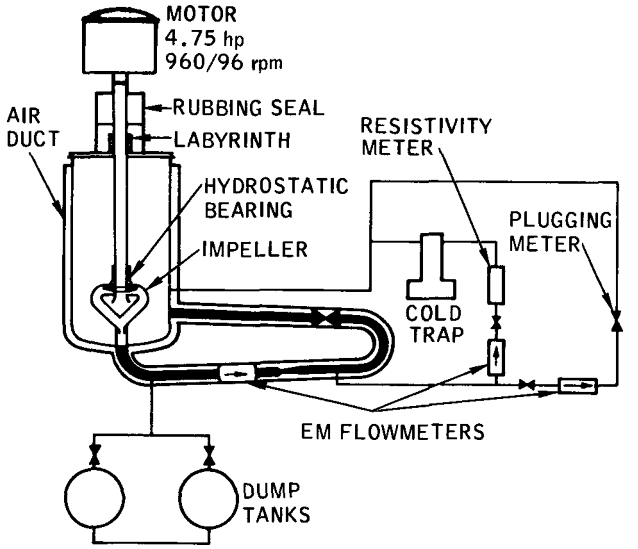


Fig. 1.37 Sodium Pump Test Facility (6000 gpm).

constructed entirely of 18-8 stainless steel. The loop impurity level is controlled by a small, subsidiary, pumped cleanup loop comprised of a 1-in. electromagnetic pump and a cold trap. Impurity levels can be obtained by sampling, with subsequent laboratory analysis, and operational performance is checked by a plugging meter. About 12 tons of sodium is held up in the loop, and the dump tanks are on the floor level. The loop operates at a temperature of 400°C.

(h) *Atomic Power Development Associates Sodium Technology Loop* [116]

A sodium technology loop has been operated by Atomic Power Development Associates (APDA) under the sponsorship of the USAEC's Reactor Division since 1962 to evaluate in-line instruments and purification devices for sodium impurities. The evaluation program is designed to include the following activities:

1. Instrumentation for sodium systems, including the development and evaluation of in-line instruments for the detection and determination of impurities in sodium.
2. Sodium cleanup processes, including the development and evaluation of sodium purification techniques and devices.
3. Chemical and physical behavior of sodium impurities, including the investigation of the chemical and physical behavior of impurities in sodium-loop environment.
4. Laboratory analysis, including complementary development and refinement of analytical techniques for the determination of sodium comtaminants.

The APDA sodium technology test loop is shown in Fig. 1.38. The

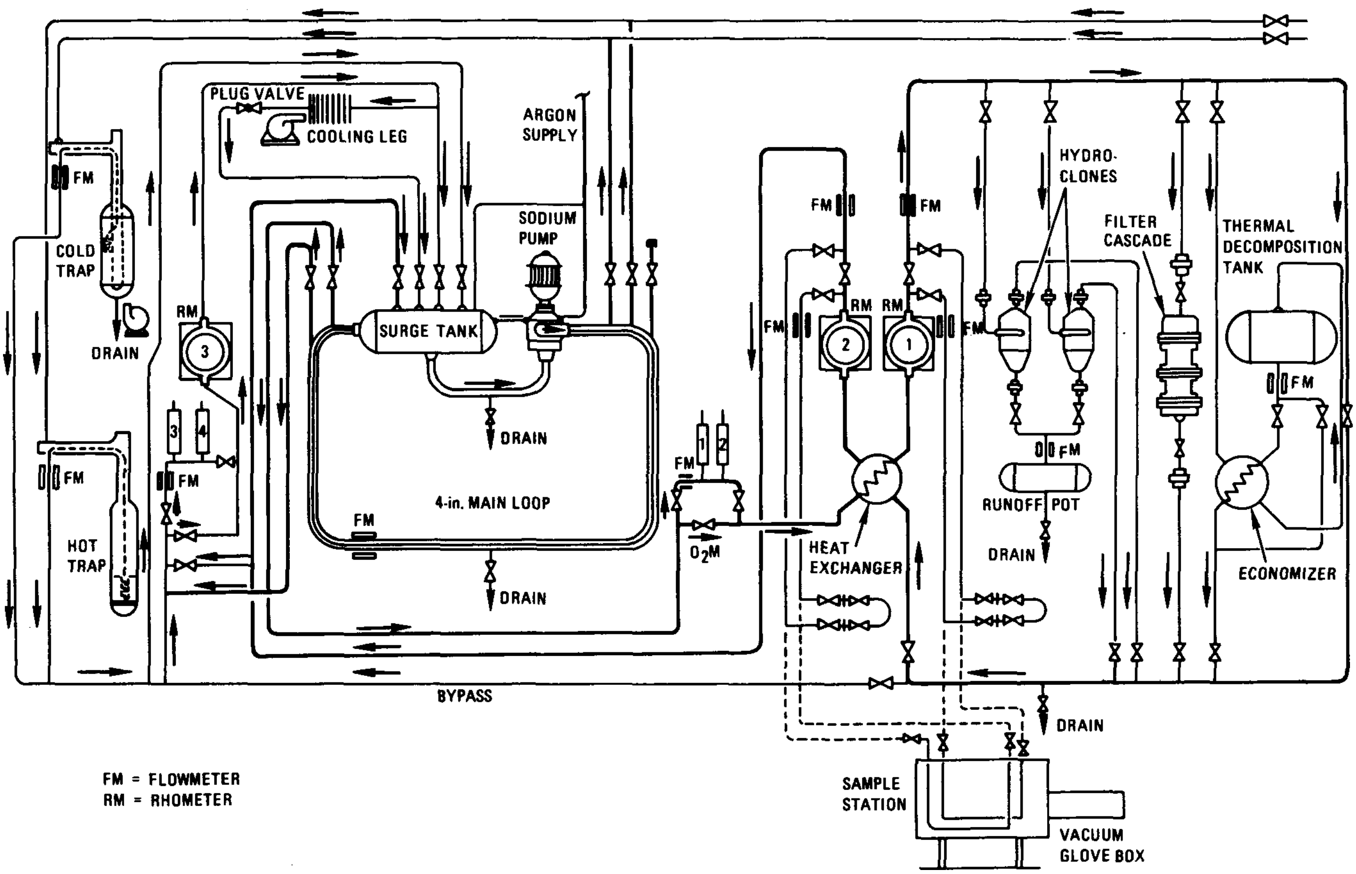


Fig. 1.38 Diagram of APDA Sodium Technology Test Loop.

circuits extending from the 4-in. main loop are all 304 stainless steel and are designed to operate at temperatures up to 1000°F at an average flow rate of 7.5 gpm.

Two of the three rhometers are installed in a differential arrangement so that it is possible to monitor the inlet and outlet streams from any of the cleanup devices installed in the circuit. An economizer located upstream of both meters equalizes the temperature at the two monitoring points. Oxygen cells 1 and 2 are installed near rhometer 1 (RM-1) and cells 3 and 4 near rhometer 2 (RM-2). Thus the cell readings can be directly compared with the rhometer indications.

The effluent header returns either to the pump surge tank directly or to the plugging meter and rhometer installed in the 4-in. main loop. The supply header and effluent header may be operated in series (with no cleanup devices across the line), passing the circulating sodium through the differential rhometers and through the two sample stations.

The sample stations are U-bends of stainless-steel tubing that can be isolated from the circuit when a sample is desired. The U-bends will be placed in a vacuum dry box to eliminate possible atmospheric contamination when sample tubes are removed or replaced.

The extended loop and components are serviced by a 200-gal auxiliary storage tank (not shown) into which the system drains by gravity. The thermal decomposition tank is equipped with manual heaters so that its temperature can be raised to 1200°F.

The filter cascade is an arrangement of three progressively finer micrometallic filters in series; Grayloc fittings are used to drain and isolate the assembly for removal from the loop. When this assembly is transferred to a dry box for disassembly and examination, each filter chamber can be reached by breaking open the three-flange separators in the cascade assembly. Filter elements can also be removed and disassembled.

The Doxie hydroclone installation consists of two Dorr-Oliver units mounted in parallel. This arrangement is designed to pass a 7.5-gpm flow of sodium through the differential rhometers with an anticipated 30- to 40-lb pressure and with a calculated ability to effect a 95% separation of particles 2 μ or larger. For operating flexibility, the hydroclone units are provided with plugging rods to deactivate any number of the individual cyclone separators. These units were adapted for sodium service by sealing the removable high-pressure heads with a stainless-steel Flexitallic Gasket Co. ring gasket. The overflow, or clean discharge stream, empties into the effluent header; the underflow stream, which contains the removed contaminants, passes through a throttle control and a flowmeter to a runoff pot for accumulation and sampling.

1-5.3 *Sodium-Water Reaction Test Loops*

When designing a steam generator, the designer must consider the possible occurrence of a sodium-water reaction. The double-wall tube concept carries economic penalties without presenting a firm guarantee against failure in a plant built to operate for many years.

Several organizations have built loops for the purpose of studying the effects of sodium-water reactions and of identifying the significant parameters involved. A few of these loops are described briefly in this section.

(a) *APDA Sodium-Water Reaction Test* [117]

Figure 1.39 is a schematic diagram of the APDA test loop. The test stand supports five main systems: (1) a sodium system, (2) a circulating-water system, (3) a reaction-water system, (4) a reaction-products system, and (5) a nitrogen cover-gas system.

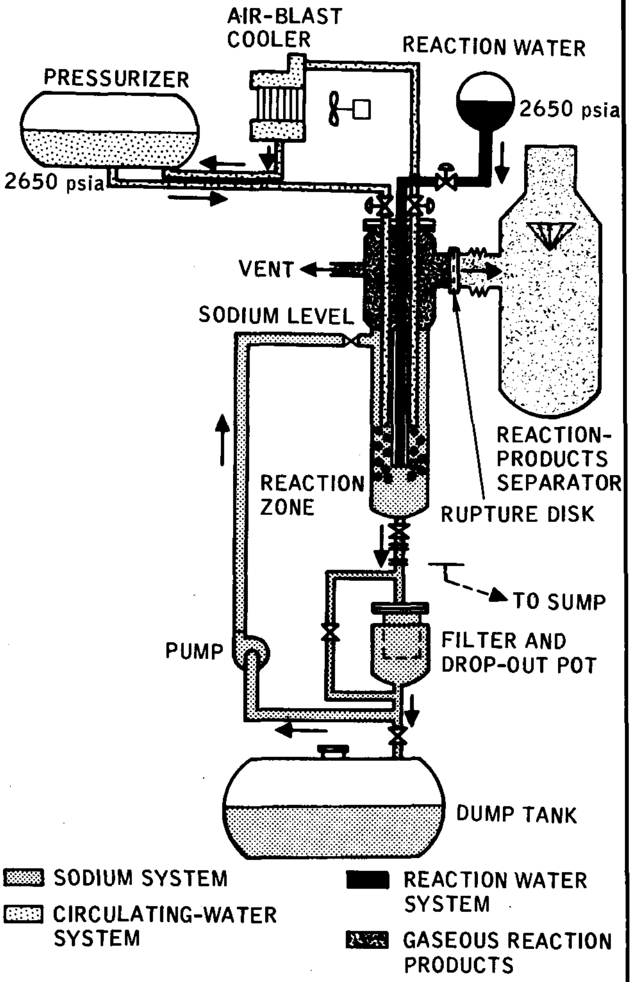


Fig. 1.39 Sodium-water reaction test.

During a small-leak test, sodium is circulated by a centrifugal pump from the bottom of the test unit through the filter tank and back to the test unit. Large particles are removed from the sodium by a fine-mesh filter screen designed to be removed through the top of the filter tank for cleaning. The sodium system also contains a cold trap and a dump tank.

The circulating-water loop contains a pressurizer, an air-cooled heat dump, and three quick-acting valves for emergency isolation. The system is pressurized from a 6000-psi nitrogen station. High-purity boiler feedwater at 2650 psia and 600°F flows by natural circulation from the pressurizer down through the test coil where it is heated. The hot water passes through the air-cooled heat dump and returns to the pressurizer.

The reaction-water supply is contained in a storage tank that is separate from the circulating water. The same high-purity water as that used in the circulating system will be used and can be heated to 600°F with electric heaters. The system is pressurized from the same 6000-psi nitrogen supply used to pressurize the circulating-water system. The reaction water flows through a Schedule 160 steel pipe, which is flanged to the reaction-water trigger tube. The line contains a quick-closing valve for emergency operation.

The reaction products can be vented through two paths during a reaction. During the tests the hydrogen, with entrained sodium, will be vented through the hydrogen cooling tank to the atmosphere. In the event of an uncontrolled reaction, the products will be discharged through the 24-in. rupture disk, located in a 30-in. pipe, into a reaction-products separator.

The test unit consists of a pressure vessel, 3 ft in diameter and 16 ft long, containing a removable bundle of tubes, one of which is a natural-circulation water coil. The remaining tubes have nitrogen sealed inside. The bundle is approximately 2 ft high and is positioned at the bottom of the vessel under 10 ft of sodium.

The trigger-tube assembly is installed and removed through the top flange of the test unit. This device is used to inject a controlled amount of water into the sodium for the reaction tests. The trigger tube is approximately 16 ft long, the flow-control orifice for the reaction water is located at the lower end, and a set of valves and flange connections that connect to the water and nitrogen supply vessels is located at the upper end.

The water-flow orifice, located at the lower end, is isolated from the sodium before the reaction by a rupture disk set to burst at a maximum of 2500 psia (2300- to 2500-psia range). Nitrogen is used to pressurize the 600°F reaction water to 2650 psia in the storage vessel. The valve in the trigger-tube supply line is opened, and the pressure, transmitted through the water column in the tube, bursts the rupture disk.

(b) *Empire State Atomic Development Associates Sodium-Water Reaction Tests*

The Empire State Atomic Development Associates (ESADA) [118] sponsored a sodium-water reaction test program at AI. The study was conducted to derive information that would permit the design of a modular steam-generator system in which damage to the system will be minimized in the event of a sodium-water reaction.

The major objective of the test program was determination of the shell, or sodium side, pressure-time relation for a given mass flow rate of water and steam at operating conditions during a sodium-water reaction. This information, correlated with performance characteristics of relief devices and the relief system, is to be used as the basis for the design of an integrated system in which pressure effects are minimized. An additional objective was the accumulation of data needed to ensure adequate structural design of the steam-generator module.

A simplified test system was used to obtain relative pressure-time data. A tube was forced to rupture within the system, and resulting pressure-transient measurements were made, which will be extrapolated to a full-size system by a mathematical model. These experiments should provide the basis for additional tests using the steam-generator module.

The test system (Fig. 1.40) consists of the test section in which reaction takes place, the relief system and receiver tank for the products of the reaction, a high-pressure steam supply system, a high-pressure water supply, and a sodium storage and supply system.

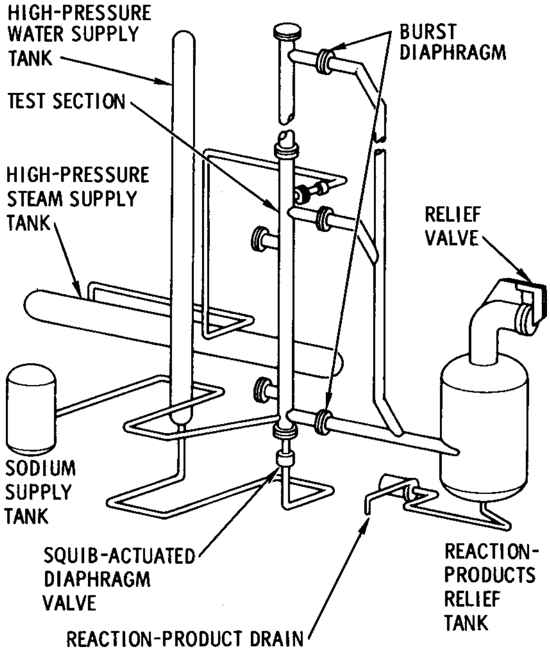


Fig. 1.40 Empire State Atomic Development Associates sodium-water reaction test system.

The electrically heated steam supply system was designed to provide steam at 2400 psi at 1000°F. The water supply, also electrically heated, was designed to provide water at average conditions of 2800 psi and 470°F; the rate of flow was approximately 18 lb/sec. Capacity for 10- to 15-sec flow was provided by each system.

The relief system provided three locations for the installation of 6-in.-diameter burst diaphragms. Normally two were used, one at each end of the test section. They were rated at 125 psi. When the diaphragms ruptured, the reaction products and unreacted sodium discharged into the reaction-products tank through 6-in. pipes. The tank was rated at 150 psi at 850°F. A 16-in. relief valve on top of the tank passed up to 100 cu ft of vapor per second at 5 psi. During each test, low-pressure steam flowed into the tank to complete reaction of sodium received from the relief system. After the test, the relief system, test section, and reaction-products tank were flushed with water and drained.

The sodium supply tank was used for intermediate storage of sodium at approximately 400°F. It has sufficient storage capacity for four barrels. The test section was filled through the transfer line by pressurizing this tank with inert gas. After the test section had been filled, two valves in the transfer line were closed and the line was allowed to cool. The sodium remaining in the line solidified and thus aided in isolating the sodium supply tank from the test section during tests.

Figure 1.41 is a photograph of the completed test facility. The longest pipe column in the center of the photograph was the main test section. All auxiliary test sections were assembled, as shown, during construction to ensure proper assembly and fit-up. Sections not required for the first tests were

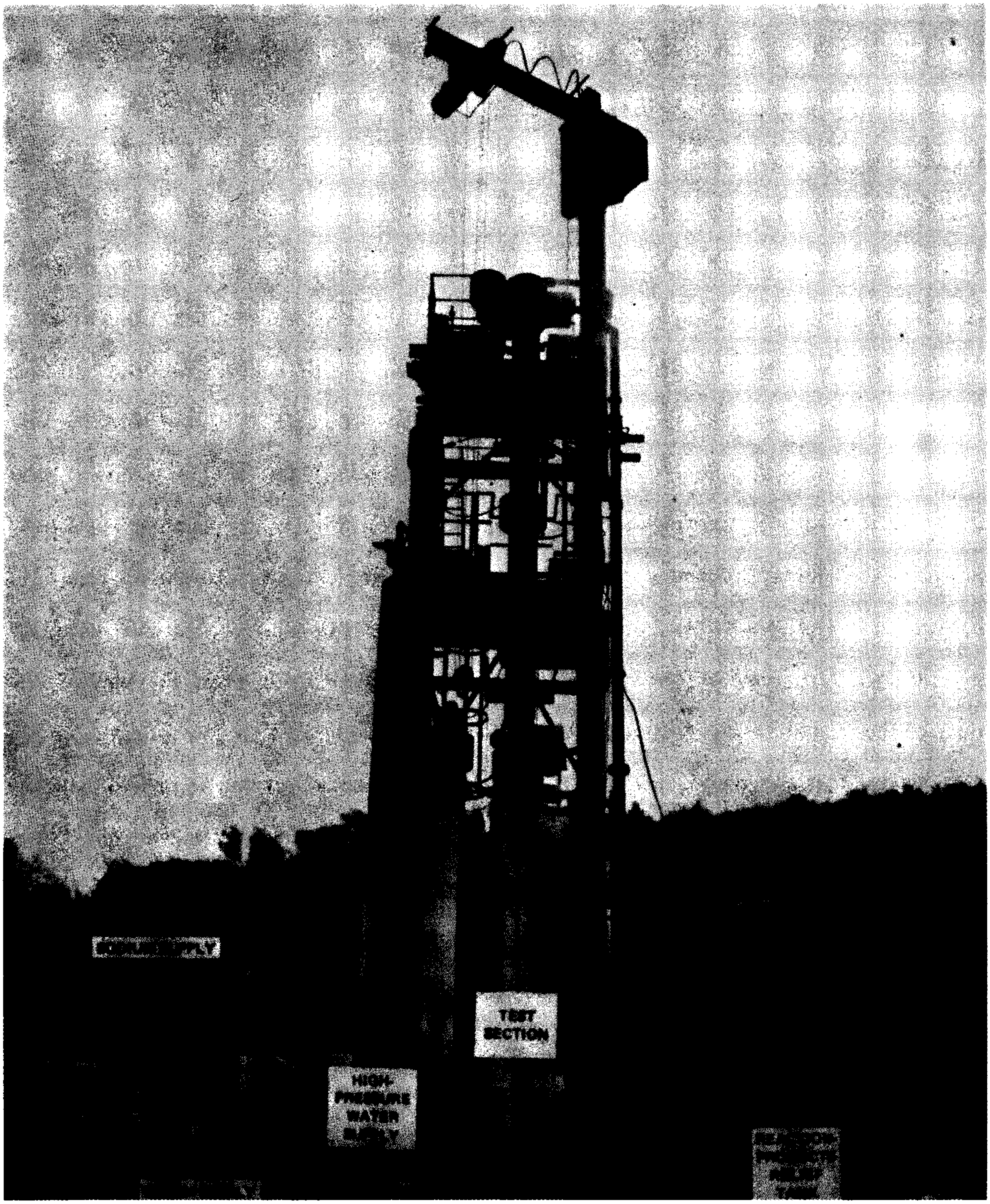


Fig. 1.41 Empire State Atomic Development Associates sodium-water reaction test facility.

subsequently removed.

The valve cover on the reaction-products relief tank was arranged to pivot upward to open, and the adjustable weights on the cover were such that 1 1/2 psi could be maintained in the tank. Unreacted sodium discharged from the test section and relief system was exposed to low-pressure steam in the reaction-products tank. This steam was supplied at 90 psi by a gas-fired utility boiler. All sodium was thus reacted before the system was flushed with water and drained.

The main test assembly in which the initial reaction occurred is shown in Fig. 1.42a. It consisted of a tube bundle that surrounded a rupturable tube, all of which was enclosed in a large heavy-wall pipe. The tube bundle was made of 36 stainless-steel tubes, 4 or 14 ft long and sealed at both ends. Spacers, of the same design and material as those used for the modular steam generator, space the tubes radially on approximately 1-in. pitch. This established three rows of tubes radially around the center. The center was occupied by the rupturable tube.

The main test assembly shell was made of 8-in. Schedule 80 stainless-steel pipe. When assembled, the main test section had a total length of 16 ft. The lower section had four lateral nozzles; the two that are shown closed with blind flanges were connected to auxiliary test sections when required. The remaining two nozzles were connections to the relief system. The two flanged joints contained the 125-psi burst diaphragm assemblies.

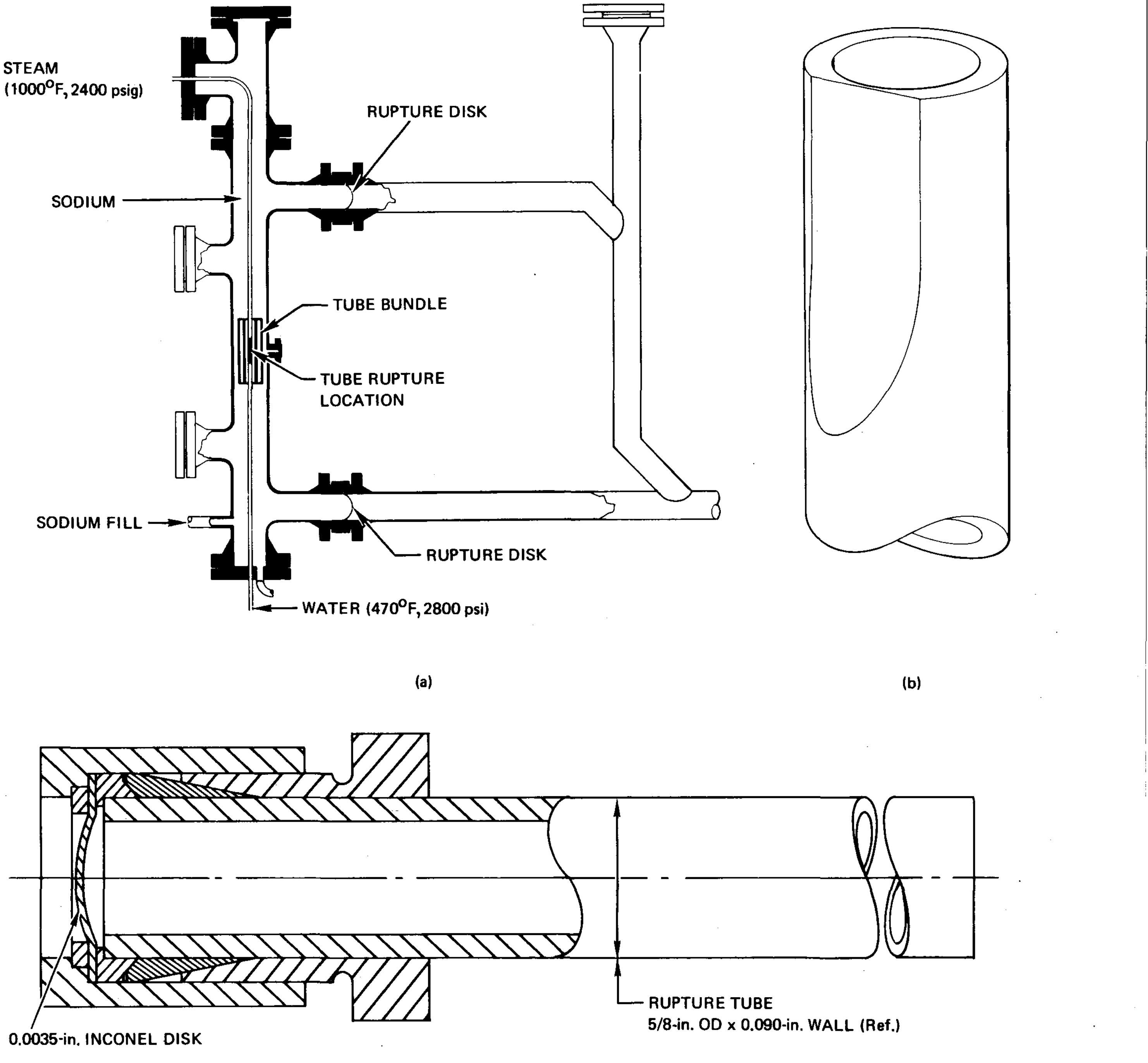
The upper section of the test assembly was an 8-in. Schedule 80 stainless-steel tee. The upper and lower ends of the test assembly, shown closed with blind flanges, were connected to additional test sections to increase the length of the complete test assembly to 44 ft.

The rupturable tube entered through the lower blind flange, passed centrally up through the tube bundle, and emerged through the upper blind flange. It was made of 321 stainless-steel tube, 5/8-in outside diameter and 0.090-in. wall thickness, the same material as that used for tubes in the modular steam generator. Two methods were used to obtain a rupture in the desired location. In the first method, used for 12 of the 17 tests, a 4-in.-long flat region was machined on the tube outside diameter to reduce the wall thickness to 0.005 to 0.007 in. at a point tangent to the inside diameter of the tube, so that rupture would occur when the internal pressure of the tube reached approximately 1100 psi.

A cross section of the rupture tube is shown in Fig. 1.42b. Toward the end of the experimental program, a "dead end" type of rupture was designed to get more uniform rupture pressures than had been possible with the milled flat. The redesigned rupture point, shown in Fig. 1.42c, consisted of a rupture disk made of 0.0035-in.-thick Inconel, secured over the end of the rupture tube with a high-pressure tube fitting.

Steam entered at the upper end of the rupturable tube and water at the lower end (not in the same test). Pressure was withheld from the tube by a blocking disk that was inserted at either end of the tube. When flow was required, the disk was pierced with a spring-driven pointed valve stem. Before use, the spring was compressed and held by a latching mechanism which, in turn, was secured by an explosive bolt. When the bolt was electrically fired, the spring was released and the pointed valv stem was driven into the blocking disk. In this way the rupturable tube was abruptly pressurized.

Pressure transients occurring in the test section were detected by unbonded strain wire and piezoelectric transducers. Specifications for the unbonded strain-wire transducers include operating ranges up to 5000 psi, maximum



(a) (b)

(c)

Fig. 1.42 Sodium-water reaction test section. (a) Test section. (b) Section f rupture tube showing milled rupture location. (c) Dead-end rupture point.

continuous temperature of 600°F, and a frequency response of 800 cycles/sec (limited by a "spider legged" arrangement which transfers the diaphragm motion to the strain wires). The transducer bridges were excited by a 5-volt 20-kc carrier. After suitable amplification and demodulation, the signal was recorded on a 3000-cps galvanometer in an oscillograph. This response level was marginal, in terms of defining accurately the transient behavior of the test-section pressure; in providing data input for analyzing the vessel response, it was adequate. The strain-wire transducer proved reliable for use at all sensor locations except at the point of water introduction. In this position the rate of pressure increase was so great that the diaphragm would deflect well past the strain-wire rupture point. In the other locations the strain-wire transducers functioned dependably.

During the course of the program, quartz crystal pressure transducers that were suitable for operation at 700°F became available. These transducers are designed for intermittent gas temperatures, in the pressure environment, of 3000°F. Nominal frequency response is 130 kc, and sensitivity is near 5×10^{-2} coulomb/psi. Pressure ranges are available to 5000 psi. These transducers provided the means for measuring and recording the pressures at the point of water introduction.

Five pressure transducers were installed on the test-section shell by flanged pipe nipples such that the transducer diaphragm was in direct contact with liquid sodium but at a maximum temperature of 500°F: one on the shell at the point where tube rupture and initial reaction took place; one 5 ft above the point of rupture and another 5 ft below; and one on each of the two lateral nozzles leading to the relief system. Up to 11 transducers could be installed on the 44-ft test assembly. Pressure-time data were obtained by observing pressure at each location.

Thermocouples were mechanically attached to the rupture tube (and were thus immersed in the sodium at the point of tube rupture) and at points 5 ft above and 5 ft below, con junctional to pressure-transducer locations. The thermocouples were 1/8- sheathed Chromel-Alumel type with the junction grounded.

The results of 17 tests performed in the ESADA rig and the various test conditions and configurations employe are presented in Ref. 77.

(c) *NOAH Rig*

The sodium-water reaction is also being studied in the United Kingdom, where work is in progress at Dounreay on the NOAH rig [115]. The rig is a 1/16th-scale model of the 250-Mw shel and-tube steam generator. The shell is filled with sodium, which is circu lated by an electromagnetic pump givi a downward flow. The tube section is contained in a square section ducting within the main vessel. Because of the complexity of the tube assembly in the model, this is represented mainly by a number of perforated meta plates packed loosely in the square duct to give approximately the same geometry. One water loop is provided and this is taken to the base of the duct assembly where it is looped in the design layout and surrounded by a group of wire dummy water tubes arranged in the same way. A leak in the vessel is simulated by using a special pipe-fracturing device in thi line. Termination of the leak is con trolled by a quick-acting shutoff valve. The loop is fed by a pressuri vessel in which a reserve of water is maintained at the correct test conditions. Temperature and pressure changes in the test vessel which are due to reaction are measured and recorded on a high-speed recorder unit. Excess pressure in the test vessel ca be relieved by a bursting disk, which allows the gaseous reaction products to vent into a large surge vessel. The rig is housed in a concrete vesse and is remotely controlled.

1-5.4 *Heat- and Mass-Transfer Loops*

(a) *United Kingdom Fuel Element Thermal Test Facility* [115]

A 4-in. test-loop facility has been constructed in Britain at the REL at Warrington. This facility (Fig. 1.43) was designed primarily to provide appropriate flow and temperature conditions for testing fast reactor fuel-element subassemblies.

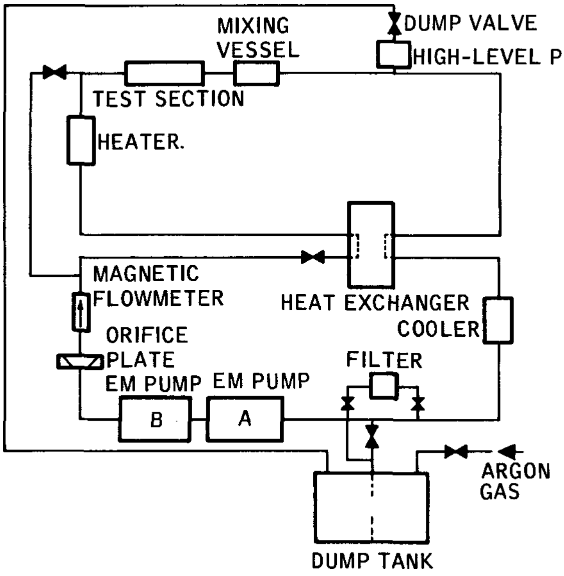


Fig. 1.43 Fuel-element thermal test rig.

The loop was designed around the electromagnetic pumps originally built for Dounreay, which can deliver 50 lb of sodium per second at 35 psi head and 430°F. By fitting these pumps with a specially developed high-temperature winding, the allowable metal temperature has been raised to 705°F, and two of these pumps are used in series to provide 350 gpm at 70 psi.

The loop is fitted with a 10-Mw heat exchanger, a 350-kw heater, and a suitable cooler to provide sodium at 1200°F at the test section. An additional 4-in. pipe allows cold sodium to bypass the heat exchanger and heater and feed directly into the test section. Thus thermal shocks of an amplitude of 450°F and at rates of 90°F/sec can be obtained. Considerable difficulty was experienced with the immersion heaters, in commissioning this loop, and an alternative induction-type heater had to be designed. The standard cold trap and impurity monitor and sampling system are provided. Information on impurity levels and cleanup in sodium circuits has been obtained from tests.

A subsidiary test section connected to this loop contains an experiment to measure the eddy diffusivity of heat as a function of the Reynolds number. The ratio of this value to the eddy diffusivity of mass is needed in the design and evaluation of hot spots in subassemblies. The experiment measures the decay of a spike of hot sodium along the axis of a large tube and, for its performance, the development of high-precision thermocouple scanning equipment has been carried out. Initial results from this section show that at Reynolds numbers around 6×10^4, the ratio $\varepsilon_H/\varepsilon_{mass}$ is of the order of 0.6.

This loop is also used for instrumentation testing, particularly the development of flowmeters and temperature-measuring systems. An experiment with a model subassembly containing 70 heated pins, designed to study a-c temperature-measurement systems, has been completed.

(b) *Dounreay Experimental Reactor Establishment 4-in. Loop*

This loop is similar in concept to the REL loop previously described but differs in certain details. It uses only one 4-in. DFR pump, which can supply 90 gal of NaK per minute at 1110°F with a pressure drop of about 30 psi. This loop has been used for the check-out on the subassemblies for operation in the DFR. Some cold-trap development is planned in this loop, and therefore it has glove-box facilities.

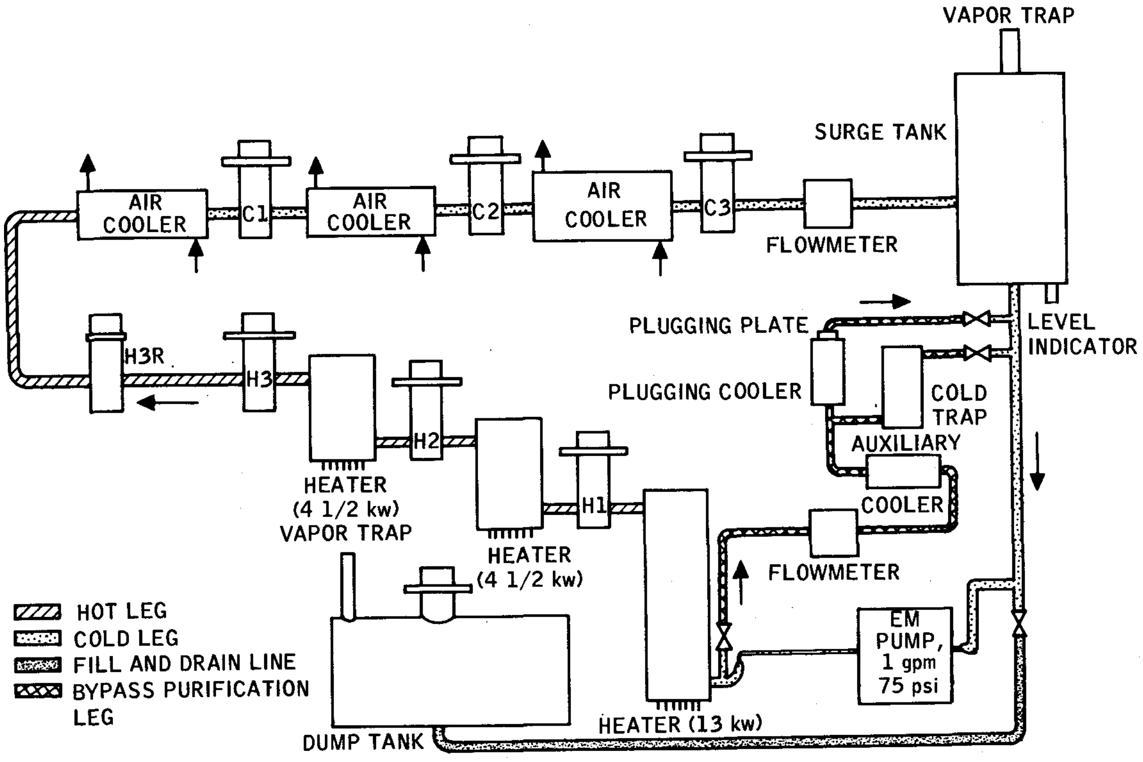


Fig. 1.44 Flow sheet for mass-transfer test loop. C1, C2, and C3, cold-leg sample holders. H1, H2, H3, and H3R, hot-leg sample holders.

In 1965, plans were discussed for a study of boiling heat transfer in small rod clusters. Acoustic techniques are being developed to detect the onset of boiling, and hence accident conditions, in fast reactors. These experiments should give the basic information necessary for designing such detection systems. A series of experiments on boiling under various conditions will continue for some time.

(c) *General Electric Sodium Mass Transfer Loops* [119]

Six experimental test loops have been built by the General Electric Company under the sponsorship of the USAEC to investigate the effect of sodium on various steels at temperatures up to 1300°F. The loops are identical in design, differing only in the construction material. The flow sheet for a typical test loop is shown in Fig. 1.44.

One complete loop is fabricated from 316 stainless steel, one from 2 1/4 Cr-1 Mo alloy steel and one from 5 Cr-1/2 Mo-1/2 Ti alloy steel; two loops are constructed of 316 stainless steel in the heated or hot-leg portion and 2 1/4 Cr-1 Mo alloy steel in the cooled or cold-leg portion. The purification side stream on these last two loops is also fabricated from 2 1/4 Cr-1 Mo steel. The sixth loop is constructed of 316 stainless steel in the hot leg and 5 Cr-1/2 Mo-1/2 Ti in the cold leg and purification leg. The sodium coolant is purified in each loop in a side stream by a forced-convection cold trap. A plugging indicator is mounted in parallel with the cold trap to determine the oxygen impurity in the sodium. The test loops that contain low-alloy steel are designed to operate at a maximum temperature of 1200°F, and the 316 stainless-steel loop is designed for operation at 1300°F.

All loops have sample holders located in the maximum and minimum temperature regions as well as in two intermediate regions in the hot leg and also in the cold leg. In addition, there is a special sample holder in the maximum temperature zone that can be biologically shielded. An activated-steel specimen will be located in this sample holder when the radioactive-tracer technique is being employed. The corrosion samples are fabricated from the same material as the sample holder and are 1/16 in. thick by 3/16 in. wide by 3 in. long. After they are cleaned, the samples will be weighed before and after the test to ± 0.1 mg to determine their change in weight. This weighing accuracy will provide a sensitivity of less than 0.06 mil of uniform loss of steel sample material per year.

Electric heaters preceding the first three sample holders in the hot leg and extended-surface air coolers preceding the three cold-leg sample holders are used to obtain prescribed test temperatures in the sample holders. Manual adjustments establish test conditions. Automatic control of some of the electric power to the heaters and of some of the air to the coolers provides a trim control to maintain prescribed temperature conditions during daily changes in line voltage and ambient conditions. This control permits unattended loop operation for a period of several work shifts.

For independent operation, each loop has an individual power transformer and an electrical distribution system. A contactor interrupts all power to the loop if the stop button or any of three over-temperature trips are activated. Electric power distribution, circuit breakers, automatic temperature controllers, inert-gas control system, and temperature indication for about 30 locations on each loop are provided on the individual operating panels. The seventh instrument panel contains a level, temperature and flow recorder for all loops, and a two-pen recorder for cold-trap or plugging indicator data.

One of the criteria for designing the test loops was to simulate, or prototype on a miniature scale, possible operating conditions for a liquid-metal-cooled reactor system. These loops could be representative of either the primary or the secondary circuit in a reactor system. For example, the hot leg would represent the reactor (with no nuclear effects on the steel) or the secondary side of an intermediate heat exchanger. The cold leg, correspondingly, would represent either the primary side of the intermediate heat exchanger or the steam generator. The emphasis on the low-alloy steels is deemed necessary because most of the presently installed steam generators are fabricated from this type of water-side-corrosion-resistant and less-expensive material and because future steam generators probably will be fabricated from this type of steel.

The design conditions for the loops and components are listed in Table 1.29.

(d) *Large TREAT Sodium Loop* [120]

The design and development of future fast breeder and power reactors are intimately involved with the development of fuel capable of satisfactory performance in such devices. One aspect of fuel development is associated with the behavior of the fuel when the reactor experiences a rapid addition of reactivity resulting in the generation of excessive power and temperatures in the fuel and surrounding coolant. The solution to this problem can be approached only by experiment, suitably engineered specifically to the reactor fuel and to the environmental conditions provided within such a reactor.

The TREAT reactor, located at the

TABLE 1.29 - Design Conditions for GE Sodium Mass-Transfer Loops

Temperature	
Main loop (max. temperature)	
316 S.S. (monometallic)	1300°F
All other loops	1200°F
Surge tank	1000°F
Dump tank	1000°F
Bypass purification leg	
Inlet	800°F
Outlet	300°F
Pressure	
Surge tank	50 psi
Sodium valves	40 psi
Remainder of system	100 psi
System ΔT	500°F
Velocity	
Hot-leg samples	
High velocity	30 ft/sec
Low velocity	10 ft/sec
Cold-leg samples	10 ft/sec
Flow	
Main loop	1.0 gpm at 1000°F
Cold trap (with auxiliary cooler)	0.2 gpm at 800°F
System pressure drop	70 psi at 1 gpm
Total heat input	
Preheat	4 kw
Test conditions	25 kw

Allowable stress

The loops were designed in accordance with the code for pressure piping, ASA B31.1-1955, and with Sec. VIII of the ASME boiler code. (Stress values for the ferritic materials were extrapolated.)

Material	Temp., °F	Allowable stress, psi
316 S.S.	1300	4000
2 1/4 Cr-1 Mo	1200	2000
5 Cr-1/2 Mo-1/2 Ti	1200	1200

National Reactor Testing Station in Idaho, is a pulsed reactor available for transient experiments on fuel elements [121]. A sodium loop has been designed and has now been constructed at this site. The loop structure is shown in Fig. 1.45. In this figure the major portion of the loop is shown. The region contains the piping, control valves, electromagnetic pump, and tankage. The sodium flow is directed to the top of the reactor where it flows through the test section located at the approximate center of the reactor core. After the sodium flow passes through the test section, it returns to the equipment room. Several modes of flow are possible by manipulation of appropriate valv Sodium can recirculate locally in the equipment room piping by isolation of the in-pile portion, or it can recirculate through the test section. Finally, a once-through flow can be maintained for 90 sec while a transient is executed; the returning sodium is directed to a dump tank situated below floor level. In this way

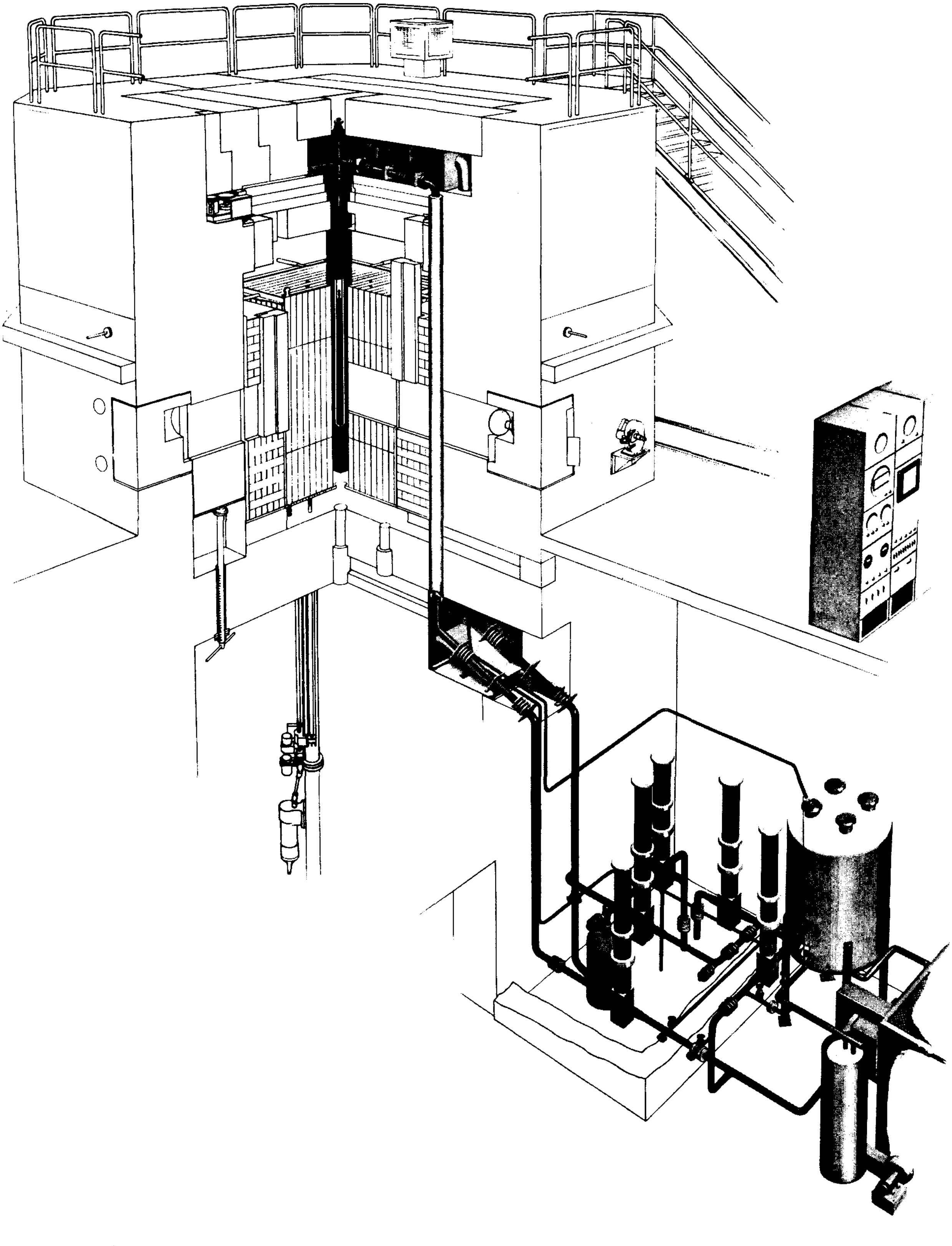


Fig. 1.45 Large TREAT sodium loop.

isolation and shielding of radioactive particulate debris and contaminated sodium will result in maximum protection of personnel.

The problems involved with the design of such a loop are unique. Unusual pressure and temperature interactions had to be considered during the design phase. The maximum ambient temperature for this loop will be 930°F.

For the most extreme conditions resulting from the maximum credible accident, the transient pressure pulse of 514 psia is considerably below the test-section steady-state ASME design pressure of 1990 psia at the operating temperature. Also, the calculated reflected pressures transmitted to remote regions of the loop do not exceed the steady-state capabilities of the components used.

The large TREAT loop is a unique facility for fuel-meltdown studies under flowing sodium. A facility of this type has not been previously available to experimenters working in the area of fast reactor safety.

REFERENCES

1. K. Kummerer, Selection of Liquid Metals in Reactor Technology, *Atomkernenergie*, *9*: 159-165 (July 1964).

2. S.A. Ulybin, *Coolants for Nuclear Power Engineering Installations*, Russian Report JPRS-38717, Chap. 10, Paragraph 5-6, November 1966.

3. F.A. Comprelli, F.J. Hetzler, and T.A. Lauritzen, Clad Compatibility with Mixed Oxide Fuel and Sodium, in *Proceedings of the Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors, Argonne National Laboratory, Illinois, Oct. 11-14, 1965*, USAEC Report ANL-7120, October 1965.

4. J.D. Gracie and J.J. Droher, *A Study of Sodium Fires*, USAEC Report NAA-SR-4383, Atomics International, Oct. 15, 1960.

5. D. Strominger et al., Table of Istotopes, *Rev. Mod. Phys.*, *30*: 585-904 (1958).

6. A.I. Leipunskii et al., *Atomic Power Plant BN-350*, Report CEA-tr-1538 Oct. 10, 1966.

7. J.G. Yevick (Ed.), *Fast Reactor Technology: Plant Design*, pp. 121-240, The M.I.T. Press, Cambridge, Mass., 1967.

8. M. Shaw and M. Whitman, Nuclear Power: Suddenly Here, *Sci. Technol.*, No. 75: 22-34 (March 1968).

9. D. Mars (Ed.), *1000 Mwe LMFBR Follow-on Study, Quarterly Progress Report, June 1 to Aug. 31, 1967*, USAEC Report BAW-1312, Babcock and Wilcox.

10. C.W. Higby, *Heat Removal System Concept Evaluation, Loop Concept versus Pool Concept*, Report BNWL-CC-1013, Gulf General Atomic, Jan. 30, 1967.

11. J.H. Campo, Atomics International Division, North American Rockwell Corporation, private communication.

12. D.C. Hamilton, F.E. Lynch, and L.D. Palmer, *The Nature of the Flow of Ordinary Fluids in a Thermal Convection Harp*, USAEC Report ORNL-1624, Oak Ridge National Laboratory, Mar. 16, 1954.

13. S.K. Hellman et al., Use of Numerical Analysis in Transient Solution of Two-Dimensional Heat Transfer Problems with Natural and Forced Convection, *Mech. Eng.*, *76*: 683 (1954).

14. M.C. Rowland, D.E. Plumlee, and R.S. Young, *Sodium Mass Transfer*.

XV. *Behavior of Selected Steels Exposed in Flowing Sodium Test Loops,* USAEC Report GEAP-4831, General Electric Company, March 1965.

15. F. Beyer and M. Norin, The Effect of Mixing in the Outlet Plenum of the Fermi Reactor, *Trans. Amer. Nucl. Soc., 3*: 186 (1960).

16. W.W. Sabol and R.W. Lockhart, *Sodium Mass Transfer.* VII. *Methods for Determining Impurities in Sodium Samples,* USAEC Report GEAP-4178, General Electric Company, September 1963.

17. Power Reactor Development Company, *Enrico Fermi Atomic Power Plant Technical Information and Hazards Summary Report,* Vols. 1, 2, and 3, October 1962.

18. General Electric Company, Atomic Motor Section, Helical Electromagnetic Pumps for Alkali Metals, Schenectady, N.Y.

19. O.P. Steele, *High Temperature Mechanical Canned Rotor Liquid Metal Pumps,* Nuclear Science and Engineering Conference Preprint 76, Session II, March 1958.

20. D.R. Nixon and C.C. Randall, *Survey of Sodium Pump Technology,* USAEC Report WCAP-2255, Westinghouse Electric Corp., June 1963.

21. E.M. Simons and S.J. Basham, *Control of Coolant Purity in Sodium-Cooled Reactors,* Document 66-WA/NE 17, paper presented at the annual Winter Meeting of the American Society of Mechanical Engineers, New York, Nov. 27 to Dec. 1, 1966.

22. R.C. Andrews, R.H. Hiltz, L.H. Kirschler, S.J. Rodgers, and F. Tepper, *Effect of High Temperature Sodium on Austenitic and Ferritic Steels. Mechanical Properties of Materials. Topical Report No. 8. Results of Mechanical Properties Tests of 304 SS Specimens Conducted in: 1. 1200°F Sodium Contaminated With Carbon,* USAEC Report MSAR-67-103, Mine Safety Appliances Research Corp., July 1967.

23. W.J. Anderson and G.V. Sneesby, *Carburization of Austenite Stainless Steel in Liquid Sodium,* USAEC Report NAA-SR-5282, Atomics International, Sept. 1, 1960.

24. S.J. Rodgers, C.A. Palladino, and T.J. Wildeman, *Effect of High Temperature Sodium on the Mechanical Properties of Candidate Alloys for the LMFBR Program. Topical Report No. 9. Analysis of High Oxygen and High Carbon Cold Traps.* USAEC Report MSAR-67-203, Mine Safety Appliances Research Corp., December 1967.

25. V.I. Subbotin et al., Freeing Sodium from the Products of Its Reaction with Water in a Circulation Loop, *At. Energ. (USSR), 19*(3): 298-300 (September 1965).

26. S.H. Wright and J. Herb, *Examination of the Enrico Fermi Sodium Cold Trap,* USAEC Report WCAP-4321, Westinghouse Electric Corp., November 1965.

27. R.B. Hinze, *Control of Oxygen Concentration in a Large Sodium System,* USAEC Report NAA-SR-3638, Atomics International Div., North American Aviation, Inc., Dec. 1, 1959.

28. H.W. Savage, E.L. Compere, W.R. Huntley, B. Fleischer, R.E. MacPherson, and A. Taboda, *SNAP-8 Corrosion Program Summary Report,* ORNL-3898, Oak Ridge National Laboratory, December 1965.

29. W.J. Anderson, *Removal of Carbon from Liquid Sodium Systems,* USAEC Report NAA-SR-6386, North American Aviation, Inc., Dec. 15, 1960.

30. R.C. Andrews and K.R. Barker, *Effect of High-Temperature Sodium on the Mechanical Properties of Candidate Alloys for the LMFBR Program, Quarterly Progress Report, July-September 1967,* USAEC Report MSAR-67-207, Mine Safety Appliances Research Corp., November 1967.

31. W. Caplinger, *Carbon Meter for Sodium,* USAEC Report UNC-5187, United Nuclear Corp., Aug. 31, 1967.

32. E.L. Kimont, Engineering Development of a Practical 1200°F Sodium Vapor Trap, *Trans. Amer. Nucl. Soc., 8*: 147 (1965).

33. D.H. Thompson, Vapor Traps Protect Liquid Metal Systems, *Power Reactor Technol., 8*(4): 259-270 (Fall 1965).

34. W.A. Deaton, *Grade A Helium,* U.S. Bureau of Mines Helium Activity, Amarillo, Texas, Revision December 1966.

35. J.E. Antill et al., The Purification of Helium in High Temperature Reactors, in *Progress in Nuclear Energy,* Ser. IV, Vol. 4, pp. 63-101, Pergamon Press, Inc., New York, 1961.

36. Argonne National Laboratory, *Chemical Engineering Division Research Highlights, May 1964 to April 1965,* USAEC Report ANL-7020.

37. J.R. Dietrich, Technology of Sodium Systems, *Power Reactor Technol., 8*(1): 75-76 (Winter 1964-1965).

38. R.C. Koch and G.L. Grandy, *Retention Efficiencies of Charcoal Traps for Fission Gases,* USAEC Report NSEC-7, Nuclear Science and Engineering Corp., Aug. 23, 1957.

39. M.H. Lloyd and R.A. McNees, *Absorption of Krypton and Xenon by Various Materials,* USAEC Report ORNL-3228, Oak Ridge National Laboratory, Dec. 1, 1961.

40. H.W. Lohman, *Induction Heating Tests in the Hallam Nuclear Power Facility Development Program,* USAEC Report NAA-SR-4206, Atomics International Div., North American Aviation, Inc., Nov. 15, 1959.

41. P.B.F. Evans and W. Long, Sodium Technology at REL, *Nucl. Eng., 12*(232): 356-360 (May 1967).

42. E. Fielder and D. Davidson, An Induction Heater for a Sodium Circuit, in *Alkali Metal Coolants,* Symposium Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/143).

43. A.I. Leipunskii et al., *Nuclear Power Plant BN-350,* USAEC Report AEC-tr-6663, April 1965.

44. L. Vautrey, Test Rigs for the Rapsodie Coolant Circuits, *Nucl. Eng., 8*: 321-323 (1963).

45. R. Wagner and J. Stearns, Evaluation of Non Fuel Material Behavior in HNPF, in *Proceedings of the Sodium Components Development Program Information Meeting, Chicago, Ill., June 16-17, 1965,* USAEC Report CONF-650620, pp. 47-85.

46. A.I. Leipunsky et al., Sodium Technology and Equipment of the BN-350 Reactor, *At. Energ. (USSR), 22*(1): 13-19 (January 1967).

47. A.I. Leipunsky et al, The BN-350 and the BOR Fast Reactors, *At. Energ. (USSR), 21*(6), 450-462 (December 1966).

48. Babcock and Wilcox Co., *Sodium-Heated Steam Generator Development. Progress Report 22,* USAEC Report BAW-1280-24, Feb. 22, 1965.

49. Babcock and Wilcox Co., *Preliminary Design Report-Prototype Steam Generator*, USAEC Report BAW-1280-28 (Vol. 3), November 1965.

50. A. Lacroix et al., Etudes de Sûreté des Générateurs de Vapeur Sodium-Eau, Méthode de Calcul et Résultats Expérimentaux, in *International Conference on Safety of Fast Neutron Reactors, Aix-en-Provence (France), Sept. 19-22, 1967.*

51. R.S. Baker, *Design of an Eddy-Current Brake for a Sodium-Cooled Nuclear Power Reactor*, USAEC Report NAA-SR-2986, Atomics International, September 1958.

52. Atomics International, *Final Summary Safeguards Report for the Hallam Nuclear Power Facility*, USAEC Report NAA-SR-5700, Apr. 15, 1961.

53. C.P. Zaleski and L. Vautrey, *Le Réacteur Rapide Surrégenérateur Rapsodie, Vols. 1 and 2,* French Report CEA-2193, Oct. 23, 1961.

54. Atomic Power Development Associates, Inc., *A Plutonium-Fueled Fast Breeder Atomic Power Plant*, Report APDA-129, April 1959.

55. L.J. Koch, W.B. Loewenstein, and H.O. Monson, *Hazards Summary Report on EBR-II*, USAEC Report ANL-5719 (Add.), Argonne National Laboratory, Jan. 7, 1964.

56. Atomics International, *Final Summary Safeguards Report for the Hallam Nuclear Power Facility*, USAEC Report NAA-SR-5700, Apr. 15, 1961.

57. J.M. Harrer, *Nuclear Reactor Control Engineering*, D. Van Nostrand Company, Inc., Princeton, N.J., 1963.

58. P. Evans et al., Control and Instrumentation of Prototype Fast Reactor, in *British Nuclear Energy Society Conference on Fast Breeder Reactors, London, May 17-19, 1966*, Paper 5A15.

59. E. Duncombe et al., Some Analytical and Process Instruments for Measurements in Sodium, in *Alkali Metal Coolants*, Symposium Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/143).

60. J.A. Shercliff, *The Theory of Electromagnetic Flow-Measurement*, Cambridge University Press, New York, 1962.

61. G.H. Reicks, *Sodium Level Detectors in the Enrico Fermi Atomic Power Plant*, USAEC Report APDA-300, Atomic Power Development Associates, Inc., Nov. 30, 1965.

62. T.R. Johnson, F.G. Teats, and R.D. Pierce, *Induction Probe for Measuring Liquid Levels in Liquid Metals*, USAEC Report ANL-7153, Argonne National Laboratory, February 1966.

63. U.S. Industrial Chemicals Co., *Handling Metallic Sodium on a Plant Scale*, commercial pamphlet, 1959.

64. R. Matthews et al., Performance and Operation of the Dounreay Fast Reactor, in *Proceedings of the Third United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 6, p. 23, United Nations, New York, 1965.

65. A.I. Leipunsky et al., Five Year Operation Experience on Reactor BR-5, in *Proceedings of the Third United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 6, p. 51, United Nations, New York, 1965.

66. W. Kunkel and S. Berger, Fission Product Retention in Sodium and Applications to Vented Fuel Element

Design, in *International Conference on Safety, Fuels and Core Design in Large Fast Power Reactors, Argonne, Illinois, Oct. 11-14, 1965*, USAEC Report ANL-7120, pp. 855-861, Argonne National Laboratory.

67. A.I. Lèipunsky et al., Operating Experience with the BR-5 Reactor, in *Operating Experience with Power Reactors*, Symposium Proceedings, Vienna, 1963, International Atomic Energy Agency, Vienna, 1963 (STI/PUB/77).

68. H.O. Charnock and S. Berger, *Conceptual System Design, Helium Purification, Fast Flux Test Facility*, Report NAA-SR-Memo-12150, North American Aviation, Inc., October 1966.

69. K. Goldmann and B. Minushkin, Sodium Technology, in *Reactor Technology, Selected Reviews - 1965*, Leonard E. Link (Ed.), USAEC Report TID-8541, p. 326, January 1966.

70. R.C. Andrews, R.H. Hiltz, L.H. Kirschler, and R.J. Udavcak, *Limited Comparison of the Relative Merits of 304 vs. 316 Stainless Steel for Liquid Metal Service*, USAEC Report MSAR-67-216, MSA Research Corp., December 1967.

71. W. Berry, Some Facts About Stress Corrosion of Austenitic Stainless Steels in Reactor Systems, *Reactor Mater.*, *7*(1): Spring 1964.

72. S.P. Rideout and R.F. Mittelberg, Factors Controlling Chloride Stress Corrosion of Type 304 Stainless Steel, in *Metals/Materials Congress, Philadelphia, October 1964*, USAEC Report CONF-778-3, October 1964.

73. R.C. Anstine, *The Combined Effects of a Sodium Environment and Extended Life on Type 316 Stainless Steel and Croloy 2-1/4 Alloy Steel Design Stresses, Sodium Heated Steam Generator Development*, USAEC Report BW-67-3, Babcock and Wilcox, Co., September 1964.

74. H.W. Savage, E.L. Compere, R.E. MacPherson, W.R. Huntley, and A. Taboada, *SNAP-8 Corrosion Program. Quarterly Progress Report for Period Ending November 30, 1964*, USAEC Report ORNL-3784, Oak Ridge National Laboratory, March 1965.

75. W. Ashburg, Another Look at Stress Corrosion Cracking of Stainless Steel Under Thermal Insulation, in *20th Annual Conference of the National Association of Corrosion Engineers, Chicago, Ill., Mar. 9-15, 1964.*

76. Corrosion of Non-Aqueous Liquids, Steels in Sodium, *Reactor Mater.*, *10*(3), 162 (Fall 1967).

77. L. Goodman, *Effects of a Sodium-Water Reaction in a Modular Steam Generator, An Experimental Study*, USAEC Report AI-66-152, Atomics International, Sept. 24, 1966.

78. C. Starr and R.W. Dickinson, *Sodium Graphite Reactors*, Addison-Wesley Publishing Company, Inc., Reading, Mass., 1958.

79. R.L. Loftness, *Nuclear Power Plants*, D. Van Nostrand Company, Inc., Princeton, N.J., 1964.

80. H. Cartwright et al., Dounreay Fast Reactor, Basic Problems in Design, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958*, Vol. 9, p. 316, United Nations, New York, 1958.

81. W.P. Rosenthal, EBR-II, *Nucl. News*, *10*(8): 22 (August 1967).

82. A.H. Barnes, L.J. Koch, H.O. Monson, and F.A. Smith, The Engineering Design of EBR-II, A Prototype Fast

Neutron Reactor Plant, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955,* Vol. 3, p. 330, United Nations, New York, 1956.

83. R.E. Peterson, Los Alamos Molten Plutonium Reactor Experiment No. 1, in *Sodium Reactors Technology,* Symposium Proceedings, Lincoln, Neb., May 1961, USAEC Report TID-7623, pp. 52-62, June 1962.

84. E.O. Swickard (Comp.), *Los Alamos Molten Plutonium Reactor Experiment (LAMPRE) Hazards Report,* USAEC Report LA-2327, Los Alamos Scientific Laboratory, June 1959.

85. C.J. Raseman and L. Green, Commercial Power Reactors Cooled with Sodium, Heavy Water, or Organic Liquids, in *Reactor Technology, Selected Reviews - 1964,* Leonard E. Link (Ed.), USAEC Report TID-8540, pp. 93-94, 1964.

86. U.S. Atomic Energy Commission, *Nuclear Reactors in the Soviet Union,* USAEC Report WASH-1060, U.S. Government Printing Office, Washington, 1965.

87. G. Billuris, K. Hikido, E.E. Olich, and A.B. Reynolds, SEFOR Plant Design, in *Fast Reactors National Topical Meeting, San Francisco, Calif., Apr. 10-12, 1967,* USAEC Report CONF-670413, pp. 5-1 - 5-30.

88. General Electric, Major Fast Breeder Projects: SEFOR, *Nucl. News,* *10*(8): 35-36 (August 1967).

89. R. Carle et al., The Phenix Reactor, in *Fast Reactors National Topical Meeting, San Francisco, Calif., Apr. 10-12, 1967,* USAEC Report CONF-670413, pp. 3-39 to 3-59.

90. A.G. Frame et al., Design of the PFR, in *British Nuclear Energy Society Conference on Fast Breeder Reactors, London, May 17-19, 1966,* Paper 3/3.

91. E.R. Astley et al., *Fast Flux Test Facility Reference Concept. Progress Report,* USAEC Report BNWL-470, Battelle-Northwest, August 1967.

92. R.F. Sweek and A. Amorosi, The U.S. Program on the Liquid Metal Fast Breeder Reactor, *Nucl. News,* *11*(3): 45-49 (March 1968).

93. U.S. Atomic Energy Commission, *Civilian Nuclear Power - The 1967 Supplement to the 1962 Report to the President,* pp. 33-36, U.S. Government Printing Office, Washington, Feburary 1967.

94. *Power Reactor Technol., 8*(2), 147-156 (Spring 1965).

95. Allis-Chalmers Mfg. Co., Atomic Power Development Associates, Inc., and Babcock and Wilcox Co., *Large Fast Reactor Design Study,* USAEC Report ACNP-64503, January 1964.

96. Combustion Engineering, Inc., *Liquid Metal Fast Breeder Reactor Design Study,* USAEC Report CEND-200, Vols. I and II, January 1964.

97. M.J. McNelly, *Liquid Metal Fast Breeder Reactor Design Study,* USAEC Report GEAP-4418, Vols. I and II, General Electric Co., Atomic Power Equipment Dept., January 1964.

98. R.B. Steck (Comp.), *Liquid Metal Fast Breeder Reactor Design Study,* USAEC Report WCAP-3251-1, Westinghouse Electric Corp., Atomic Power Div., January 1964.

99. Atomics International, *Feasibility Study of a 1000 Mwe Sodium-Cooled Fast Reactor,* USAEC Report NAA-SR-11378, Vols. I, II, and III, July 1966.

100. Chicago Operations Office, *An Evaluation of Four Design Studies of a 1000-Mwe Ceramic-Fueled Fast Breeder Reactor,* USAEC Report COO-279, Dec. 1, 1964.

101. L.E. Link et al., *1000-Mw(e) Metal-Fueled Fast Breeder Reactor,* USAEC Report ANL-7001, Argonne National Laboratory, June 1966.

102. Argonne National Laboratory, *Proceedings of the Conference on Safety, Fuels and Core Design in Large Fast Power Reactors, Argonne National Laboratory, Illinois, Oct. 11-14, 1965,* USAEC Report ANL-7120.

103. General Electric Co., Major Fast Breeder Projects: SEFOR, *Nucl. News, 10*(8): 11 (August 1967).

104. K.A. Hub et al., *Feasibility Study of Nuclear Steam Supply System Using 10,000-Mw, Sodium-Cooled Breeder Reactor,* USAEC Report ANL-7183, Argonne National Laboratory, September 1966.

105. G.S. Budney, *Advanced SNAP Reactor Thermoelectric Space Power Systems,* Presented at American Nuclear Society Winter Annual Meeting, Pittsburgh, Oct. 31-Nov. 3, 1966.

106. C.E. Johnson and D.G. Mason, *SNAP-8 Reactor and Shield Design and Operation Experience,* Report AI-65-473, Atomics International, July 1965.

107. Aerojet General Corporation, *A Study for the Application of SNAP-8 to Manned Missions,* Report TM-335-63-9-135, September 1963.

108. J.J. Morabito and H.W. Savage, Major Components and Test Facilities for Sodium Systems, in *Fast Reactor Technology,* American Nuclear Society National Topical Meeting, Detroit, Report ANS-100, pp. 308-332, American Nuclear Society, April 1965.

109. M.G. Robin, *Grand Quevilly Thermal Tests Station, the 5 Mw Sodium Circuit with Steam Generator Superheated at 545°C,* French Report CEA-R-2520, July 1964.

110. R. Harde et al., A Contribution to the Advancement of Sodium Technology, in *VIII Nuclear Congress, Symposium on Fast Reactors, Rome, June 17-19, 1963.*

111. C.W. Griffin (Ed.), *Study of SCTI Control System,* USAEC Report NAA-SR-8119, Atomics International, Dec. 1, 1964.

112. Atomics International, *A Description of SGR Test Installations Available at Atomics International,* USAEC Report NAA-SR-Memo-4411 (Rev.), June 15, 1960.

113. R.W. Atz, *The Large Component Test Loop-Description and Operating Capabilities,* USAEC Report NAA-SR-Memo-8217, North American Aviation, Inc., Feb. 18, 1963.

114. C.F. Braun and Co., *Conceptual System Design Description I, Sodium Pump Test Facility (SPTF),* Report CFB-2964-101, Nov. 17, 1967.

115. P.B.F. Evans, The United Kingdom Liquid Metal Development Programme, in *Proceedings of the Sodium Components Development Program Information Meeting, Chicago, Ill., June 16-17, 1965,* USAEC Report CONF-650620, pp. 133-142, 1965.

116. E.F. Hill, Sodium Technology Loop Evaluation of In-Line Instruments and Purification Devices, in *Proceedings of the Sodium Components Development Program Information Meeting, Chicago, Ill., June 16-17, 1965,* USAEC Report CONF-650620, pp. 255-270, 1965.

117. H.O. Muenchow, Review of Atomic Power Development Associates'

Sodium-Water Reaction Program, in *Proceedings of the Sodium Components Development Program Information Meeting, Chicago, Ill., June 16-17, 1965,* USAEC Report CONF-650620, pp. 232-243, 1965.

118. R.E. Douglas, ESADA Sodium-Water Reaction Tests, in *Proceedings of the Sodium Components Development Program Information Meeting, Chicago, Ill., June 16-17, 1965,* USAEC Report CONF-650620, pp. 244-254, 1965.

119. R.W. Lockhart, G. Billuris, and M.R. Lane, *Sodium Mass Transfer. I. Test Loop Design,* USAEC Report GEAP-3725, General Electric Co., Atomic Power Equipment Dept., June 1962.

120. E.S. Sowa, D.H. Thompson, and W.L. Kolb, A Large Loop Facility for the Meltdown Study of Fast-Reaction Fuel Elements in High-Temperature Flowing Sodium, in 13th Annual Meeting of American Nuclear Society, San Diego, June 11-15, 1967, *Trans. Amer. Nucl. Soc.*: *10*(1): 345-346 (1967).

121. G.A. Freund et al., *Design Summary Report on the Transient Reactor Test Facility (TREAT),* USAEC Report ANL-6034, Argonne National Laboratory.

Chapter 2
Safety

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2-1 INTRODUCTION

The alkali metals - sodium, potassium, and NaK - require special considerations in safety and fire protection because of their high degree of reactivity with many common materials.

This chapter concerns characteristics of sodium and NaK related to the hazards connected with their use and methods for controlling and minimizing these hazards. Because of the increased utilization of liquid sodium as a coolant in nuclear power plants, more attention is given to the safeguards requirements for sodium systems.

The alkali metals possess many properties that make them hazardous for certain applications, but handling and systems operations precautions have been conducted by manufacturers and users of large quantities of sodium and NaK for more than two decades with excellent safety records. Both are, in fact, no more hazardous than many materials handled daily in tonnage quantities and in many cases require less stringent safeguards. However, field operators stipulate that NaK is very unpredictable.

2-2 HAZARDOUS PROPERTIES

The hazards associated with sodium and NaK are due primarily to their high chemical reactivity with many common materials or substances and with human tissue. The reaction products themselves pose problems as irritants (sodium and potassium oxides), and they may be highly corrosive (sodium and potassium hydroxides). Residual sodium in the reactants or superoxides can cause fires and hydrogen release, and hydrogen release can lead to explosions unless properly controlled. Sodium and NaK exposed in a reactor core or neutron flux pose an additional hazard because of the induced radioactivity of the constitutent isotopes. Those responsible for the design, operation, and maintenance of systems and facilities in which these metals are used must have a thorough knowledge and constant awareness of these characteristics and potential hazards to safely handle and operate these facilities without property damage and personnel injury.

2-2.1 *Sodium*

The chemical symbol for sodium is Na (from the Latin word *Natrium*). This silvery white metal is a soft, malleable solid at room temperature. It can be cut easily with a knife and, when cut, the surfaces rapidly oxidize to a dull gray if exposed to air. Sodium melts at 207.5°F (96°C). Extreme care in handling is required because of its chemical reactivity. The reaction with water is most violent. Hot sodium also combines chemically with common fire-extinguishing agents such as carbon dioxide, carbon tetrachloride, dry chemical foam, etc. to cause explosions and fire. Mixing sodium with the standard halogenated hydrocarbon cleaning compounds, trichloroethylene, methyl bromide, ethyl chloroform, etc., can cause spontaneous explosions.

Liquid sodium exposed to the air ignites at a temperature as low as 257°F (125°C) and, in a comparatively dry atmosphere, it burns quietly, giving off clouds of dense white caustic smoke (sodium monoxide) which is extremely irritating to skin, nose, and throat. The temperature of the burning mass increases quickly to between 1200 and 1630°F (650 to 890°C). In this condition sodium spalls concrete (this results in a secondary hazard of flying debris); consumes asbestos, firebrick, Transite, and similar materials; and reacts with glass.

A sodium fire burns very quietly, cannot explode by itself, and can be approached closely without danger so long as water or other antagonistic materials do not come in contact with it. Burning sodium is very distinctive; the flame is small or nonexistent, depending on oxygen level, and the surface is dominated by a large number of bright yellow, glowing spots or nodules. Details on burning rates, oxide release and deposition, agglomeration, and iodine retention are discussed in Secs. 2-4.5(a) and (b).

Molten sodium combines directly and vigorously with hot hydrogen to form the hydride NaH, which is a relatively stable, white-to-grayish powder that is very hygroscopic.

2-2.2 *Potassium*

The chemical symbol for potassium is K (from the Latin word *Kalium*). It is a silvery white metal with a touch of violet and a brilliant metallic luster. It is the second lightest metal known, having a specific gravity of only 0.87. It melts at 144.1°F (61°C) and at room temperature it can be cut into any shape very easily. Potassium also reacts violently with water to cause fires and explosions. If glass vessels containing metallic potassium are heated to temperatures much in excess of the melting point of potassium, a vigorous-to-explosive reaction with the glass can ensue. Potassium is not discussed further since it is not used directly in current reactor concepts.

2-2.3 *NaK*

NaK is an alloy of the metals sodium and potassium. The composition may vary over slight limits but is always specified; e.g., a commonly used composition is 22 wt.% sodium, 78 wt.% potassium. This forms the lowest melting alloy (9.95°F) of the two metals and is therefore known as eutectic NaK. As the percentage of sodium is increased, the heat-transfer properties improve, but the melting temperature increases. Fluidity at ambient temperatures is the main reason for using NaK rather than sodium in some reactor heat-transfer systems.

Typical of the alkali metals, NaK is very reactive chemically and therefore requires special precautions in its use. At room temperature bulk NaK open to the air reacts slowly with oxygen to form a surface scum. In NaK alloy systems oxygen is preferentially attached to the sodium, forming sodium oxide; however, formation of potassium superoxide can occur. In contact with moderate-temperature liquid metals, the potassium superoxide, KO_2, is reduced to the lower oxides K_2O and KO; however, the superoxide may be present on the walls of tanks or equipment where it is not in direct contact with the bulk of the liquid metal. The superoxide can also exist on the surface of a pool of NaK where an oxide layer is formed. Immediate cleanup is recommended to avoid formation of superoxides in equipment not in use since superoxides can cause fires or explosions if they contact burnable material.

Under these conditions extreme care must be used when hydrocarbons are used for equipment cleaning. In several instances explosions have occurred in NaK systems, and in all cases there was a possibility that both superoxides and hydrocarbons were present. If superoxide contamination is suspected, superheated steam should be used as the cleanup medium.

2-2.4 *Common Chemical Reactions*

(a) *Reaction with Water.* The alkali metals, designated M in the following equations, react violently with water, usually with an accompanying explosion caused by the secondary reaction of the liberated hydrogen with the oxygen of the air:

$$2M + 2H_2O \rightarrow 2MOH + H_2 + \text{heat} \qquad (2.1)$$

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (2.2)$$

The heat liberated by the reaction in Eq. 2.1 is sufficient to cause the reaction in Eq. 2.2. When an explosion occurs, the unreacted metal is usually scattered over a wide area where it can cause further trouble. In view of the foregoing, a cardinal rule when handling the alkali metals is to keep them completely isolated from water or aqueous solutions.

(b) *Reaction with Steam.* Although water and steam are identical so far as chemical composition is concerned, steam does not necessarily react with the alkali metals with the same physical violence as does water. The hydrogen resulting from the reaction is often so diluted that the danger of an explosive reaction with oxygen from the air is greatly minimized. Therefore dry steam (steam free of condensed water) is used extensively to clean apparatus or piping containing sodium. The steam not only dilutes the byproduct hydrogen but also helps to exclude oxygen from the reaction site and to dissipate the heat of the reaction.

(c) *Reaction with Carbon Dioxide.* The reactions of the alkali metals and carbon dioxide are complex but can be simply and adequately summarized:

$$2M + CO_2 \rightarrow M_2O + CO \qquad (2.3)$$

$$M_2O + CO_2 \rightarrow M_2CO_3 \qquad (2.4)$$

Principally because of the reaction in Eq. 2.3, it is not advisable to use carbon dioxide as an extinguishant on alkali-metal fires. This reaction produces not only the highly caustic oxide M_2O but also poisonous carbon monoxide, CO. The formation and accumulation of CO in a laboratory or in a closed environment raises the possibility of asphyxiation of personnel using CO_2.

(d) *Reaction with Carbon Tetrachloride.* The reaction of the alkali metals with carbon tetrachloride, CCl_4, and other halogenated hydrocarbons (e.g., the reaction trichloroethylene → dichloracetylene) is characterized as being of explosive violence. Consequently, it is sound design practice to isolate completely the alkali metals from these materials. Furthermore, deadly phosgene gas can form when CCl_4 is used on alkali-metal fires. Thus carbon tetrachloride should never be used on alkali-metal fires.

(e) *Reactions with Alcohols.* Alkali metals react with alcohols in basically the same way they react with water, but the reaction proceeds more slowly:

$$M + ROH \rightarrow ROM + 1/2H_2 \tag{2.5}$$

R represents an organic radical such as CH_3 (methyl), C_2H_5 (ethyl), C_3H_7 (propyl), C_4H_9 (butyl), etc. If a large volume of alcohol is used with a small amount of metal, the reaction can be controlled to provide a safe means for the disposal of waste alkali metals. Care must be taken,of course, because both hydrogen and heat are produced by the reactions and the alcohols themselves are flammable. In general, the rate of the reaction decreases as the molecular weight of the alcohol increases; e.g., the reaction is markedly slower with butyl alcohol (butanol-C_4H_9OH) than with ethyl alcohol (ethanol-C_2H_5OH). Because the chemical activity of the alkali metals increases with increasing atomic weight, it is advisable when disposing of waste alkali metals to use the higher weight alcohols with the higher weight metals. Also, NaK alloys react more vigorously with a given alcohol than does sodium. Therefore, if a given amount of a certain alcohol is known to give a smooth, safe reaction with sodium, a greater amount of a heavier (i.e., higher molecular weight) alcohol should be used for reaction with NaK.

Since the alcohol-alkali-metal reaction is controllable, alcohols are often used to free intricate apparatus or equipment from alkali metals. Precautions should be taken to make certain that the hydrogen released by the reaction does not build up a potentially explosive concentration. The ROM compounds, or alcoholates, formed by the alcohol-alkali-metal reaction are not considered as corrosive as the alkali hydroxides (ROH). Thus they are not as dangerous to handle. They are corrosive, however, and should be handled with respect and care as should all chemicals. If splashed on the skin and clothing, they should be washed off immediately.

(f) *Inertness to Noble Gases and Nitrogen.* Sodium and NaK, reactive as they are, will not react with nitrogen nor with any of the elements collectively known as the noble gases: He, Ne, Ar, Kr, and Xe. Hence the readily available and inexpensive nitrogen gas and the two most readily available and least expensive noble gases, helium and argon, are often used as cover gases to exclude oxygen. Helium and argon are most commonly used at high temperatures since nitrogen can react with the solid, metallic components of a system to form nitrides that alter the physical properties of the system piping, tanks and other components.

(g) *Summary of Reactions.* Various laboratory materials of significance to intended use and their reactions with sodium or NaK are:

Material	Reaction	No Reaction
Water	X	
Alcohol	X	
Acids (all)	X	

Material	Reaction	No Reaction
Halogenated hydrocarbons (methylbromine, methylchloride, etc.)	X	
Polyhalogenated hydrocarbons (Freon, carbon tetrachloride, difluorodichloromethane)	X	
Calcium carbonate		X
Sodium chloride (dry		X
Graphite		X
Dry sand (below 300°F)		X
Met-L-X compound		X
Dry soda ash		X
Glass (below 300°F for Na; below 150°F for K)		X
Oxygen	X	
Argon		X
Dry nitrogen		X
Helium		X

(h) *Summary of Hazards*. The previous discussions indicate that hazards can be divided into two specific classes:

Class I: Hazards that must be guarded against during operations, maintenance, or laboratory tests.

1. Skin or inhalation burns.
    a. Heat of fire or hot liquid-metal spills or sprays.
    b. Heat of water reaction.
    c. Caustic from fire or water reactions.
    d. Reaction with body moisture.
    e. Dispersion caused by using improper fire-fighting materials for liquid-metal fires.
2. Radiation.
    a. Activated liquid metal.
    b. Careless cleaning of activated primary system or core components.
3. Asphyxiation.
    a. Use of improper fire-fighting materials.
    b. Entering inert-atmosphere areas without adequate breathing protection.

Class II: Hazards for which design precautions must be taken to protect against damage to equipment, personnel injury, or danger to the general public.

1. Damage caused by chemical re-

a. Proximity to water.
b. Proximity to tetrachloride or alcohols.
c. Proximity to carbon dioxide.
d. Lack of ventilation in the event of hydrogen generation.
e. Sodium spills in an oxygen atmosphere (fire).

2. Caustic effluent damage to:

a. Paint, insulation, etc.
b. Base material.
c. General public health or equipment.

3. Personnel radiation damage from:

a. Inadequate primary system shielding.
b. Inadequate containment of cover gas.
c. Inadequate area-access control.

4. Accidental release of radioactive fission products to atmosphere.

In view of the clearly separable aspects of these two types of hazards, safety and precautionary considerations are treated separately.

2-3 PLANT OPERATIONS, MAINTENANCE AND LABORATORY SAFETY CONSIDERATIONS

2-3.1 *General Safety Precautions*

The following general safety precautions should be observed at all times when handling alkali metals:

1. Personnel handling the metals should wear safety clothing prescribed for the areas being occupied or traversed.

2. Alkali metals should be stored in a segregated area in unsprinklered, fire-resistant buildings arranged so there is no possibility of water or moisture contacting the metals. Containers should be raised off the floor to permit periodic inspections for leakage. Metal storm covers extending 3 or 4 in. down the sides should be placed on top of the containers. Adequate ventilation of the storage area must be provided to remove any hydrogen that may evolve.

3. Drum covers should be replaced as soon as the work at hand is finished. Exposure of the metals to moist air generates hydrogen, which can be ignited. Also, hydrogen can form from small quantities of moisture absorbed from the air when the cover was last removed. If there is a hissing sound when the cover is loosened, hydrogen may be present in dangerous quantities. The hydrogen should be allowed to escape slowly before the cover is entirely removed.

4. Wherever there is a danger of hydrogen accumulation, *No Smoking* signs should be posted, and explosion-proof electrical equipment should be used in place of standard equipment. Workers must not smoke when opening containers or handling metal in the open since there is a danger of igniting the hydrogen that may be present.

5. Only specified powder extinguishing agents should be used on metal fires. Chemical-solution-type, vaporizing-liquid-type, or carbon dioxide extinguishers are not effective, and their use will add to the hazard instead of reducing it. The chemical-solution type of extinguisher (soda acid) contains water, and the vaporizing-liquid type (carbon tetrachloride) and carbon dioxide both react violently with some alkali metals. Adequate supplies must be ensured by routine inspection.

6. Before the metals are removed from their shipping containers, the equipment to receive them should be thoroughly dried and kept dry while the metal is added. Equipment and tools to be used in the operation or maintenance should also be clean and dry. Every precaution should be taken to prevent moisture, even perspiration, from drop-

ping onto the metals. A suitable inert gas should be used as an atmosphere for blanketing the metals wherever possible during handling. For example, nitrogen is suitable for blanketing sodium or NaK.

7. Solid alkali metals should be handled only with tongs or with nonporous, washable gloves. The residue from burned metal must be handled with the same care as the original metal. Gloves must be worn for handling metal and metal-contaminated waste.

8. Personnel who may possibly be exposed to toxic fumes should wear the prescribed respirators or respiratory protective equipment and protective clothing.

9. Personnel should examine their bodies for metal residues and brush their clothes thoroughly after being exposed to any metal or metal residues. If this brushing is not thoroughly done, severe burns or damage to clothing may result. Fires may start in lockers after the clothing has been stored. All caustic or metal residues on tools and clothing must be removed by copious flushing with water. Washing with dilute acetic acid or sodium bicarbonate will neutralize the caustic; this should be followed by thorough rinsing with water.

10. Molten metals should be transferred at the lowest possible temperature to minimize fire and handling hazards. The metal should not be exposed to the atmosphere during transfer.

11. Appropriate signs should be posted in areas where alkali metals are stored or used, warning of the hazards to be encountered, delineating materials to be kept from contact with the metal, and advising which extinguishing agents are suitable for use.

In addition, the following good work habits should be instilled in personnel in basic training:

1. Do not start on a job involving alkali metals until you have personally contacted the person in direct charge of the apparatus or system you will be using and have told him exactly what you are going to do.

2. Be sure you have been thoroughly briefed on all phases of the operation. Never take anything for granted.

3. Never leave a partially completed alkali-metal operation unattended even for a few seconds.

4. Talk the job over. Never work alone. Do not rush. Stop long enough to work out all the angles. *Think* about every move you will have to make; then go ahead.

5. When sampling or draining liquid metals operating under pressure, satisfy yourself that this pressure has been reduced to a minimum before exposing the metals to the atmosphere.

6. When cutting or welding alkali-metal piping that may contain residues, reduce the internal system pressure to a minimum and maintain an external inert gas bleed at the point of contact.

7. In circulating alkali-metal systems, keep a constant check on your pressure gauges. Most alkali-metal piping and components are heated externally with electric blankets, heating wire, or calrods. However, plugs occasionally develop when the metal "freezes" in relatively cool sections of piping or valving. This is especially true in sodium. A plug usually indicates faulty or shorted electrical circuits on the heating system. Do not use a torch to free a sodium or NaK plug. When the oxide of sodium or NaK is heated above 630°F, it fuses into a solid plug. Metals will expand with heat. Be sure at least one end of the piping or apparatus is vented or free

to take up expansion.

8. Never attempt to carry liquid sodium or NaK in a can sealed with solder or in a galvanized container.

9. Since valves sometimes jam, when you have opened a valve, back off about a quarter of a turn. In an emergency the next man will know immediately whether the valve is open or closed. Never force a valve. In many instances bellows rupture in bellows-seal valves results from careless operation.

10. Avoid breathing the smoke from a sodium or NaK fire. The smoke from such a fire can irritate the throat and lung tissues.

2-3.2 *Waste Disposal*

(a) *Conversion of Sodium and NaK to Nonreactive Form.* Assurance of safe disposal of sodium or NaK metals, residues containing sodium or NaK, or equipment contaminated with sodium or NaK usually requires that the alkali metals be converted to a nonreactive form. This is necessary to avoid the possibility of subsequent chemical reactions that could injure the public or the personnel handling the waste (e.g., burns, fires, or hydrogen explosions). Sodium or NaK can be converted to a less reactive form by burning or reacting with water, steam, or other chemical compounds under controlled conditions. The conversion can be accomplished before disposal (e.g., in pans, incinerators, or solution tanks) or during the actual disposal operation (e.g., in controlled underwater ejection or remote ocean disposal). Techniques and procedures for accomplishing these operations are discussed in detail in Chap. 3.

(b) *Neutralization.* Neutralization of converted wastes is necessary if containers or waste systems (e.g., waste drums, storage tanks, drain lines, sewer lines, etc.) may corrode. Similarly, if large quantities of caustics are released to the environment, the potential effects on ecological systems (particularly effects on fish and wildlife) must be considered. Safe disposal can be assured by adequate dilution or pH adjustment with acids prior to or during release.

(c) *Radioactivity.* If sodium or NaK contains radioactivity, special precautions (e.g., anticontamination clothing, ventilation, respirators, monitoring, etc.) must be taken to prevent excessive exposure of personnel performing the conversion or waste-handling operations. Care must be exercised to prevent the spread of contamination to other equipment or facilities; pans, tanks, ventilation control, filters, etc., must be used to confine or control the activity. Excessive release of radioactivity to the environment from both the waste-handling and disposal operations must be prevented. In general, the rules and regulations in the *Code of Federal Regulations*, Title 10, should be used as a guide in determining appropriate exposure or release limits.

(d) *Disposal Methods.* Small amounts of sodium (gram batches) can be conveniently disposed of by burning in a gas flame in a heavy metal dish under a hood. The residues can be flushed to normal waste systems with water. Small amounts may also be disposed of by reacting with appropriate alcohols in a pan under a hood. The mixture can then be disposed of as normal industrial waste. If radioactivity is involved, released quantities must be limited and dilution must be adequate to assure compliance with permissible release rates and quantities specified in the code, Title 10, 20, and local ordinances.

Larger amounts of sodium or NaK can be burned in large shallow pans in controlled, isolated, or remote areas. Ignition is induced and maintained with such combustibles as wood or kerosene.

Stirring with a long-handled tool may be required to ensure complete reaction (personnel carrying out this operation must wear protective equipment). Sufficient ventilation must be provided to prevent potential hazards from hydrogen buildup, to protect operating personnel, and to prevent the spread of contamination. If the operation is performed in a remote area, natural ventilation (wind) may be sufficient. The residues are then prepared and packaged for safe disposal. If radioactivity is involved, land burial at approved sites or deep ocean disposal may be required.

Many schemes have been developed and utilized for disposal of large quantities of sodium or NaK. For example, special equipment to react NaK underwater at a controlled rate has been developed and tested [1]. This requires access to a water source where disposal is permissible (e.g., a storage pond or deep ocean). Artificial ponds have been made where sodium or NaK can be reacted at safe distances (the material is projected or conveyed to the center of the pond and released). Incinerator units can be used for burning sodium, NaK, or contaminated material. Filtering of the exhaust effluent can be a safety problem unless a remote area is available, especially if radioactivity is involved. Equipment and operating procedures for waste disposal are described in Chap. 3.

(e) *Residues from Fire or Cleaning Operations.* Residues from fires or cleaning operations may contain unburned metal, hydroxides, oxides, superoxides, and fire-extinguishing media. This material should be shovelled or scooped up as soon as possible and placed in a dry metal container. Since disturbing the residue can cause the metal to reignite, the operation should be carried out quickly, and a lid should be placed on the container to exclude oxygen and extinguish any fire inside. NaK is a liquid at room temperature, but small quantities of waste can be mixed with dry soda ash to form a semisolid paste that is more readily handled and removed to a disposal area. If large quantities are involved, it may be necessary to transfer some of the liquid to a container by suction, leaving a small quantity to be cleaned by the soda-ash method.

The containers of sodium or NaK residue (material from fires or cleaning operations) should be taken to an isolated area (decontamination room or waste-treatment area) where the material can be processed by methods previously described and packaged for ultimate disposal. An approved land burial site or deep-ocean disposal is required if radioactivity is involved.

A distinct hazard is associated with handling equipment in which KO_2 (superoxide), a strong oxidizing agent, may be formed. Numerous accidents involving superoxide have been reported in the U.S. Atomic Energy Commission (AEC) safety bulletins. Superoxide may form in stagnant containers that air has entered. If its presence is suspected, contact with hydrocarbon fuel materials should not be permitted.

2-3.3 *NaK-System Loading*

(a) *Shipping Containers.* NaK is shipped from the factory in 25-, 100-, or 200-lb containers provided with two valve connections at the top. One of these connections is used to pressurize the tank, and the other leads to the tank bottom to remove NaK. The material is shipped under nitrogen pressure of a few pounds per square inch, so that it will flow from the top NaK connection if the valve is opened.

(b) *NaK Transfer.* Temporary connections are made from the NaK valve on the shipping container to the system to transfer NaK. Certain fluoridated and chlorinated hydrocarbon compounds (such as stopcock grease and Teflon) react explosively with NaK at room temperature and should not be permitted to contact it. Tygon tubing is satisfactory for transferring NaK at room temperature with small pressure differentials (nitrogen, helium, or other inert gas regulated to about 1 psi connected to the gas side of the NaK shipping container). The system tank should be evacuated and then loaded either under vacuum or by displacing inert gas through a separate vent. The loading line and the regulated gas line are either evacuated or purged with inert gas. Shipping containers are not designed for pressures of more than a few pounds per square inch. Overpressure can cause the supply container to rupture. Neither are shipping containers designed for a vacuum. A partial vacuum can cause the supply container to collapse and rupture.

2-3.4 *Maintenance Procedures on NaK Systems*

Several precautions should be taken for maintenance of NaK Systems.

(a) *System Drain.*

1. Provide a waste container with about 3 in. of dry, white mineral oil as a blanketing film between the NaK and the air. Use oil from a new, unopened can since white oil can breathe air moisture.

2. Drain the system to the waste container underneath the dry, white mineral oil. Replace the drained NaK in the system with dry inert gas.

3. Manipulate all valves and components to be sure all possible traps and pockets are emptied.

4. When draining is completed, maintain a slight positive pressure on the system.

(b) *Component Removal.* If a component is to be removed from the system for maintenance or replacement, drain the system and remove the component as follows:

1. Place a drip pan containing white oil or other insulation under the component to be removed to catch all leaking NaK.

2. Maintain a low-pressure argon or helium purge through the system.

3. Cut out the component. Leakage caught in the drip pan is sprinkled liberally with dry calcium carbonate.

4. Block off the open ends of the system with stoppers, masking tape, or other inert barrier.

5. Clean component immediately.

2-3.5 *Entering Vaults and Galleries*

The following steps are typical of those taken to ensure that an alkali-metal system piping vault or gallery is safe for personnel to enter:

1. Analyze the atmosphere in the vault or gallery for oxygen content.

2. Disconnect all electric power circuits feeding components and lines in the work area. All other power circuits within the vault can remain energized.

3. Check for radiation hazards.

4. Check for conditions that might constitute fire, explosion, or high-temperature hazards.

5. Check for and correct conditions that might cause a worker to fall while performing the desired operation in the vault.

6. Before anyone enters, reduce the ambient temperature to 150°F or less. Areas accessible only by crawling should not be entered unless piped flow is stopped.

7. Do not walk on piping that has a temperature above 650°F.

2-3.6 *Component-Cleaning Precautions*

For details on component cleaning, refer to Sec. 3-9.2. Steam, hot oil, alcohols, ammonia, and water have been used for cleaning sodium components. Some of these require special safety precautions.

(a) *Steam Cleaning.* Superheated steam is recommended for piping-system cleanup if the system is (1) well vented and well drained and (2) rugged enough to withstand occasional hydrogen explosions. Explosions can be minimized by replacing any air in the system with an inert gas such as nitrogen. Since hydrogen will always be present, good ventilation is essential. The liquid resulting from the cleaning operation is caustic and must be handled with care. Maintaining the entire system above 212°F minimizes steam condensation and thus helps to control the reaction rate. An inert diluent gas such as nitrogen or argon can be mixed with the steam to further increase the safety of the operation. Steam cleaning of components, especially when restricted passages are involved, must always be carried out cautiously. Even though no chemical explosion occurs, by-product hydrogen can accumulate and build up enough pressure to explosively fracture the unit being cleaned. Precautions are necessary after the cleaning to ensure, e.g., by rotational means, that all material has been removed or released.

(b) *Hot-Oil Cleaning.* The basic idea of a hot-oil sodium-cleaning system is to prevent air from coming in contact with molten sodium regardless of whether or not the sodium is radiologically contaminated. Residual sodium in the submerged component is melted in a 300°F oil bath while being agitated. When melting is assumed completed, the molten sodium is allowed to settle, and the oil temperature is reduced to solidify the removed sodium before the component is exposed to air.

(c) *Chemical Reactions with Solvents*

(1) *Dowanol EB or Butyl Alcohol.* Dowanol EB and butyl alcohol are the acceptable solvents. Because the odor of Dowanol is detectable only after the threshold limit value (TLV) is exceeded, much care is required in its use. If Dowanol is used in an open container, flexible ducting should be connected to the ventilation system with the open end placed directly over the container. If a Protectoseal cabinet is used, it must be properly connected to the ventilation system. While the component is being immersed or removed from the solvent, respiratory protection for personnel is advisable. These precautions are not necessary when butyl alcohol is used unless the odor becomes detectable. If this occurs, take prompt action as in the preceding situation. Since both Dowanol and butyl alcohol are toxic and can be absorbed through the skin, direct contact should be avoided (see Sec. 2-3.8).

Chemically reacting sodium with solvent is a slow process. The surface area of sodium exposed to the solvent affects the reaction time. If the component contains an appreciable quantity of sodium, it may be necessary to replenish the solvent since the chemical reaction stops when the solvent becomes saturated. Gas bubbles can be observed escaping from the solvent when the reaction is in progress. The component is treated as if it contains sodium until it is definitely verified that all sodium has been removed. Since this reaction is very slow, a common practice is to accelerate the final cleaning of small components by using methyl alcohol. However, extreme caution is necessary since the methyl alcohol can react very violently if too much alkali metal is still present. A fine water spray is often used as a final cleaning process for large components.

(2) *Ammonia.* Ammonia is also an excellent solvent and has no chemical reactions at temperatures below about

400°F if the cleaning process is not prolonged. Otherwise, potentially explosive sodium amide can form. (See Chap. 3.)

The normal precautions for handling pressurized containers should be used for handling ammonia containers. Ammonia containers should never be subject to bumping or abnormal mechanical shock, thaw-out of frozen cylinders by steam or electrical heat, or storage near a source of heat or flammable substances. Ammonia cylinders should not be stored in direct sunshine in hot weather; they may become overpressurized. Each piece of line or each tank must be adequately protected with safety valves when using ammonia. A tank should not be filled to more than 88% by volume in order to allow adequate vapor space for thermal expansion. All stationary containers should be properly grounded.

Fire and explosion hazards are present but are considered small. Ammonia elicits violent respiratory reflexes such as coughing and respiratory arrest. A concentration in air as low as 0.5% by volume is lethal in a few minutes. Gas masks should be worn when opening containers or breaking ammonia lines or connections. The data on physical tolerance in Table 2.1 are taken from the Chemical Safety Data Sheet, SD-8, of the Manufacturing Chemists Association, Washington, D.C.

Persons who regularly work with ammonia and are liable to be exposed to the liquid or vapors should be fully clothed and should wear cotton-lined rubber or neoprene gloves, chemical or face goggle shields, and a brimmed hat. Emergency safety equipment should be readily available. An eye-wash fountain should be in close proximity to the operation. Care should be taken

TABLE 2.1 - Physical Effects of Ammonia

Concentration vapor, ppm	Effect on unprotected worker	Exposure period
50	Least detectable odor	Permissible for 8-hr work exposure
100	No adverse effects for average unprotected worker	Permissible for 8-hr work exposure
400	Causes irritation of throat	Ordinarily no serious results on infrequent exposure (less than 1 hr)
700	Causes irritation of eyes	Ordinarily no serious results on infrequent exposure (less than 1 hr)
1,720	Causes convulsive coughing	No exposure permissible (may be fatal after one exposure of less than 1/2 hr)
5,000 to 10,000	Causes respiratory spasms, strangulation, asphyxia	No exposure permissible; rapidly fatal!

to see that the operation is downwind from inhabited buildings or areas. An industrial gas mask with a full face mask and green canister as approved by the U.S. Bureau of Mines should be available. Self-contained breathing apparatus may be used in lieu of this type. Spare canisters should be available.

One-piece rubber or neoprene suits should be worn by persons entering ammonia-contaminated areas.

Fire hoses or other sources of water should be available; this is the simplest means of containing or combating ammonia leaks, since ammonia is soluble in water.

If a worker is trapped in an ammonia atmosphere, he should refrain from breathing, keep his eyes closed as much as possible, and immediately evacuate the area. Since ammonia vapor is lighter than air, it normally rises into the atmosphere. If trapped without means of exit, a worker should stay close to the floor.

2-3.7 *Protective Clothing and Equipment*

(a) *Introduction.* Personnel protective equipment ideally should be both nonreactive with sodium and NaK and resistant to breakdown from high temperatures possible from burning alkali metals. Nonreactive material is available, but equipment impervious to the burning metals is not currently on the market.

(b) *Clothing.* Flameproof cotton coveralls without cuffs on sleeves or pants and without pockets or other potential traps for splashed metal are recommended. Chrome-leather leggings and aprons are commonly used, but their value is questionable. Clothing designed for rapid removal is preferred. Fire-fighting garments usually consist of bunker clothing (turnout pants and coat). Pants should be worn outside the boots to prevent the metal from running down into the boot. Studies have been conducted at Atomics International and Battelle Northwest Laboratories (BNL) to find more adequate materials for protective clothing.

Special carbon-fiber materials for fire fighting which do not break down when NaK is burning on them were tested. Initial work on this material, backed by high-temperature-resistant insulation, indicated that a suit might be made which offers protection from both alkali-metal burns and thermal burns from ignited sodium or NaK. Certain other materials, such as some vinyl and rubber products, appear to shed liquid metals even when burning. Trapped burning metal penetrates rapidly. Nonetheless, these shedding-type materials may be useful for such items as gloves where thick insulation is prohibitive for working.

(c) *Head Protection.* A complete hood, a hood with a hard hat underneath, or a hard hat alone is recommended. Hard hats made of reactive materials or aluminum must be avoided; a phenolic resin is the preferred material.

(d) *Face Protection.* Minimum face protection consists of a face shield worn during any liquid-metal handling or operations. Since plastic face shields cannot withstand high temperatures or guard against splashes, tight-fitting goggles are also required for hot liquid-metal handling. Personnel wearing contact lenses should always wear both goggles and face shield.

(e) *Gloves.* The use of polychloride gloves is recommended. Flameproof cotton or heavy moleskin, preferably the latter, is also suitable. Loose-fitting gloves are best because they can be easily thrown off if splashed with metal. Wool and leather should be avoided because they disintegrate rapidly in contact with sodium hydroxide. Asbestos is not recommended, because it reacts with and absorbs sodium. As mentioned previously, "shedding type" materials that encourage the metals to roll off and avoid sticking to the material may be preferable.

The specific operation hazard dictates whether the gloves should be worn over or under the suit cuff. Wearing the glove over the cuff makes it easier to throw off the glove if it is splashed but provides a trap for splashed material to roll inside the glove. Wearing the glove inside the cuff may be preferable if material cannot splash up the sleeve and if the glove can still be quickly removed.

(f) *Foot Protection.* Either leather shoes and chrome-leather leggings or safety shoes are required for liquid-metal workers. Fire-fighting personnel use standard fire-rubber boots with a metal plate in the sole.

Regarding the use of leggings, one worker is known to have been injured when molten sodium ran down inside his shoe tops. The leggings had crept up the man's leg, exposing the top of the shoe. It is therefore recommended that rubber boots be worn inside the pants legs to offer best protection. A nonreactive metal plate (not aluminum) in the sole of the boot should offer additional protection if liquid metal is stepped on.

(g) *Respiratory Protection.* Respiratory protection is necessary in the presence of compounds generated by burning liquid metals. The low short-term emergency exposure level of 4 mg of NaOH per cubic meter of air recommended by the National Academy of Sciences (NAS) National Research Council makes it a requirement that fire fighters wear self-contained breathing apparatus. Filter respirators using a high-efficiency filter (Bureau of Mines approved for particles more toxic than lead) can be used but will plug up quickly in high airborne concentrations of sodium compounds. If half-face respirators are used, eye protection must be provided. The danger of skin burns must also be taken into consideration.

Workers in and around a liquid-metals facility should have protective equipment available for use during excape in case of an emergency. It is recommended that half-face masks with high-efficiency filters and goggles be carried on the person. One large sodium facility requires goggles and a small escape mask with high-efficiency filter of the type that has a mouthpiece and nose clamp. The small size and low cost of this type of respirator make it suitable to be carried on the person of every worker in the facility. However, it should be used only as an escape mask and not as protection for fire-fighting or work in sodium aerosols.

Tests have indicated that some special Fiberglas materials may be capable of removing virtually all sodium aerosols from an airstream without plugging up as rapidly as high-efficiency filters. Fiberglas cartridges for respirators may prove to be more desirable than the high-efficiency filters.

Finally, the limitations of respiratory apparatus must be considered. Hazards other than sodium aerosols (e.g., radioactive materials, oxygen deficiency, and other toxic gases, vapors, or particles) may be present in an emergency. A training program in the use and limitations of respiratory equipment is mandatory for all personnel who may be exposed to such environmental hazards.

2-3.8 *First Aid*

(a) *Mechanisms of Human Tissue Damage - General.* Skin or eye damage from contact with sodium or NaK is caused by burning. The heat generation of the hot or burning metal causes thermal burning simultaneously with chemical burning from reaction between the metal and body moisture. Generation of caustic hydroxides continues the chemical reaction if it is not removed. Serious burns also result from contact with the caustic effluents of sodium-water reactions. The tissues of the mouth, throat and lungs are particularly sensitive to alkali-metal oxides and hydroxides since the moisture of these areas reacts quickly with the oxides to form the caustic hydroxides that cause the chemical burning.

(b) *Inhalation Exposure Tolerance.* The oxides and hydroxides of sodium and potassium are considered irritants and are not known to be systemic poisons. The Manufacturing Chemists Association [2] states that no form of chronic toxicity, either systemic or local, for sodium has been recognized. Some coughing, throat soreness, and nasal irritation may be experienced by persons unaccustomed to exposure to alkaline materials when the same exposure would cause no symptoms to a worker in that atmosphere [3]. Characteristic irritation of nasal tissue frequently causes sneezing [3]. The TLV for sodium hydroxide established by the American Conference of Governmental Industrial Hygienists (ACGIH) is 2 mg per cubic meter of air [4]. Because of the similarity to sodium hydroxide, Patty [3] suggested a TLV of 2 mg per cubic meter of air for potassium hydroxide also (the ACGIH has not established a TLV for potassium hydroxide). The TLV of 2 mg per cubic meter of air was established on the basis of irritant effects of caustic mists. The present TLV represents a concentration in air that is noticeably, but not excessively, irritant [5].

Ingestion of alkali metals is unlikely to occur. Immediate and violent local reaction would cause severe burns, probably fatal [2]. There would be no known toxic action.

A short-term emergency exposure limit was requested from the AEC to plan for accident conditions. The AEC in turn made the request to the NAS National Research Council. The NAS recommendations were:

The corrosive action of alkalis on the eye, skin, and mucous membranes is well known and need not be reviewed in this report. Inhalation of mists of sodium hydroxide may produce effects varying from mild irritation to severe pneumonitis depending upon the concentration. There is a wide variability among persons in their subjective response to caustic dust but it has been observed that, in general, 6.0 mg/m^3 produces intolerable respiratory discomfort.

On the basis of the available data, the Committee on Toxicology recommends the following emergency exposure limits:

10 minutes, 4.0 mg/m^3
60 minutes, 2.0 mg/m^3

Eye contact with mists and dust of sodium hydroxide may produce severe damage, and it is therefore recommended that workers be required to wear tight-fitting eye goggles when there is a potential exposure to concentrations above 2.0 mg/m^3.

In the case of sodium and sodium oxide, the Committee feels that the levels recommended for sodium hydroxide may be used since these materials are known to react with moisture to form sodium hydroxide.

(c) *Prevention and Treatment of Injury*

(1) *Skin Damage.* A safety shower should be available for use by personnel splashed with sodium or NaK. The spray type is superior to the deluge type. Immediate flushing is recommended (1) to wash off gross sodium contamination and cool tissues and (2) to react quickly with sodium clinging to skin to reduce the chemical hydroxide reaction with body fluids. Clothing should be removed and the metal scraped from the skin. Fire blankets should not be used.

At some facilities personnel handling NaK used mineral oil with a small addition of stearic acid to reduce the potential for spread of NaK burns before it reacts with additional exposed skin. The advisability of using safety showers to deal with NaK burns was questioned at these facilities. At other facilities the use of mineral oil or other ointments and/or acetic acids in the treatment of sodium burns is not recommended since mineral oil and acetic acid from wounds can aggravate an already serious injury. The recommended first-aid treatment is cold water or iced sterile compresses applied over the affected area. The service of an emergency hospital and a medical doctor should be obtained.

(2) *Eye Injury.* Even if eye protection is worn, minute particles of sodium and its hydroxides may enter the eye during effluent release. Water flushing is recommended, and the services of an ophthalmologist should be obtained immediately.

Treatment of sodium eye injuries with boric acid and/or mineral oil or other types of eye medication is discouraged. The materials are difficult to remove from the eye and interfere with evaluation of the extent of the injury. However, personnel must know the individual laboratory or installation policy or practice.

Persons wearing contact lenses should be discouraged from working with sodium or NaK systems regardless of the type of eye protection used. Loss of a contact lens in an emergency situation, rotation of the lens behind the eyeball, and the reaction of sodium and NaK with plastics used in contact lenses may cause more serious injury. A minute particle of sodium worked under a contact lens produces a much more aggravated injury than the reaction of sodium with tears or water flushing.

(3) *Mouth, Throat, and Lungs.* Immediate use of the safety shower, eye wash station, drinking fountain or other sources of water is recommended. Complaint of soreness in the mouth, throat, and lungs should be noted and the services of a medical doctor, preferably an otolaryngologist, should be obtained immediately.

2-3.9 *Fire Fighting*

When exposed to air, sodium can ignite spontaneously at a temperature as low as 230°F, depending on such conditions as humidity, dispersion, etc. Upon ignition the temperature of the burning sodium or NaK increases rapidly to 1200 to 1600°F, and it continues to burn, giving off large quantities of opaque, white smoke that makes visibility very poor. Very little flame is visible; one sees mostly a flowing mass of the alkali metal. The burning material cannot explode but reacts violently with almost all common fire-extinguishing materials.

There is usually exothermic surface reaction at room temperature; this rapidly increases the NaK temperature above the ignition temperature and may be the source of the belief that NaK is unpredictable.

An alkali-metal fire is generally extinguished by the removal of oxygen. Extinguishing materials normally used to suppress fires should not be applied to alkali-metal fires because of the violent reaction of these metals with such common extinguishing materials as water, carbon tetrachloride, sodium bicarbonate, and carbon dioxide. The exclusion of oxygen can be effected by covering the burning sodium with any of the materials described in the following paragraphs. Any of these will control or extinguish a fire temporarily but are susceptible to burn-through and reignition of the fire. One of the best methods of fire prevention is to maintain a low oxygen concentration in the atmosphere in areas where alkali-metal loops are being operated. This is obviously limited in its application to areas that can be effectively sealed.

Fire-fighting materials recommended for use on alkali-metal fires are discussed briefly in the following paragraphs.

1. *Soda Ash (Anhydrous Na_2CO_3).* Only the anhydrous and completely moisture-free material is suitable for use and should be kept in a controlled, dry environment. This substance can be sprinkled or shovelled on the fire or sprayed on from an extinguisher using CO_2 pressure. The powder blankets the

fire and tends to prevent the reaction of the carrier gas (CO_2) with the metal. Soda ash is often used on sodium fires and is generally accepted as suitable for use on potassium and NaK fires.

2. *Zirconium Carbonate.* (See general comments under Soda Ash.) This material has been used effectively on alkali-metal fires. It is expensive in comparison to soda ash, however, and does not appear to have any specific advantages.

3. *Powdered Graphite.* This is an excellent blanketing agent and has been widely used in fighting alkali-metal and NaK fires. Care should be taken to distribute the graphite powder smoothly over the burning metal and to avoid dumping it on the fire. Dumping may cause splattering of the burning metal or the mass of graphite may sink through the burning metal and thus fail to provide the desired blanketing effect. The action of graphite on a liquid-metal fire is apparently twofold: (1) By blanketing the surface, the powder excludes air and thus suffocates the fire. (2) Since it is a respectable conductor of heat, the graphite probably cools the burning metal somewhat and thus helps to extinguish the fire.

4. *Met-L-X.* This fire-fighting material is a dry, free-flowing, treated sodium chloride distributed by the Ansul Co.; it is available in pressurized extinguishers. When Met-L-X is sprayed on an alkali-metal fire, it forms a crust that excludes oxygen from the fire and thus extinguishes it. It is usually considered advisable to intermittently sprinkle the Met-L-X lightly on the burning surface. This procedure hastens the formation of the crust. Met-L-X is not combustible and thus will not cause secondary fires. Because of its ability to adhere to molten sodium, Met-L-X is particularly suitable for use on sodium fires on walls and piping. After the fire is extinguished, the high-temperature equipment in the area where Met-L-X has been used must be cleaned thoroughly to avoid corrosion problems in subsequent operation.

5. *Pyrene G-1 Powder.* This material is a graphite-base extinguishant produced by the Pyrene Manufacturing Co. It may be applied from tubes or if it is available in bulk form may be spread from tubes or sprinkled from shovels. Since it is not combustible, secondary fires will not result from its application to burning alkali metal.

6. *White Silica Sand.* This has proved to be an effective and inexpensive tool for fighting sodium fires or damming NaK flow to isolate the fire. It is easy to store and transport.

7. *Ansul Purple K* (potassium bicarbonate). This is a very good extinguisher for secondary materials in a sodium-NaK fire. It was used on several occasions to put out wood, electrical insulation, etc., burning concurrently with the NaK. Although it has no effect on the burning alkali metal, it does an excellent job on the other materials. Also, Purple K will not cause trouble if it is sprayed inadvertently on burning NaK.

8. *Calcium Carbonate.* This works well on small leaks or fires when applied with a shovel in such a way as to prevent the metal from flowing and to gradually blanket and smother the burning area. If the flames are too high and too intense for the source to be approached with a shovel, pressurized calcium carbonate extinguishers are of some help in knocking down the flames.

Sodium and NaK fires burn slowly and usually are not difficult to control and extinguish provided smoke or inaccessibility does not mask the location of the fire. Practice in proper suppression techniques is essential in this as in any other method of fire fighting. Complete coverage of the burning area is essential if the fire is to be extinguished. Met-L-X, for example, fuses when heated to form a "crust" that excludes air from the sodium or NaK. Until this crust is formed, the fire can be controlled but not extinguished. Formation of this crust is best accomplished by careful application. The importance of practice in liquid-metal fire fighting cannot be overemphasized. Panic is difficult to avoid.

Extinguishing agents should be applied carefully to prevent splashing of the burning metal. Since no volatile combustibles are evolved from alkali-metal fires, there is no flame but merely a glowing mass of burning sodium or NaK. If the material is contained in a metal pan, it burns quietly and can be approached with little danger to fire-fighting personnel. A sodium fire in itself is not particularly hazardous except for resulting airborne concentrations. The secondary reactions with other materials increase the hazard. A sodium fire on a concrete floor will overheat, spall the concrete, and throw burning sodium over a wide area, spreading the danger and damage far beyond the original area of the fire. Fire fighting and rescue work under such conditions can be quite hazardous. Provision of a metal pan or vault lining to confine possible sodium spills reduces the hazard and permits effective fire fighting.

Because of the large quantities of caustic smoke evolved from sodium fires, respiratory protection is recommended for personnel engaged in fire fighting.

The following rules should be followed to ensure prompt action, prevent spread of the fire, and effect its prompt extinction:

1. Make certain that self-contained breathing apparatus and fire-fighting materials are available for instant use.

2. Remove as much of the potential fire hazard as possible by dumping the alkali metal remaining in the system into a sump tank or by isolating the ruptured portion of the system.

3. Isolate the leak with adjacent valves and shut off pipe or system heaters.

4. Apply a blanket (using caution to prevent spattering) of Met-L-X, graphite, Pyrene G-1, dry soda ash, etc., to exclude oxygen and extinguish the fire.

5. Clean up and dispose of all remaining spilled alkali-metal or oxide residue immediately. Water absorption from the air will make cleanup hazardous if material is allowed to stand.

6. When fire has subsided, remove several feet of insulation from area and dispose of it.

If only a small amount of metal is involved, the simplest and safest procedure may be to do nothing, to simply allow the metal to burn and to keep a safe distance away from the smoke. Discreet judgment is required in determining whether the leak causing a fire is small and easily controlled with materials at hand or whether the area should be evacuated immediately. Good judgment is a function of training.

The effectiveness of the metal spill pan can be improved by using a perforated plate with about 35% of the total area open as a false top. The bulk of the alkali metal passes through the plate and is held on the solid bottom of the spill pan. The perforated plate assists in restricting the flow of oxygen to the burning metal in the pan and in extinguishing the fire by oxygen starvation. If desired, the perforated plate can be covered with Met-L-X to complete the smothering action. For NaK fire burning in depth, a metal grating placed not less than 1/2 in.

below the surface has sometimes been used effectively to prevent sinking of crust into the NaK. A series of 3/8-in.-diameter holes spaced on 9/16-in. centers has been successfully used.

2-3.10 *Training*

(a) *Administration of Program.* A formalized training course in sodium and NaK handling techniques is necessary. Such a program should be written and presented by safety and/or fire-fighting personnel under the sponsorship of the persons or group responsible for the operation of the sodium and NaK systems and of the company medical personnel.

(b) *Contents of Course.* The training program should include, as a minimum, the following techniques and topics.

1. Classroom presentations.

    a. Physical properties of sodium and NaK.
    b. Toxicology of sodium and NaK.
    c. Protective-clothing requirements.

        1. Eye protection.
        2. Gloves.
        3. Garments.
        4. Shoes and other foot protection.
        5. Hats and hoods.

    d. Respirators.

        1. Respirator and cartridges.
        2. Self-contained breathing apparatus.
        3. Fitting program.

    e. Discussion of known accidents involving sodium and NaK.
    f. Documentary films.
    g. Fire protection and fire fighting, including display of approved extinguishers.

2. Field demonstrations. (Include all techniques and materials used at the specific facility.)

    a. Physical examination of sodium and NaK metals.
    b. Reactions of sodium.

        1. Block sodium and hard stream of water.
        2. Block sodium and water fog.
        3. Block sodium and steam.

    c. Reactions of sodium and NaK with cleaning agents. (Include discussion of toxicology and demonstration of protective clothing and respirators.)

        1. Ethyl alcohol.
        2. Butyl alcohol.
        3. Dowanol.

    d. Demonstration of effects of extinguishers on fire. (Allow trainees to participate in demonstrations.)

        1. Met-L-X extinguishers.
        2. CO_2 extinguishers.
        3. Calcium carbonate.

    e. Demonstration of use of a safety shower and eye-wash fountain.

    f. Demonstration of use of a fire blanket.

3. Study and demonstration of first-aid techniques. (Include trainee participation.)

4. Study and consideration of all conceivable accidents and preparation for emergency procedures.

5. Final written examination and certification.

(c) *Periodic Review*. Retraining should be done on a periodic basis as deemed necessary by the approving authority, at intervals of two years maximum.

2-4 DESIGN SAFETY CONSIDERATIONS

Proper selection of construction materials, application of good system-design concepts, and adherence to high quality and performance standards in design, construction, and testing are essential and of prime importance for assuring safety. Provision of adequate safeguards and protective equipment can limit damage and prevent injury even in the event of unlikely accidents involving major release of liquid metals from the system.

2-4.1 *Liquid-Metal-System Safety Requirements*

The principal safety requirement for a liquid-metal system (especially one containing radioactive material) is to ensure containment of the liquid metal and to prevent water, air, or other contaminants from entering the system. A coolant envelope with a high integrity against rupture, leakage, or corrosion and provisions for maintenance of a high coolant purity are essential to ensure safety. These requirements must be met for:

1. All normal operating conditions.

2. Anticipated or expected abnormal operating or environmental conditions that could affect the integrity of the system.

3. The design or scheduled life of the system.

Applicable generally recognized codes or standards on design, materials, fabrication, construction, inspection, and testing should be used. If such codes or standards do not suffice to ensure a high-quality product in keeping with the safety function, they must be supplemented as necessary. Some of the important factors to consider (in addition to standard structural requirements) are discussed in the following sections.

(a) *Material Requirements*. The interaction of materials of construction, coolant chemistry, and radiation effects (as they affect safety) should be recognized, considered, and handled early in the design.

Materials selected for the system envelope and its associated environment should be compatible with each other and with the liquid metal for all normal and anticipated abnormal operating or environmental conditions expected during the life of the system. This includes materials in auxiliary systems that may be involved in the event of abnormal operations or accidents (e.g., instrument lines, vent lines, hold-up tanks, etc., which should be compatible for the worst anticipated conditions). The designer should be fully aware of the many unsafe factors associated with the chemical incompatibility of sodium and NaK with several structural materials. A brief summary of some of these hazards follows:

1. Metals. Most irons and steels are relatively inert and resistant to attack by liquid sodium and NaK and present no immediate safety hazards due to chemical reactions. However, not all irons and steels are suitable for system use at high temperature and for long system lifetimes. For example, excessive corrosion or solubility can degrade the system integrity and lead to hazardous conditions (plugging, fouling, leaks, rupture). The known corrosion and solubility rates for the various irons and steels are presented in Vol. V, Chap. 2. Selection and applicability for specific

system design, operating, and environmental conditions are discussed in Vol. IV, Chap. 4.

Aluminum melts at about 1200°F and thus should not be expected to provide isolation or containment for sodium and NaK at high temperatures or under accident conditions when temperatures approaching or in excess of 1200°F prevail. In general, many metals, including tin, zinc, magnesium, copper, aluminum, etc., some of which have high solubility coefficients, should not be used in a system that will be in contact with liquid sodium or NaK for prolonged periods of time. A more detailed discussion of melting points, corrosion, and solubility rates for these metals is given in Vol. V, Chap. 2.

2. Concrete. Liquid sodium or NaK spilled onto concrete may react with water or chemicals in the concrete and damage or destroy the surface (particularly if the metals are released at high temperature). If fire results and if it is not extinguished, a rapid rise in temperature occurs. The temperature of the concrete soon increases to well above the boiling point of the water of hydration in the concrete. Spalling of the concrete occurs as a result of heat, steam, and additional chemical reactions between the metal and constituents of the concrete. Splattering and dispersal of hot sodium, caustics, and concrete particles occurs; this can cause additional fires and injury to personnel in the immediate vicinity. Use of exposed concrete is not generally a good design practice if liquid sodium or NaK spills are possible. In practice, drip pans or steel liners over concrete are usually used to prevent reactions and protect the surface.

3. Insulating materials. Significant quantities of insulating materials are required in any plant handling liquid metals. The largest quantities are used for thermal insulation for systems, components, and the facility. However, significant quantities may be used for electrical insulation, and this should be considered as well.

In general, if the materials are dry or do not contain chemically bound water (as, e.g., in calcium silicate or magnesia), the reactions do not present a direct hazard. However, the materials can be consumed if they contact hot sodium or NaK, and thus their function is destroyed. The temperature of the liquid metal and system will determine the most suitable material. Caution is required in their use. As a specific example, caustic salts resulting from sodium reaction with the thermal insulation removed considerable material from a stainless-steel nozzle at Hallam Nuclear Power Facility (HNPF). Mine Safety Appliances Company [6,7,8] has evaluated the sodium compatibility of thermal insulating materials. These characteristics should be checked by designers and operating personnel before any insulating material is used. Recommended materials for specific applications are discussed in Vol. IV, Chap. 5.

In nuclear systems materials with low corrosion rates are necessary to avoid undesirable conditions such as fouling, plugging, radiation buildup, increased corrosion, and other effects associated with mass transfer - all factors that can degrade system integrity and safety. Radiation effects on materials in high radiation fields should be considered and appropriate precautions taken to ensure that structural integrity is not compromised.

Compatibility, corrosion rates, and mass-transfer rates for materials suitable for sodium service are discussed in detail in Vol. V, Chap. 2.

(b) *Design Requirements*. Piping and components in the coolant system envelope must comply with the requirements of applicable piping codes, American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Codes* and United States of America Standards Institute (USA Standards) requirements. If radioactivity is involved, the system should be designed in accordance with additional requirements specified in such AEC codes and standards such as the General Design Criteria For Nuclear Power Plant Construction Permits [9]; Chapter 10 of the *Code of Federal Regulations*, and applicable portions of the AEC Design Manual.

Because of the possible serious consequences of leaks or rupture in systems handling liquid-metal coolants, system integrity requirements above and beyond those required by ASME and USA Standards may be appropriate, especially where potential radioactivity exists. Systems developed for liquid-metal service which employ all-welded piping, free-surface and electromagnetic (EM) pumps, freeze stem or bellows-seal valves, and other special equipment should be used whenever possible (see Vol. IV, Chap. 5).

Similarly, because of the severe effects of potential reactions between liquid metals, air, water, and structural materials the systems must have a high safety margin to avoid rupture. This is particularly important where internal reactions with water are possible (e.g., in liquid-metal-to-water or -steam heat exchangers). Designs using double-jacketed piping and components (concentric piping) with an intervening monitoring coolant (argon or helium) were successfully employed [10]. Single-pipe systems designed to withstand full or credible accident peak-system pressures were also considered [10].

Details and specific recommendations concerning the application of special equipment and design techniques for such coolant systems are discussed in Vol. IV, Chap. 5 and Vol. V, Chap. 5.

Special venting and draining provisions in NaK or sodium systems permit reduction in system pressures and loss of potential flammable material if leaks do occur or if excessive internal pressures develop as a result of interactions. The need and safety requirements for these subsystems are discussed in greater detail in subsequent sections of this chapter.

(c) *Fabrication, Construction and Testing.* Current engineering procedures and practices (Vol. IV, Chap. 5) applicable to quality control, inspection, cleaning and preoperational testing of liquid-metal systems must be employed. Specific requirements in ASME, USA Standard and AEC codes and standards and special techniques should be used. Inadequate attention in these phases of design and testing can seriously degrade the desired system integrity and safety. Testing to verify absence of leaks, pressure integrity, and proper operation of relief, monitoring, and safeguard functions is of particular importance.

(d) *Inert-Gas Blankets.* Inert-gas blankets are essential for systems containing liquid metals. The object is to exclude oxygen, moisture, and other impurities that can lead to potentially hazardous conditions (accelerated corrosion, mass transfer, plugging, fouling, etc.).

Helium, argon, or nitrogen is normally used for this application. Argon, since it is inert and is the heaviest gas, is preferred as a blanket for many nonnuclear applications. Helium is preferred for nuclear systems because it does not become radioactive. However, argon is less soluble in liquid metals than helium and less apt to interfere with pumps and the core hydraulics in the event of temperature changes. If the induced ^{41}Ar activity can be tolerated or controlled, argon may have advantages in some nuclear applications. If cover-gas purification systems using liquid nitrogen are used, a helium cover gas may be the only practical choice because of its low boiling point (argon would be removed in the liquid-nitrogen system). Nitrogen is inexpensive but may have undesirable effects on structural materials (e.g., nitriding) which can affect both the system integrity and safety. (The temporary use of nitrogen as cover gas appears to have contributed to reactor damage.) When irradiated, nitrogen produces ^{14}C, which may have undesirable safety implications. The characteristics of these gases and the factors involved in their selection and application to particular systems are discussed in greater detail in Chap. 3.

A reliable inert-gas supply, adequate monitoring facilities, and a suitably sized off-gas handling system must be provided (regardless of the type of gas chosen) to prevent damaging or compromising the integrity of the coolant envelope. Pressure controls, alarm provisions, and proper handling of off-gas fumes must be provided to prevent system or subsystem rupture and release of hazardous fumes, and/or fires. Additional monitoring, shielding, and waste-handling provisions are required for the potentially radioactive primary-system cover gas.

(e) *System Relief Protection*. The serious consequences of liquid-metal system rupture may require additional relief protection beyond that provided by the normal vent or off-gas handling systems. This is particularly important if interaction between dissimilar cooling systems is possible (as, e.g., between high-pressure steam and sodium or NaK in a heat exchanger). Rupture disks and/or relief valves can be used to accomplish this function. Safe methods for handling vented bases, fumes, or vapor must be provided to prevent fires or exposure to toxic or radioactive materials. Water inleakage and sodium outleakage require complex leak-detector systems (see Chap. 4).

If isolation valves are provided in coolant systems, the system should be designed to ensure that no section is isolated without appropriate relief protection.

(f) *Remote-Control Requirements*. Systems handling liquid metals should be provided with means for controlling and monitoring system process variables, i.e., temperature, flow, pressure, liquid level, valve position, and radioactivity.

Remote operation from a convenient accessible location is necessary to permit rapid operation of pumps and valves and thus limit discharge or leakage of coolant in the event of failures (e.g., to permit immediate depressurization, venting, draining, or isolation of portions of systems). Controls should be located in an isolated and protected area to allow remote operation to avoid potential injury to operating personnel in the event of ruptures, leaks, or fires. Provision of a continuously habitable area containing all essential monitoring readouts, alarms, and means for taking corrective action is the most effective way of preventing or minimizing system damage or personnel injury.

The requirements for remote control and monitoring may result in additional penetrations and extension of the coolant envelope beyond containment boundaries. These subsystems must not compromise leakage or integrity of the containment function. In general, instrument design should provide double barriers to contain leakage caused by failure of a single barrier. Designs requiring no penetration of the system piping, and therefore avoiding possible points of failure, are preferred. Because of the importance of the remote control and monitoring function, redundancy and testability of instruments should be considered to ensure high reliability and performance standards.

Instruments and monitoring techniques for sodium and NaK systems are discussed in detail in Chap. 4.

(g) *Draining Requirements*. Drain or sump tanks are normally provided for each system containing large quantities of liquid metal, and provisions must be made for dumping all liquid metal in an emergency or to permit subsequent repairs. The first requirement is necessary to minimize or limit the quantity of material that can be released in the event of system leakage or rupture. If radioactivity is involved, system draining may be necessary to permit accessibility for inspection, maintenance, and repair. However, in a reactor system the core can be drained only after fuel has been removed.

When a closed system must be drained rapidly, some means must be provided to prevent the development of a vacuum in the cover gas (this inhibits draining). This condition can be prevented by providing appropriate relief protection devices. An effective scheme is to interconnect the gas phases of the coolant system and drain tank by providing a common inert atmosphere and line connecting the high point of each system.

Coolant drain lines leading to the drain tank must be of sufficient size and must be maintained at an adequate temperature to ensure fluidity at all times. The components should be designed to prevent cold trapping and/or stoppage in the lines or valves. This condition can be avoided by maintaining the line at a higher temperature than the system cold trap.

The relative elevation of the drain- or sump-tank system is very important. For example, the drain line should originate at the lowest point in the system, and the liquid should flow by gravity from this point to the top of the drain tank, which is at a lower elevation. If this is not practical, a sump should be installed at the low point of the system to transfer the metal from the system to the sump or drain tank. The arrangement should always be such that the system need not be pressurized for draining.

Complete drainage and avoidance of pockets is necessary for radioactive systems if early access after shutdown is desired. All lines must be sloped to provide positive draining by gravity if this is to be accomplished. Techniques and procedures for draining, cleaning, and repairing sodium or NaK systems are discussed in Chap. 3.

(h) *Containers for Spills and Leakage*. Spills or leaks to the atmosphere from systems handling liquid metals are always possible as a result of equipment failures or operator errors. Pressure relief, draining, and isolation provisions previously described can minimize the amount of material released. Specific design provisions previously discussed should be incorporated to avoid or minimize potential hazards from the released material.

2-4.2 *Auxiliary Facility Requirements and Safeguards*

(a) *Proximity of Water*. Liquid metals should not be used or stored near water, and the system should be designed to preclude commingling of water and liquid metals in the event of an accident. Special care must be used in the design and construction of the facility, area, or room to prevent inleakage of water from rain, snow, groundwater, or from adjacent areas or structures. Accumulation of moisture from ventilation air or evaporation of water from concrete should be considered. Sprinkler systems using water should not be used in areas where liquid metals are stored, handled, or transferred. Routing of water pipes, steam lines, etc., through such areas should be avoided. Washrooms and toilet areas should be designed to prevent overflow of water to areas containing sodium or NaK. Use of water in space heaters or coolers should be avoided.

(b) *Control Area and Personnel Protection*. The facility should be provided with an area or areas from which personnel can remotely control, monitor, and observe operations to maintain the plant in a safe operating status at all times. The areas should be sufficiently isolated or provided with adequate protection to permit occupancy and access under accident conditions. For example, if a leak or rupture occurs, the operators must be able to control pumps, isolation valves, drain systems, ventilation systems, etc., without danger of injury or exposure to caustic, toxic, or radioactive materials. Consideration should be given to protection against missile and blast hazards, heat and radiation hazards, and contamination and inhalation hazards that may occur in the facility as a result of fires or release of radioactivity.

Escape routes and exits should be preplanned and provided in the design; personnel protective devices should be available at convenient locations (emergency showers, eye-wash stations, protective clothing and equipment, etc.).

(c) *Inert-Gas Atmospheres.* Exposed liquid metals should be handled in inert atmospheres. Open containers should be provided with inert-gas blankets, and glove-box or sampling operations should be done under inert atmospheres.

For reactor primary-system loops, metal-lined vaults containing inert atmospheres may be required to control potential hazards. Monitoring for impurities in the atmosphere should be provided, and appropriate indication of measurements and alarms should be included to permit supervisory control.

(d) *Ventilation.* Adequate mechanical ventilation should be provided to maintain a negative pressure within enclosures or areas containing sodium or NaK. Airflow should be from occupied areas and areas of low-potential airborne hazards to areas of higher potential hazard. Temperatures should be maintained and controlled to prevent freezing, overheating of materials, or loss of fluidity in sodium or NaK coolant lines. Humidity should be controlled to prevent accumulation of moisture on surfaces or in materials such as insulation which could come in contact with sodium or NaK.

Special ventilation provisions to cope with fires and air-cleaning requirements are discussed in Sec. 2-4.6.

2-4.3 *Radioactivity and Radiation*

(a) *Introduction.* This section is concerned primarily with the radiation hazards associated with the use of sodium or NaK.

Liquid metals exposed to a neutron flux in a static system or exposed as a result of passage through a reactor core become radioactive because of activation of the pure coolant (natural sodium and potassium isotopes). Impurities that are not removed from the coolant are also activated to produce radioisotopes. The activation products from these reactions may remain in the coolant or they may be deposited or may collect on surfaces or in specific portions of the nuclear or heat-transfer system (e.g., cold traps, surge tanks, pumps, piping, etc.).

Liquid metals also pick up impurities as a result of corrosion and erosion of materials in contact with the coolant. In circulating systems these impurities may be preactivated from core-area surfaces or become activated as they pass through the core or neutron fields. This activity may remain in the coolant (entrained or in solution) or may be redeposited in specific components or portions of the system (mass transfer).

In addition to these sources of activity (activated coolant, impurities, and system materials), the coolant may contain fission products from uranium contamination on surfaces or from failed fuel-element cladding. Fission products produced or released from the core in this manner may remain in the coolant or may be deposited in system components.

These processes produce additional sources of radioactivity, and, more important, some fraction of these sources circulates or collects in systems or components outside the core. Although these sources do not add appreciably to the activity level during operation, they may have a significant bearing on the amount, location, and arrangement of shielding required for maintenance access during shutdown.

Radioactive sources collecting outside the core can have a significant bearing on the ability to maintain or repair the system in the event of malfunction or failures (accessibility problem). Appropriate decay periods and local shielding may be required to permit maintenance on the shut-down systems. Finally, radioactivity may be released from the system during normal operations if leaks occur (particularly gases), or in the event of component failure or accidents.

Therefore an accurate determination of the production rate and fate or location of the isotopes produced or introduced in the coolant as a result of these processes is necessary to assist designers in producing a safe, economical, and efficient system. This is also important for continuing evaluation of operating conditions, for planning maintenance and repair of the shut-down system, and for evaluating the consequences of accidents. The determination and significance of this radioactivity is discussed in the following order:

1. Activation of pure coolant (sodium or potassium isotopes).
2. Activation of normal coolant impurities.
3. Activation of corrosion and erosion products (mass transfer) and recoils.
4. Behavior of fission products in sodium or NaK.

(b) *Determination and Significance of Pure Coolant Activity Levels (Activated Sodium or Potassium Isotopes).* The buildup of radioactivity in an object or material exposed to a constant flux level and the subsequent decay of the activity after exposure can be determined from [11]

$$\lambda_2 N_2 = \frac{N_{10}\phi\sigma_1\lambda_2}{(\phi\sigma_2 + \lambda_2) - \phi\sigma_1} \times \left[e^{-\phi\sigma_1 t} - e^{-(\phi\sigma_2 + \lambda_2)t}\right] e^{-\lambda_2 T} \qquad (2.6)$$

where

$\lambda_2 N_2$ = activity from daughter isotope (N_2) under consideration (dis/sec/cm^3)
N_{10} = original number of target-isotope atoms in the material being exposed or irradiated (atoms/cm^3)
ϕ = neutron-activation flux level applicable to the nuclear reaction under consideration (reaction leading to daughter isotope N_2) (neutrons/cm^2/sec)
σ_1 = activation cross section for isotope N_1 and for the nuclear reaction under consideration (cm^2/atom)
σ_2 = absorption cross section for isotope N_2 (cm^2/atom)
λ_2 = radioactive decay constant for daughter isotope N_2 (sec^{-1})
t = time period over which the material is exposed (irradiation time) (sec)
T = time period following cessation of exposure or removal of material from flux field (decay time) (sec)

Equation 2.6 includes the effect of burnup of both the target isotope and the daughter isotope. However, the decrease in the number of target isotope atoms (burnup) in a sodium or NaK system is usually small and relatively insignificant from a safety or activation standpoint. Thus the equation can be simplified to

$$\lambda_2 N_2 = \frac{N_{10}\phi\sigma_1\lambda_2}{\phi\sigma_2 + \lambda_2} \times \left[1 - e^{-(\phi\sigma_2 + \lambda_2)t}\right] e^{-\lambda_2 T} \qquad (2.7)$$

Burnup of daughter isotopes may be significant under certain conditions. For example, ^{22}Na, which results from the $(n,2n)$ reaction with ^{23}Na, has a high (n,γ) capture cross section (9000 barns). Since ^{22}Na can be a significant factor in shutdown radiation levels, particularly in a fast reactor system, the decrease caused by burnup can be important if prolonged access or maintenance is necessary.

However, for most practical purposes the effect is insignificant, and Eq. 2.7 can be further simplified to

$$\lambda_2 N_2 = N_{10}\phi\sigma_1\left(1 - e^{-\lambda_2 t}\right)e^{-\lambda_2 T}$$

$$(\phi\sigma_2 \ll \lambda_2)$$
$$(\phi\sigma_1 \ll 1) \qquad (2.8)$$

The number of target-isotope atoms, N_{10}, in the object or material under consideration is

$$N_{10} = \rho_m f_e f_1 \frac{\text{Avogadro number}}{W_1} \qquad (2.9)$$

where

ρ_m = density of material or object being irradiated (g/cm^3)
f_e = fraction of target-element species (composition or impurity) in the material or object (elemental weight fraction)
f_1 = fraction of target-isotope species in the element, normally the natural abundance
W_1 = atomic weight of target isotope (g/gram mole)

Values for ρ_m and f_e as a function of temperature and composition for sodium and NaK are given in Vol. I, Chap. 1. Values for f_1 are given in Table 2.2.

The major nuclear reactions of interest for sodium and NaK are shown in Table 2.3. (See Refs. 12 to 14 for specific cross sections.)

The gross radiation characteristics of the product isotopes are indicated in Table 2.2. Detailed characteristics for the product isotopes of greatest interest for sodium and NaK systems are shown in Figs. 2.1 to 2.3.

The flux term, ϕ, in Eqs. 2.6 to 2.9 is based on a flux level that remains constant with respect to time - a reasonable assumption for power reactor systems. However, the probability of occurrence of the reaction, σ, and the activity production depend on the individual neutron energies and on the number of neutrons at the point of irradiation (neutron population and energy distribution). These flux-spectrum characteristics depend on the type of reactor and the system configuration.

The total activity for a specific product isotope is the sum of the activities in each region. The procedure is represented mathematically by

$$A_{\text{total}} = \sum_{t,k} N_j\phi_{j,k}\sigma_{j,k}V_j(1 - e^{-\lambda t})\, e^{-\lambda T} \qquad (2.10)$$

where

A_{total} = total activity in system and for product isotope under consideration (dis/sec)
N_j = number of target-isotope atoms in the jth region (atoms/cm^3)
$\phi_{j,k}$ = neutron flux in jth region and in energy group k (neutrons/cm^2/sec)
$\sigma_{j,k}$ = cross section for atoms in jth region and for neutrons in energy group k (cm^2/atom)
λ = radioactive decay constant (sec^{-1})
V_j = volume of jth region (cm^3)
t = time period over which the material is exposed (irradiation time) (sec)
T = time period following cessation of exposure or removal of material from flux field (decay time) (sec)

Activation of pure sodium can produce

TABLE 2.2 - Nuclear Characteristics of Sodium and NaK

Element and parent isotope	Natural abundance, %	Nuclear reaction	Product isotope	Half-life	Radiation type and energy, Mev (max.)
Sodium					
^{23}Na	100	(n,γ)	^{24}Na	15 hr	β = 1.39 γ = 2.75 (100%) 1.37 (100%)
	100	(n,p)	^{23}Ne	38 sec	β,γ
	100	(n,α)	^{20}F	11 sec	β,γ
	100	$(n,2n)$	^{22}Na	2.6 years	β^+ = 0.54 γ = 1.28 (100%)
Potassium*					
^{39}K	93.1	(n,γ)	^{40}K	1.3×10^9 years	β+ = 1.32 γ = 1.48 (10%)
	93.1	(n,p)	^{39}Ar	270 years	β = 0.57 (no γ)
	93.1	(n,α)	^{36}Cl	3×10^5 years	β = 0.71 (no γ)
	93.1	$(n,2n)$	^{38}K	7.7 min	β+ = 2.7 γ = 2.2
^{40}K	0.0118	(n,γ)	^{41}K	Stable	
	0.0118	(n,p)	^{40}Ar	Stable	
	0.0118	(n,α)	^{37}Cl	Stable	
	0.0118	$(n,2n)$	^{39}K	Stable	
^{41}K	6.88	(n,γ)	^{42}K	12.4 hr	β = 3.53 γ = 1.52 (20%)
	6.88	(n,p)	^{41}Ar	1.83 hr	β = 1.2, 2.49 γ = 1.29 (100%)
	6.88	(n,α)	^{38}Cl	37.3 min	β = 4.8 γ = 2.2
	6.88	$(n,2n)$	^{40}K	1.3×10^9 years	β+ = 1.32 γ = 1.48 (10%)

*The naturally occurring radioisotope ^{40}K emits about 1600 dis/min per gram of potassium; its specific activity is 7×10^{-4} μc/g. It emits a 1.48-Mev gamma photon for each 10 disintegrating atoms (gamma emitted 10% of the time).

TABLE 2.3 - Maximum Permissible Concentration for Sodium and NaK Activation Products of Radiological Significance*

Isotope	Chemical form or exposure mode	MPC† for restricted area based on 40-hr exposure in 7 consecutive days		MPC† for unrestricted area based on average over 1-year period	
		Air, μc/cm³	Water, μc/cm³	Air, μc/cm³	Water, μc/cm³
^{24}Na	Soluble	1×10^{-6}	6×10^{-3}	4×10^{-8}	2×10^{-4}
	Insoluble	1×10^{-7}	8×10^{-4}	5×10^{-9}	3×10^{-5}
^{22}Na	Soluble	2×10^{-7}	1×10^{-3}	6×10^{-9}	4×10^{-5}
	Insoluble	9×10^{-9}	9×10^{-4}	3×10^{-10}	3×10^{-5}
^{42}K	Soluble	2×10^{-6}	9×10^{-3}	7×10^{-8}	3×10^{-4}
	Insoluble	1×10^{-7}	6×10^{-4}	4×10^{-9}	2×10^{-5}
^{41}Ar	Submersion‡	2×10^{-6}		4×10^{-8}	

*From *Code of Federal Regulations*, Title 10, 20.
†Maximum permissible concentration.
‡Submersion in a semispherical infinite cloud of airborne material.

radiologically significant quantities of ^{24}Na and ^{22}Na. Activation of pure NaK can produce ^{42}K, ^{41}Ar and ^{39}Ar. These isotopes may also require consideration in addition to the ^{24}Na and ^{22}Na activity.

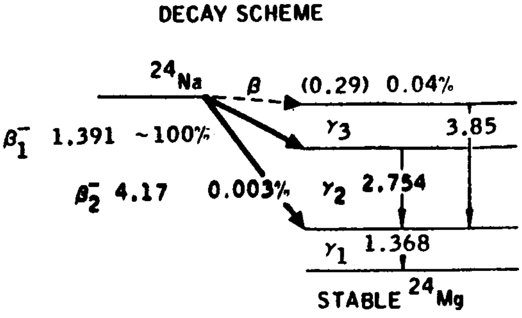
The ^{24}Na and ^{42}K produce the major gamma radiation source from the coolants during normal operation. The half-life of ^{24}Na is 15 hr, and that of ^{42}K is 12.5 hr. Both reach equilibrium in a relatively short time (a week or so) in an operating system, and both remain uniformly distributed throughout the entire coolant (no concentration or deposition). Since these isotopes establish an unavoidable minimum operational radiation level, the concentration or inventories in system components must be accurately known in advance of system and facility design. The total inventory can be obtained by assuming static conditions in the loop and by appropriate application of Eq. 2.10.

Activity levels of ^{24}Na or ^{42}K can also be calculated by the neutron economy method. Sodium-24 activity levels for HNPF were determined by this method [15]. Basically, the neutron economy approach determines activity by assuming that the neutron absorption is proportional to the ratio of the macroscopic cross sections. If P is the reactor power in watts and N is the number of neutrons released per neutron absorbed in fuel, the activity (dis/sec) is

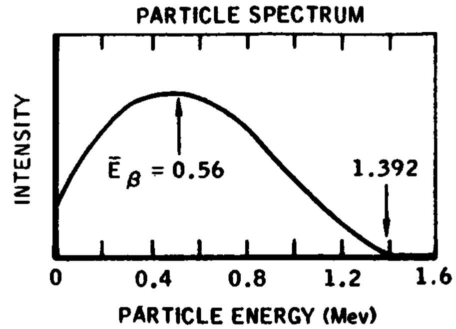
$$N_2\lambda_2 = \frac{3.2 \times 10^{10} P(N-1)N_1\sigma_1}{\sum_{i=1}^{\infty} \sigma_i N_i} \qquad (2.11)$$

Caution must be exercised using this method to ensure that sodium activation occurring outside the core region is also taken into account.

The average concentration in the

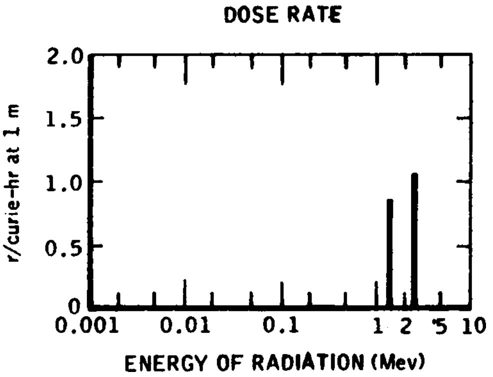


PARTICLE RADIATION



TYPE	ENERGY (Mev)	$\bar{E}_\beta$ (Mev)	INTENSITY	RANGE IN WATER (cm)
β_1^-	1.392(MAX.)	0.56	~100%	0.62
β_2^-	4.17 (MAX.)		0.003%	2.12

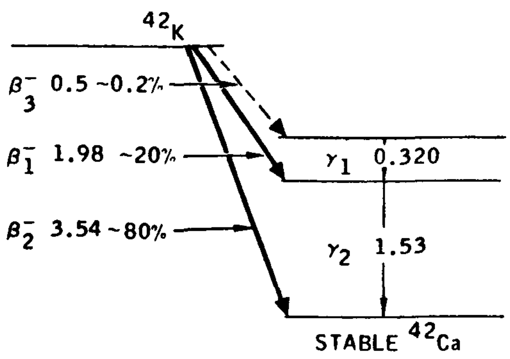
ELECTROMAGNETIC RADIATION



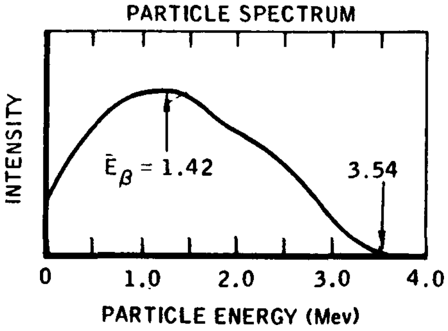
TYPE	PHOTON (Mev)	ENERGY INTENSITY	DOSE RATE (r/curie-hr at 1 m)	1/2 THICKNESS (cm)	
				WATER	LEAD
γ_1	1.368	100%	0.71	11.5	1.12
γ_2	2.754	~100%	1.17	16.7	1.44
γ_3	3.85	0.04%	0.001	20.2	1.48
			1.88		

Fig. 2.1 Radiation characteristics of ^{24}Na (half-life: 14.97 ± 0.02 hr.), which is usually produced by ^{23}Na(n,γ). The natural isotopic abundance of ^{23}Na is 100%, and its thermal neutron cross section is 0.54 barn.

DECAY SCHEME

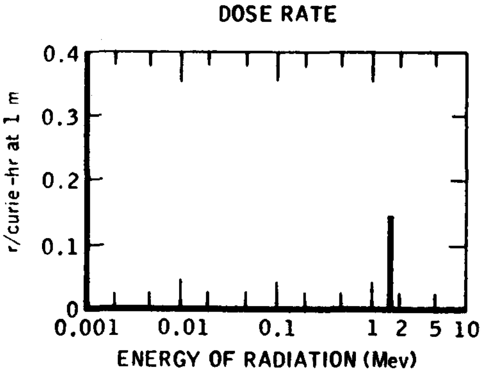


PARTICLE RADIATION


PARTICLE SPECTRUM

TYPE	ENERGY (Mev)	$\bar{E}_\beta$ (Mev)	INTENSITY	$\bar{E}_\beta$ (Mev) EFFECTIVE PER DISINTEGRATION	RANGE IN WATER (cm)
β^-_1	1.98 (MAX.)	0.82	~19.8%	0.16	0.95
β^-_2	3.54 (MAX.)	1.57	~80%	1.26	1.8
β^-_3	~0.5 (MAX.)	>0.00	~0.2%	—	0.16
				~1.42	

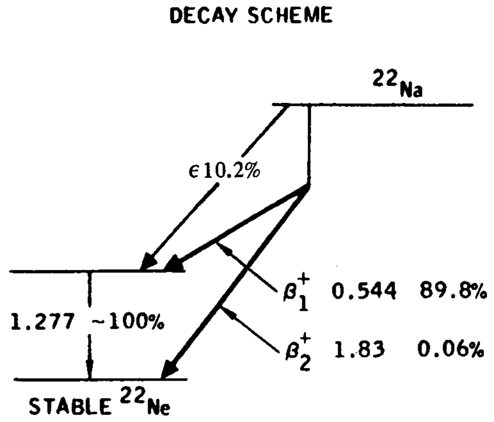
ELECTROMAGNETIC RADIATION


DOSE RATE

TYPE	ENERGY (Mev)	PHOTON INTENSITY	DOSE RATE (r/curie-hr at 1 m)	1/2 THICKNESS (cm) WATER	LEAD
γ_1	0.320	~0.2%	<0.001	6.0	0.20
γ_2	1.53	~20%	0.154	12.1	1.21
			0.155		

Fig. 2.2 Radiation characteristics of ^{42}K (half-life: 12.42 ± 0.03 hr.), which is usually produced by ^{41}K(n,γ). The natural isotopic abundance of ^{41}K is 6.9%, and its thermal neutron cross section is 1.2 barn.

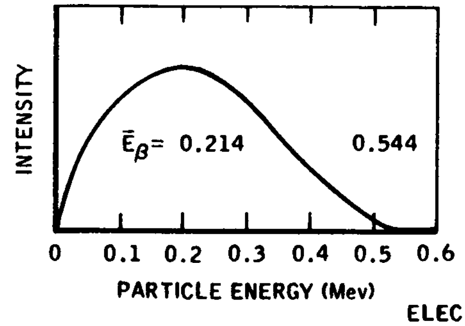
DECAY SCHEME



PARTICLE RADIATION

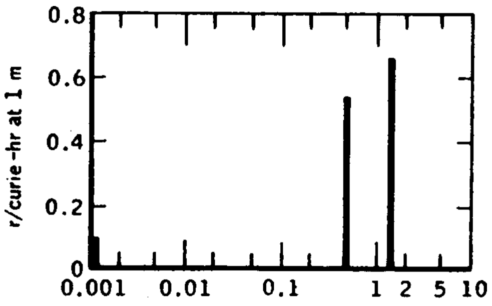
TYPE	ENERGY (Mev)	$\bar{E}_\beta$ (Mev)	INTENSITY	RANGE IN WATER (cm)
e_{A_K} *	~0.001		10.2%	<0.0001
β_1^+	0.544 (MAX.)	0.214	89.8%	0.18
ce †	1.28		<0.1%	0.56
β_2^+	1.83 (MAX.)		0.06%	0.88

PARTICLE SPECTRUM



ELECTROMAGNETIC RADIATION

DOSE RATE



TYPE	ENERGY (Mev)	PHOTON INTENSITY	DOSE RATE (r/curie-hr at 1 m)	1/2 THICKNESS (cm)	
				WATER	LEAD
X_K	~0.001	0.1%	~0.1	<0.1	<0.001
γ ‡	0.511	180%	0.54†	7.2	0.42
γ	1.277	~100%	0.67 ~1.3	11.0	1.07

*e_{A_K} denotes Auger electrons from the K shell.

†ce denotes conversion electrons.

‡Two 0.511-Mev gamma rays are produced when a positron emitted in the nuclear disintegration is annihilated in the medium surrounding the source. The dose rate from this annihilation radiation was calculated assuming that the radiation can be considered as coming from the source itself.

Fig. 2.3 Radiation characteristics of ^{22}Na (half-life: 2.58 ± 0.03 years), which is usually produced by ^{23}Na(*n*,2*n*) fast-neutron reaction.

coolant is obtained by dividing the total activity by the total volume of coolant in the system. The activity in a component is the product of this concentration and the volume of coolant in the component. Appropriate shielding can be determined by standard techniques.

Sodium-22 is produced in relatively small quantities but is of interest because of its long half-life (2.6 years). Its activity remains uniformly distributed throughout the coolant and persists long after ^{24}Na and ^{42}K have decayed. This activity thus establishes an unavoidable background radiation level from the shut-down system. The total inventory in the system can be determined from the equations given. Burnup of the ^{22}Na isotope may be important, particularly in large, fast reactor systems. System or component radiation levels from this source are reduced if the coolant is drained to an isolated or shielded area.

Argon-41 is also produced in relatively small quantities in NaK systems. It has a short half-life (1.83 hr) but is of special interest because it is a radioactive gas. It can collect and concentrate in primary- or auxiliary-system components such as surge tanks and vent or relief systems and thus constitute an independent source of radiation. It escapes readily if the system leaks, is vented, or is opened. The activity reaches equilibrium in a relatively short period of time (89% of equilibrium in 6 hr). The release rate from a continuously vented or leaking system (in curies per unit time) is

$$C_r = \frac{A_t \lambda_2 \lambda_v}{\lambda_2 + \lambda_v} \frac{1}{3.7 \times 10^{10}} \text{ curies/sec} \tag{2.12}$$

where

A_t = equilibrium value from Eq. 2.10
λ_2 = decay constant for ^{41}Ar (1.52×10^{-4} sec^{-1})
λ_v = leakage constant (sec^{-1}) = v/V
v = leakage rate (cm^3/sec)
V = free volume of surge tank or holdup tank (cm^3)

Argon-39 may be produced in significant quantities in NaK systems. It has a 270-year half-life and is a pure beta emitter. From a biological standpoint it is of minor significance, except that it can interfere with other radioactivity measurements unless its presence is known. The isotope is of special interest because it can cause accumulation of significant volumes of gas in a sealed system, for example, in SNAP systems [16].

(c) *Radioactivity from Normal Coolant Impurities.* Radioactivity from normal coolant impurities (stable impurity levels) can be estimated by the methods used to determine pure sodium or NaK activity (activation equation and assumption of static conditions).

The activity from coolant impurities is a function of the impurity concentrations in the purchased sodium or NaK, the cleanliness of the coolant system when it is filled, and the effectiveness of cold traps in removing or further reducing these impurities. Sodium and NaK can be purchased relatively free of impurities (see Vol. V, Chap. 1). The cleanliness of the system can be assured by proper care in fabrication, inspection, and cleaning of the system before use and by adherence to established procedures for filling and cold trapping prior to operation (see Chap. 3 and Vol. V, Chap. 1). Impurity-concentration conditions can and should be verified by sampling before nuclear operation begins.

If these procedures are followed, the activity resulting from the coolant impurities will be small. Radioactivity concentrations in the coolant from these sources are generally many orders of magnitude (e.g., 10^{-5}or 10^{-6}) less than the radioactivity concentration from pure sodium or NaK activation. Since impurity levels of interest are generally in the order of parts per million (10^{-6} g per gram of coolant), radioactivity levels corresponding to this ratio are expected. The 15-hr ^{24}Na activity predominates during operation and for a considerable period after shutdown (it diminishes by a factor of 10 every 2 days, or about 5×10^6 in 2 weeks). Thus radioactivity from impurities has potential radiological significance only after shutdown and after a considerable decay period has elapsed. Thus impurities remaining in the sodium but leading to short-lived activity can be ignored (certainly all those with half-lives less than 15-hr ^{24}Na).

After about 2 weeks' shutdown, the radiation resulting from coolant impurities should not exceed the radiation from the ^{22}Na activity in an undrained system if a clean system has been maintained. In NaK systems a similar condition prevails because of natural potassium activity (see footnote, Table 2.2).

Thus radioactivity from activation or normal impurities does not constitute a direct radiation hazard. However, knowledge of impurity presence and levels may be necessary to permit a continuing evaluation of operating conditions. The levels can be most effectively determined by routine sampling and monitoring programs (continuous monitoring or periodic sampling and analysis of coolant for impurities or radioactivity).

(d) *Radioactivity from Corrosion Products (Activity Level and Significance).* Evaluation of the production and rate of activity from corrosion and erosion products (mass transfer) in a dynamic system is extremely complex. Corrosion rates vary with time, temperature, material and location in the system. Even if these parameters were well defined, the manner in which corrosion products are removed from the surfaces, transported by the coolant, or deposited in the system is also dependent on a variety of ill-defined variables (chemical and metallurgical reactions, local flow rates, cold-trap efficiencies, plating out, etc.).

Because of these complexities and the lack of fundamental data, analytical estimates of activity levels resulting from corrosion or mass-transfer effects are usually made to indicate upper limits of activity. The major areas of interest from a safety standpoint are:

1. Activity levels in the coolant.
2. Activity collected in cold traps.
3. Activity deposited on piping or in components outside the core area.

The activity in the coolant as a result of the release of stable corrosion products into the coolant (corrosion and then activation) can be estimated from

$$\lambda_2 N_2 = \frac{N_{10} A C R \phi \sigma_1 \lambda_2}{V \lambda_s (\lambda_2 + \lambda_s)} \left[1 - e^{-(\lambda_2 + \lambda_s)t} - \frac{(\lambda_2 + \lambda_s)}{\lambda_2} \left(1 - e^{-\lambda_2 t} \right) e^{-\lambda_s t} \right] \qquad (2.13)$$

where

$\lambda_2 N_2$ = activity from daughter isotope (N_2) in coolant (dis/sec/cm^3)
N_{10} = original number of target-isotope atoms in the material being corroded (atoms/cm^3)
A = area of corroding material (cm^2)
C = corrosion rate (cm/sec)
R = fraction of coolant in flux field
ϕ = activation flux level (neutrons/cm^2/sec)
σ_1 = activation cross section for isotope N_1 and for nuclear reaction under consideration (cm^2/atom)
λ_2 = radioactive decay constant for isotope N_1 (sec^{-1})
t = time period over which material is exposed, i.e., irradiation or operating time (sec)

V = total volume of coolant in loop (cm^3)
λ_s = removal rate of corroded material from the coolant by the system components, e.g., by cold trap, plating out, etc. (sec^{-1})

A conservative estimate of activity in the coolant can be made by assuming no removal of material from the coolant by the system ($\lambda_s \to 0$) or

$$\lambda_2 N_2 = \frac{N_{10} ACR\phi\sigma_1}{V}\left[t - \frac{1}{\lambda_2}\left(1 - e^{-\lambda_2 t}\right)\right] \tag{2.14}$$

In a system with a cold trap, if the removal efficiency of the cold trap for the product and daughter isotope is known, the value for λ_s is*

$$\lambda_s = \frac{Q\varepsilon}{V} \ (\text{sec}^{-1}) \tag{2.15}$$

where Q is the flow rate of the coolant through the cold trap in cubic centimeters per second, ε is the cold-trap efficiency, and V is the total volume of coolant in the loop in cubic centimeters. The equilibrium value of activity of corrosion material in the coolant from noncore sources for a system with a cold trap is reached when $\lambda_s t >> 1$ or

$$\lambda_2 N_2 = \frac{N_{10} ACR\phi\sigma_1\lambda_2}{V\lambda_s(\lambda_2 + \lambda_s)} \tag{2.16}$$

The total activity in the cold trap, A_{ct}, in disintegrations per second can be estimated by using Eq. 2.16 to obtain

$$A_{ct} = N_2 Q\varepsilon\left(1 - e^{-\lambda_2 t}\right) \tag{2.17}$$

The activity in the coolant caused by corrosion of activated isotopes from core surfaces (activation and then corrosion) is

$$\lambda_2 N_2 = \frac{N_{10} AC\phi\sigma_1}{V(\lambda_2 + \lambda_s)}\left[1 - e^{-(\lambda_2 + \lambda_s)t} - (\lambda_2 + \lambda_s)\left(1 - e^{-\lambda_s t}\right) e^{-\lambda_2 t}\right] \tag{2.18}$$

and when $\lambda_s t >> 1$,

$$\lambda_2 N_2 = \frac{N_{10} AC\phi\sigma_1}{V(\lambda_2 + \lambda_s)}\left(1 - \frac{\lambda_2 + \lambda_s}{\lambda_s} e^{-\lambda_2 t}\right) \tag{2.19}$$

where A is the area of corroding material in a high neutron flux field in contact with the coolant in square centimeters and C is the corrosion rate in centimeters per second. Other parameters are as previously defined. The activity in the cold trap is then

$$A_{ct} = \frac{N_{10}\phi\sigma AC\lambda_s}{(\lambda_2 + \lambda_s)\lambda_2}\left(1 - e^{-\lambda_2 t}\right) \text{ dis/sec} \tag{2.20}$$

Prediction of corrosion-product radioactivity levels requires knowledge of the corrosion rates and the fate of mass-transfer products expected in the system. If values for these parameters are known (see Vol. V, Chap. 2) the radioactivity levels can be estimated from the previous equations. Unfortunately, there is virtually no confirmation of actual activity measurements from operating systems, and the validity of calculated values is subject to question.

No significant radiation problems have been reported as a result of corrosion-product activity. This is partially attributed to the selection of materials with low corrosion rates and to the maintenance of low impurity levels in operating systems. The ac-

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*Assuming that material is removed from the system solely by cold trapping.

tivity of ^{24}Na and ^{42}K will, of course, completely mask corrosion-product activity during reactor operation and for a considerable period of time (days) following shutdown. If fuel-element failures have occurred [as, e.g., in the Sodium Reactor Experiment (SRE), Enrico Fermi Atomic Power Plant (EFAPP), Experimental Breeder Reactor No. II (EBR-II), and SNAP-7 Experimental Reactor (S7ER)], the released fission products also mask corrosion-product activity. These factors, coupled with sampling and analysis difficulties and the fact that liquid-metal systems have not experienced long operating periods, have prevented the accumulation of meaningful data in this area.

Nevertheless, the levels predicted from corrosion rates and the equations presented in this section are useful for safety purposes. Since the resulting radiation levels and shielding are of interest only after shutdown and significant decay of ^{24}Na and ^{42}K, only isotopes with relatively long half-lives need to be considered. Isotopes of major interest for sodium or NaK systems result mainly from activation of elements and impurities in stainless steels. The major sources are ^{60}Co (5.3 years), ^{51}Cr (27.8 days), ^{99}Mo (67 hr), ^{59}Fe (45 days), and ^{54}Mn (312 days). Estimates of activity levels resulting from these isotopes may be necessary for planning, scheduling, and establishing the shielding required for maintenance and repair on systems that are shut down. Radiation levels and shielding requirements can be determined by techniques described in Ref. 17.

The behavior of fission products in liquid-metal systems is discussed in Sec. 2-4.4.

2-4.4 *Fission-Product Behavior in Sodium*

The presence of long-lived fission-product activity in the reactor sodium coolant introduces several operational or safety problems, including:

1. Radiation levels that persist in primary-sodium-system equipment removed for maintenance long after the ^{24}Na activity has decayed.
2. The transfer of certain volatile or gaseous fission-product activities to the cover gas where they may subsequently leak out of the primary system and constitute an inhalation hazard to personnel.
3. The deposition or plating of fission-product activity directly on the surfaces of primary-system equipment so that, even after the sodium is drained from the system, substantial radiation levels remain to complicate handling and maintenance operations.

This section discusses the results of experimental and analytical studies of fission-product behavior in a sodium-cooled reactor and reviews operational experience with sodium-cooled reactors in which fission products have been released into the sodium.

Other sources of radioactivity in the sodium coolant are the activation of impurities and corrosion products in the sodium and the corrosion of activated core structural material, as described in the previous section.

(a) *Fission-Product Release to Cover Gas.* Although the release of fission products into various environments, such as inert gas, steam, or air has been rather well investigated, much less is known about the behavior of fission products released into sodium and their subsequent release into the cover gas.

In a number of early experiments [18-20], the release of noble gases such as xenon and krypton into the cover gas was essentially 100% of that initially released into the sodium. These results would not be changed significantly if the effect of the small solubility of the noble gases in sodium at reactor temperatures were included (see Vol. I, Chap. 2). However, in recent vented fuel experiments [21], the daughter products of the short-lived noble gases were also observed in the sodium coolant; air presence indicates some finite transport time during which the noble gas atoms can decay to particulate daughters. This effect is probably a function of release rate, sodium depth, and other factors but should be considered in the design of sodium cleanup facilities. This behavior of the daughters of short-lived noble-gas fission products was also observed in connection with an accidental cover-gas release at the Dounreay Fast Reactor [see Sec. 2-4.4(b)].

Of particular interest in the short-lived category is ^{137}Xe (3.9-min half-life), which decays to ^{137}Cs en route through the coolant. Also, in the vented fuel-element experiment mentioned previously [21], the predominant activity detected in the sodium outside the fuel rod was ^{134}Cs. This was presumably an activation product of stable ^{133}Cs (daughter of 5.3-day ^{133}Xe). In this particular experiment, which was performed in a thermal flux, the cesium activity was 336 times the combined activity for all other sodium activation products and fission products except ^{24}Na. It was also estimated that the ^{134}Cs activity under fast-reactor conditions (fast flux) would be 10 times that expected from ^{22}Na after about 10 years if vented fuel is assumed.

Volatile fission-product species in dilute solution in the sodium coolant at reactor-system operating temperatures can exert appreciable partial pressures and hence are transported to the cover gas by vaporization.

The partial pressure, P_i, of a fission-product-solute species over a liquid-sodium solution is expressed as

$$P_i = P_i^0 \gamma_i X_i \tag{2.21}$$

where P_i^0 is the vapor pressure of pure fission-product species, X_i is the mole fraction of fission-product species in solution, and γ_i is the activity coefficient of fission-product species in sodium.

To obtain information on the activity coefficients of various fission products in sodium, we must have a knowledge of the thermodynamic properties of very dilute solutions of these systems. Methods for estimating and experimentally determining those thermodynamic properties of fission product sodium solutions needed to obtain activity coefficients at infinite dilution have been reported [22]. Activity coefficients derived by these methods for solutions of Cs, Rb, NaI, Ba, Sr, Te, and Sb in sodium were utilized with vapor pressure data in Ref. 23, Eq. 1, to obtain curves of partial pressure per mole fraction of fission product for very dilute solutions, P_i/X_i, as a function of reciprocal absolute temperature (Fig. 2.4, p. 176). The dotted curves are the relations obtained by assuming ideal solution behavior (i.e., $\gamma_i = 1$). If the concentration of a fission-product species in the liquid-sodium phase is given, the quantity of the species in the cover gas at equilibrium can be computed by using Fig. 2.4 and the ideal gas law.

The equilibrium distribution of a fission product between the liquid and gas phases can also be expressed in terms of a distribution coefficient, or relative volatility, K_d:

$$K_d = \frac{Y_i}{X_i} = \frac{P_i/(P_{\mathrm{Na}} + P_i)}{X_i} \tag{2.22}$$

where Y_i is the mole fraction of fission-product species in the cover-gas phase, X_i is the mole fraction of fission-product species in the liquid phase, and P_{Na} is the partial pressure of sodium in the cover-gas phase. For a dilute sodium solution, $P_{\mathrm{Na}} = P_{\mathrm{Na}}^0$ and $P_i \ll P_{\mathrm{Na}}$; thus

$$K_d = \frac{P_i^0 \gamma_i X_i}{X_i P_{\mathrm{Na}}^0} = \frac{\gamma_i P_i^0}{P_{\mathrm{Na}}^0} \tag{2.23}$$

The extent to which K_d differs from unity thus expresses any preferential tendency for the fission-product species to enter into the gas phase or to remain in the liquid phase. Because of the linear relation involved,

$$K_d = \frac{A_{(\mathrm{gas})}/M_{\mathrm{Na(gas)}}}{A_{(\mathrm{liq})}/M_{\mathrm{Na(liq)}}} \qquad (2.24)$$

where $A_{(\mathrm{gas})}$ and $A_{(\mathrm{liq})}$ are radioactivity levels of fission-product species in gas and liquid phases, respectively; $M_{\mathrm{Na(gas)}}$ and $M_{\mathrm{Na(liq)}}$ are mass of sodium in gas and liquid phase, respectively; and the partitioning, or fractional release of activity from the liquid phase to the gas phase at equilibrium, is

$$\frac{A_{(\mathrm{gas})}}{A_{(\mathrm{liq})}} = K_d \frac{M_{\mathrm{Na(gas)}}}{M_{\mathrm{Na(liq)}}} \qquad (2.25)$$

The mass of sodium in the gas phase can be calculated from the ideal gas law:

$$\frac{A_{(\mathrm{gas})}}{A_{(\mathrm{liq})}} = \frac{280PV}{M_{\mathrm{Na(liq)}}T} K_d \qquad (2.26)$$

where P is the sodium vapor pressure at T in atmospheres, V is the gas-space volume in liters, and T is the sodium temperature in degrees Kelvin.

Relative volatility data obtained from vaporization equilibria experiments were reported for Cs-Na and NaI-Na solutions [24]. The experimental relation for the relative volatility of cesium in sodium was

$$\log K_d = \frac{987}{T} + 0.490 \qquad (2.27)$$

For sodium iodide in sodium the experimental relation for relative volatility was

$$\log K_d = \frac{1840}{T} - 2.34 \qquad (2.28)$$

Several other investigations on the vaporization of fission products from sodium have been initiated [25,26].

(b) *Operational Experience with Fission-Product Release from Sodium.* Results from one of the earlier sodium-cooled reactor incidents [27] indicated that, after fission products were released into the sodium coolant, only noble gas and daughter-product isotopes were present in the cover gas. A summary of these data is given in Table 2.4.

The fractions of the total reactor inventory released are functions of the various fuel-temperature conditions and of the extent of cladding failure. No xenon or krypton was detected in the sodium, although many other fission products were evident. Similarly, in the more recent BR-5 (USSR) release of fission products at 1000-kw power [28], only ^{133}Xe, ^{135}Xe, ^{133m}Xe, and ^{85}Kr were found in the cover gas. The magnitude of the leak in this case was not specified, and thus no release fractions are available.

In the EFAPP reactor, where fission products were released into the sodium coolant from partially melted fuel elements [29], only the rare gases were observed in the cover gas.

Partial release of the cover gas to the containment sphere in the Dounreay Fast Reactor [30] resulted in an air activity level approximately 10^2 to 10^4 times normal. Analysis disclosed that activity was primarily from ^{88}Rb and ^{138}Cs. These two isotopes are the daughter products of the short-lived noble gas precursors ^{88}Kr and ^{138}Xe, which have half-lives of 2.8 hr and 17 min, respectively.

(c) *Fission-Product Deposition and Plating in Liquid Sodium.*

(1) *Experimental and Analysis Studies.* Very few experiments have as yet been conducted on the subject of fission-product deposition and plating in liquid-sodium systems. In an experiment at Los Alamos Scientific Laboratory [31] in which irradiated fuel was

TABLE 2.4 - Fission-Product Contamination in Cover Gas of SRE Reactor

Isotope	Cover-gas concentration, $\mu c/cm^3$	Total cover-gas inventory, curies	Total reactor inventory, curies	Fraction released
^{133}Xe	7.4	47	5.08×10^4	0.92×10^{-3}
^{85}Kr	0.016	0.2	1.1×10^3	0.18×10^{-3}

placed in a small forced-convection sodium loop, over half of the available cesium radioactivity was concentrated in the gas phase. An additional 31% was distributed through the hot traps and the stainless-steel tubing, and the remainder appeared in the stainless-steel mesh. If a small correction for the cesium dissolved in the sodium is neglected, the stainless-steel mesh was, on the average, 16 times more efficient per unit surface area than the bare tubing as a cesium collector. This difference in effectiveness was not explained. A somewhat similar experiment at Atomics International [24] showed a clear and substantial increase in ^{134}Cs activity locally when a region of an otherwise isothermal loop was cooled. The local ^{134}Cs activity returned to its original value when the loop was returned to an isothermal condition. The behavior of ^{137}Cs in these small-scale experiments indicates that cesium in sodium is probably a mobile and volatile isotope that is only weakly absorbed on metal surfaces. As can be seen in the following section, these preliminary experimental evaluations were not corroborated in all cases by reactor operational experience.

(2) *Reactor Operational Experience*. Two separate phenomena appear in the data on deposition and plating of fission products in reactor systems. These are (1) the accumulation of deposits caused by settling and sedimentation of solid particles in reactor piping areas where sodium flow is slow and (2) the deposition of radioactivity on pipe walls caused by plating or adsorption. Deposits of the latter type cannot be removed by ordinary washing. Nonuniformity of deposition on the walls has also been reported in this case.

In one operational example, BR-5 [28], removal of sodium from the primary loop after decay of the ^{24}Na activity reduced the radiation level by only about 10 to 20%. The residual activity in this reactor was identified as ^{137}Cs. The cesium deposition appeared to be maximum at the boundary-interface position between the liquid and gas. Changes in the sodium flow and temperature appeared to have little effect on the concentration of cesium on the walls. However, when the wall surface was heated, the local cesium concentration was reduced, and, conversely, as the heating was reduced, the concentration of radioactivity on the wall increased. Analysis of the radiation levels indicated that Zr-^{95}Nb and Ba-^{140}La were also present on the wall surface.

In the Dounreay reactor, Ba-^{140}La, ^{141}Ce, ^{131}I, ^{95}Zr, ^{103}Ru, ^{106}Ru, ^{132}Te, and ^{132}I were found in the spectrum of radiation remaining on the wall surface [30]; no numerical results were reported.

Data obtained from samples of reactor primary-loop piping removed from the SRE [27] indicated that appreciable deposition of fission-product contamination occurred throughout the primary piping system. A marked selectivity among elements was noted; strontium, cerium, and Zr-Nb deposits were about 50, 25, and 10 times, respectively, that of cesium. These results are shown in Table 2.5.

TABLE 2.5 - "Fixed" SRE Fission-Product Contamination in Primary Sodium Piping

Isotope	Contamination level, μc/cm²*	Ratio $\frac{\mu c/cm^2 \text{ pipe surface}}{\mu c/cm^3 \text{ primary sodium}\dagger}$
^{89}Sr	15.2	0.76
^{90}Sr	0.78	0.80
Zr-^{95}Nb	2.7	0.19
^{144}Ce	2.1	0.41
^{137}Cs	0.022	0.018

*Corrected for radioactive decay for comparison. The actual contamination levels of ^{89}Sr and Zr-^{95}Nb may never have been this high.

†Sodium contamination level as determined in first sample after reactor shutdown.

(d) *Deposition and Plating in Gas Phase.* In a recent experiment [22] CsI was dissolved in liquid sodium contained in a stainless-steel boat, and radioactivity was released into a helium stream at a fixed temperature. The vaporized species were then deposited in a thermochromatographic column having a linear temperature profile. Deposition temperatures were noted for the various activities. The deposition profiles obtained for these species were compared with those of NaI and CsI. The results showed that over the temperature range from 485 to 748°C, metallic Cs and NaI were the species transported from sodium when CsI was initially introduced. Reactor data [28] for BR-5 indicated that ^{137}Cs was found on the walls of the pump and a level gauge above the sodium level after operation.

(e) *Effect of Purification Devices on Fission-Product Levels.*

(1) *Experimental and Analytical Studies.* Recent experiments studied the effectiveness of cold trapping or hot trapping of fission products in sodium and of enhancing their deposition with carbon [31]. Initial results indicated an affinity of cesium for the cool walls in the gas space above the coolant and for the stainless-steel walls and mesh. Replacement of the zirconium hot traps in the experiment with a basket of spectroscopic-grade graphite rods caused migration of the cesium from the stainless-steel tubing and mesh surfaces to the graphite bed until eventually 85% of the cesium lost from the gas phase and from the sodium-wet-stainless-steel surfaces appeared in the bed. By means of a regenerative cooler and a thin-walled cold trap (a bulb filled with stainless-steel mesh operated at 175°C), cesium previously deposited on the walls of the gas space was returned to the sodium mass by washing the walls with sodium. Approximately 90% was removed in this manner, and one-half of this then accumulated in the cold trap. The activity in the trap, however, was not fixed but gradually moved back to the gas phase with no change in the cold-trap temperature.

The experiments at Atomics International [32], in which cooling one section of an otherwise isothermal loop caused a local increase in ^{134}Cs activity, also demonstrated the apparent affinity of cesium for cool surfaces.

(2) *Reactor Operational Experience.* In general, experimental results were corroborated by reactor operational

experience in which fission products have been introduced inadvertently into the primary loop. There have been rather marked differences in behavior in various reactors which are not as yet clearly understood. In the SRE [27], for example, cold trapping proved to be effective in removing the fission-product contamination. Whether this removal occurred primarily by the direct trapping of dissolved fission products or through the collection of contaminated carbonaceous material (Tetralin had leaked into the sodium coolant to cause core coolant-channel blockage and subsequent fuel damage) is not presently known. The specific activity of the carbon in the SRE ranged from 10^3 to 10^4 times that of the filtered sodium in which it was contained. The concentration appeared to increase with exposure time and to be generally nonselective with regard to those fission products measured.

In the BR-5 reactor operation [28], when the reactor operated at the 1-Mw power level, the residual gamma radiation of the coolant was attributed to ^{137}Cs, ^{140}Ba, and ^{95}Zr-^{95}Nb, with approximately 95% of the coolant residual activity resulting from ^{137}Cs. During this time the oxide filtration system (presumably the cold trap) worked more than 65% of the time. The cessation of cold trapping for 24 days did not produce any noticeable change in the cesium activity level in the coolant. However, later results indicated that the cesium content of the coolant depended markedly on the cold-trap operating condition; the higher the temperature of sodium in the trap, the higher the concentration of cesium in the primary coolant. When the cold-trap temperature was increased from 110 to 185°C, the cesium level in the coolant increased by a factor of three. Similarly, iodine levels appeared to be strongly influenced by cold-trap operation. Recent cleanup experience with the EFAPP reactor [29], however, indicated that the cold trap did not perform effectively in removing fission products from the coolant.

2-4.5 *Liquid-Metal-Air Reactions*

The most common reaction encountered in using liquid metals is the interaction with air. Liquid sodium and NaK generally ignite spontaneously in air, and combustion is sustained if initial conditions of temperature and environment continue to prevail. The potential hazards of gross sodium leakage from a high-temperature sodium system into air result from the liberation of the combustion energy and products from the resulting sodium fire. Although the probability of a system failure leading to a large sodium spill is very remote, consideration of such accidents is necessary in the safety analysis of nuclear power reactor systems because of the presence of radioactive sodium isotopes and other possible contamination that can become airborne in the event of a sodium fire, as well as the effects of the resulting pressurization of the containment. The reaction and effects depend on the mode of release, prevailing environmental conditions, and physical characteristics of the area into which the release occurs. To define the potential air reactions and effects, we shall consider two representative conditions as typical:

1. Reaction at surface of a pool of sodium (static or burning pool).
2. Reaction associated with a spray-type release (pressurized spray or explosive ejection).

Although peak pressure is affected by many variables, such as heat transfer to walls and oxygen depletion in an enclosed system, the energy released by the burning pool to the surrounding atmosphere tends to cause a slow increase in pressure. In pressurized spray and explosive ejection, the pressure rises at a considerably higher rate, and much larger peak pressures occur. Explosive ejection, although least likely to occur, is potentially the more severe. The significant difference between explosive ejection and pressurized spray is one of reaction rate. Under given temperature conditions, the rate of reaction is a function of the rate of sodium surface exposure, which depends on the mass rate and particle size of the sodium discharge. In a spray discharge it is most improbable that a very large discharge rate and fine particle dispersion could exist simultaneously. Only in the explosive ejection of a large mass of finely dispersed sodium are optimum conditions for the most severe reactions possible.

Information from various studies of these modes of sodium combustion are presented in Secs. 2-4.5 (a) and (b). Some considerations associated with evaluating the effects of sodium spills in sodium-cooled-reactor-system containment and equipment enclosures are presented in Sec. 2-4.5 (d). The work on NaK-air reactions is extremely sparse compared with that on sodium. Information on NaK fires is presented in Sec. 2-4.5 (c).

(a) *Sodium Pool Fires.* When a pool of liquid sodium burns in air, the combustion reaction is characterized by a very low flame region and dense clouds of white oxide smoke. Heat must be supplied to start the combustion reaction of sodium at low temperatures, but, once it is started, enough heat is liberated to maintain the reaction and to gradually raise the temperature of the molten liquid. As the temperature increases, burning occurs on glowing orange-yellow nodules of oxidized sodium crust spread over the entire molten sodium surface. When the temperature reaches 1200 to 1300°F, the nodules disappear (sodium peroxide melts at 1220°F), and the sodium pool appears reddish in color, with wispy flames on the surface of the molten crust.

(1) *Ignition Temperature.* The minimum temperature at which a pool of sodium will ignite depends on the characteristics of the particular system involved. The ignition temperature is a function of such variables as the surface-mass ratio, surface conditions, metal purity, absolute humidity, temperature of the surrounding atmosphere, and the velocity of air over the surface. Approximate values for ignition temperatures of sodium in air are listed in Table 2.6.

Some data were reported on the effect of the moisture content of the reacting atmosphere on sodium combustion and ignition. Table 2.7 presents data on the effect of water vapor on various modes of reaction between sodium and oxygen. These results appear to indicate that for the range of moisture contents normally encountered in sodium-system enclosures (including reduced oxygen atmospheres) the moisture content is not a significant factor for a sodium fire.

(2) *Burning Rate.* Data on the combustion or burning rate of sodium in air and reduced oxygen atmospheres are required to predict the rate of energy release for a fire of a given size. Another equally important quantity required is the fraction of the burned sodium that is released to the gas, or the sodium oxide smoke release rate. For certain postulated accidents in a sodium-cooled reactor, the latter quantity is one of the factors determining the amount of airborne radioactive sodium available for leakage from the building and the loading requirements for the air-cleaning system. The air-cleaning requirements for handling the effluents released from a sodium fire are discussed in Sec. 2-4.6.

Table 2.8 summarizes many sodium fire tests [32,33,36,38-41] conducted at various installations to determine approximate burning rates of sodium pools in air. The quantities of sodium burned ranged from several grams to several thousand pounds, with large variations in pool diameter and depth, initial sodium temperature, and heat losses from the container. In a majority of the experiments, systematic variation of parameters was not at-

TABLE 2.6 - Sodium Ignition Temperature in Air [33]

Configuration	Ignition temp., °F	Remarks
Extremely fine particles	RT*	Particles condensed from vapor mist
Droplets	250	Liquid sodium forced through 0.008- to 0.020-in.-diameter holes; in air, irrespective of moisture content [34]
Pool	>400	When oxide film on surface of pool is disturbed
Pool	>550	Surface oxide film undisturbed†
Pool	>800	Some instances

*Room temperature.

†Longton [35] reported that sodium heated from cold condition in the presence of oxygen acquires a thick oxide film before true ignition temperature is reached; 5- to 10-g samples heated in an open dish did not ignite until 830 to 880°F. When the sodium was heated prior to admission of the gas, ignition occurred above ∿ 550°F.

tempted, techniques for estimating burning rate were quite limited, and detailed temperature measurements were not obtained. Under these circumstances it is not surprising to find that sodium burning rates in the table vary from 1 to 17 lb/hr/sq ft with very limited correlation. Based on experiments [37,39] conducted in insulated containers with exposed sodium areas greater than about 1 sq ft, the suggested range of values for average sodium pool burning rates in air is 5 to 10 lb/hr/sq ft. For pool fires in insulated containers, the initial sodium temperature (above ignition) is probably not an important variable for average burning rate. In the experiments reported [37,39] the surface temperature of the pool rose to about 1300°F although initial sodium temperatures varied by as much as 500°F.

Reduced oxygen atmospheres are used in sodium-cooled-reactor-system enclosures to minimize the consequences of sodium leaks and spills. Data on the burning rate of sodium pools in these atmospheres are also of interest since energy and smoke are still liberated, though at reduced rates. The reduced energy-release rate generally results in a decrease in the sodium pool temperature with time, the detailed history being a function of the heat-loss characteristics of the system and the levels of oxygen reduction. Under these conditions the temperature of the sodium decreases to the point where combustion is insignificant or ceases.

Pool burning rates of sodium at 1000°F at oxygen concentrations of 1.2, 2.0, and 9.5 vol.% (nitrogen diluent) under forced-flow conditions are shown in Table 2.9. The data in the table indicate that the burning rate is proportional to the oxygen concentration

TABLE 2.7 - Effect of Water Vapor on Sodium Combustion

Oxygen content of gas		Ratio $\frac{P_{O_2}}{P_{H_2O}}$	Moisture content,* mm Hg	Observations	Temperature of sodium, °F	Quantity of sodium, lb	Remarks
mm Hg	% at 1 atm						
900		$>5 \times 10^5$	0.00002	No reaction	1020		Range of O_2 content of 10 to 900 mm Hg; maximum temperature employed
900		9×10^3 to 4×10^5	0.0001 to 0.1	Ignition	230 <ignition temp. <1020		No reaction until ignition temperature was reached; above ignition temperature, vigorous combustion
900		$<7 \times 10^3$	0.01 to 0.25	Slow reaction	220		Immediate reaction but no ignition of sodium
	6.5	∿15	3	Burning	800	0.2	Appearance of burning nodules when oxygen concentration shown was reached
	4.6	∿10	3	Burning	1000	0.2	Nodules on surface burning vigorously when oxygen content shown was reached
	5.2	∿0.3	140	Burning	1000		

*For air at 100°F, 100% relative humidity is approximately 300 mm Hg partial pressure of water vapor.

TABLE 2.8 - Sodium Pool Burning in Air

Container area, sq ft	Air circulation	Container depth, in.	Original sodium weight, lb	Initial sodium temp., °F	Burning time, hr	Burning rate, lb/hr/sq ft*	Ref.
1.67	Natural	2	14	†	0.75	11	33
0.83	Natural	2	7	†	0.75	11	33
0.14	Natural	2	1	†	0.50	17	33
6.25	Natural	3	50	850	1.6	6.3	37
6.25	Forced	3	50	675	1.6	4.9	37
	Natural			930		3.6	41
2.78	Natural	20	350	750	17	2.3	38
	Natural	22	400	750	10	2.1	38
	Natural	14	300	750	12	1.1	38
20.0	Natural	17	320	750	18	1.1	38
	Natural	40	3500	500	26	1.5	36
0.6	Natural	18	33	800	5.5	4	39
	Forced	36	83	800	11	5.5	39
3.1	Forced	48	615	350	33	6.0 (9.0 max.)‡	39

*Average burning rate based on time required for complete combustion of sodium or on estimated fraction burned, except in last test, which was accurate determination by oxygen analysis.

†Not reported.

‡Maximum burning rate reached after 1 hr.

(neglecting variations in gas flow rate) with a value of 0.35 lb/hr/sq ft/% O_2. Extrapolation of these data to air yields a burning rate of 7 to 8 lb/hr/sq ft, which indicates agreement with data for sodium fires in air reported above [37,39].

A sodium burning test [44] initiated in a closed chamber containing 3.9 vol.% oxygen continued to burn at a measurable rate until the sodium temperature and oxygen concentration had decreased to 600°F and 0.6 vol.%, respectively. The burning rate constant was found to be approximately 0.4 lb/hr/sq ft/% O_2, which is similar to the value for the data in Table 2.9.

Data on the effect of sodium temperature and gas flow rate on sodium pool burning in an enclosure ventilated with a steady, forced flow of reduced nitrogen-oxygen gas mixture [32,43] (Fig. 2.5) indicate that for a fixed sodium temperature burning rate depends on gas

TABLE 2.9 - Sodium Pool Burning in Reduced Oxygen Atmosphere

Inlet-gas oxygen concentration, vol.%	Container area, sq ft	Gas flow rate, scfm	Container depth, in.	Original sodium weight, lb	Initial* sodium temp., °F	Burning† rate, lb/hr/sq ft	Ref.
1.2	3.1	12	48	615	1000	0.3	42
2.0	3.1	20	48	615	1000	1.0	42
4.1	3.1	18	48	615	1000	1.6	42
4.0	3.1	90	12	110	1000	1.1	32
4.0	3.1	20	12	110	1000	1.0	32
4.0	3.1	150	12	110	1000	1.6	32
9.5	3.1	90	12	110	1000	2.3	43

*Auxiliary heat source required to maintain constant sodium temperature.
†Determined from oxygen analysis of inlet- and outlet-gas mixture.

flow rate, and for a fixed gas flow rate burning rate increases with sodium temperature.

(b) *Sodium Spray Fires (Pressurized Spray and Explosive Ejection).* Several investigations were reported involving combustion of sodium discharged in the form of a spray into a chamber containing various initial oxygen contents [33,45,46].

The results of an investigation conducted to measure the maximum pressure generated by forcing a spray of 850°F sodium (1-lb quantity) into an 18.8-cu ft container of various concentrations of oxygen are shown in Table 2.10.

Tests were conducted [45] with 32- to 196-lb quantities of sodium at 850°F discharged into a hemicylindrical chamber (volume of 3880 cu ft). The sodium was pressurized with 50-psig nitrogen and forced through a pipe nozzle into the chamber. During these tests the oxygen concentration was varied from 1 vol.% to 2.75 vol.%. For similar test conditions, the peak pressure generated in the chamber decreased as the oxygen concentration was decreased. The peak pressure exceeded 15.3 psig (relief valve setting) for the maximum quantity of sodium discharged (196 lb).

A series of tests [33] involving the spray discharge of 1/2-lb quantities of sodium at 1000°F into a 48-cu ft enclosure containing oxygen concentrations of 0 to 5 vol.% showed that the rate of pressure rise increases with the oxygen concentration.

In detailed tests on the explosive ejection of sodium into air [47], 200- to 1600-g (0.44- to 3.5-lb) quantities of sodium at 400°C (750°F) were explosively ejected into a vessel with a volume of 71.7 cu ft. In all cases the initial reaction-vessel atmosphere was at normal atmospheric pressure, temperature, and oxygen concentration (with the exception of two argon atmosphere tests). The tests included variations

TABLE 2.10 - Effect of Oxygen Content on Sodium Spray-Oxygen Reaction Tests*

Initial O_2 content,† vol.%	Maximum pressure attained, psig	Time to reach maximum pressure, sec
21.0	38	6
10.5	34	10
5.3	26	21
0.6	8	8

*From E. Hines, A. Gemant, and J. K. Kelley, How Strong Must Reactor Housings Be to Contain Na-Air Reactions?, *Nucleonics*, 14(10): 39 (1956).

†Initial temperature of sodium was 850°F.

in quantity of sodium, distribution, force of ejection, and water content of the atmosphere. The pressure rise per unit mass of sodium ejected decreased with increasing Na-O molar ratios up to the stoichiometric amount required for formation of sodium monoxide. The peak pressures increased with increasing Na-O molar ratio until the highest experimental peak pressures (78 to 85 psig) were realized in the 2.54- to 3.05-molar ratio runs. The magnitude of the peak pressures developed was determined not so much by the initial ejection mechanism as by the unique conditions produced by a secondary dispersion mechanism.

In all experiments reported, the peak pressures observed were lower than the maximum theoretical pressures calculated assuming an equilibrium adiabatic reaction of sodium and air. However, in several spray tests [47] (explosively ejected sprays) values of peak pressure near the theoretical maximum were reached. Theoretical calculations of the sodium-air reaction were made by several investigators [37,47-49]. The calculated equilibrium adiabatic pressures reported for the sodium-air reactions are shown in Fig. 2.6.

Agreement is fairly good between the values of Refs. 35, 48, and 49. Differences in the sodium-to-oxygen ratio and thermodynamic data appear to be responsible for the differences found. In the calculations in Ref. 47, the source of the large differences lies in the assumption of complete reaction. The calculation in Refs. 48 and 49 shows that complete reaction does not occur, particularly at higher temperatures. Indeed, for a sodium-to-oxygen ratio of 4, a stoichiometric mixture for formation of Na_2O, 21.1% of the sodium initially present is found as sodium (gas) at equilibrium.

(c) *NaK-Air Reaction.* Quantitative information on NaK burning characteristics under various initial conditions is not available. Some comparisons of NaK and sodium fires [50,51] indicated that the behavior of burning NaK and sodium are essentially the same. Some tendency for the combustion products to go into solution in the molten metal was reported. A comparison of small NaK and sodium fires [50] is shown in Table 2.11.

(d) *Effects on System Containment.* The experimental observations of small-scale sodium fires indicate that the rate of oxygen supply to the sodium surface is a major factor controlling the $Na-O_2$ reaction. The accessibility of oxygen to a liquid-sodium spill depends strongly on system geometry, and each case must be judged on its own merit. Figure 2.7 shows a simplified geometry of reactor containment following a sodium spill accident in a primary-system equipment cell when it is open to the secondary containment or reactor building. The sodium spilled on the floor of the lower compartment (cell) assumes a temperature dependent on the rate at

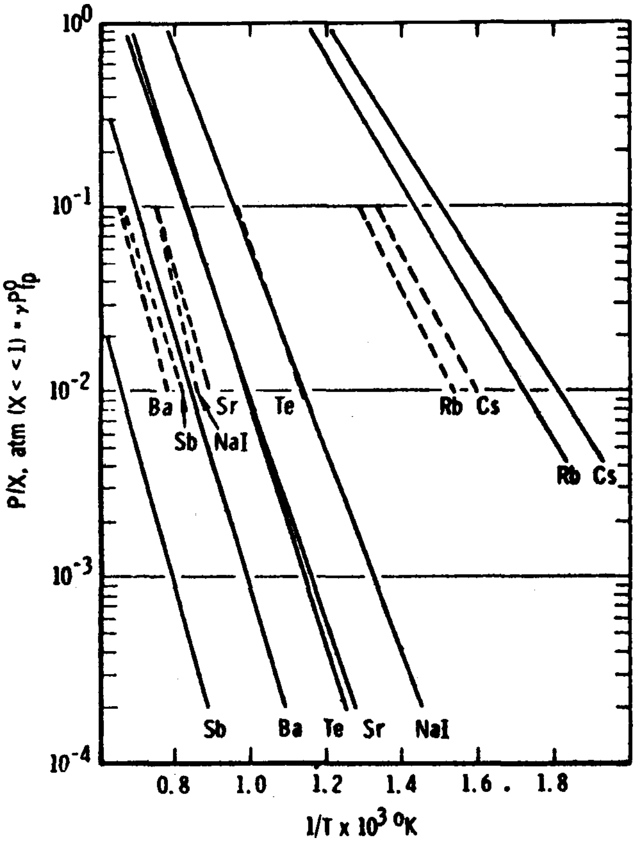


Fig. 2.4 Fission-product partial pressures over liquid sodium.

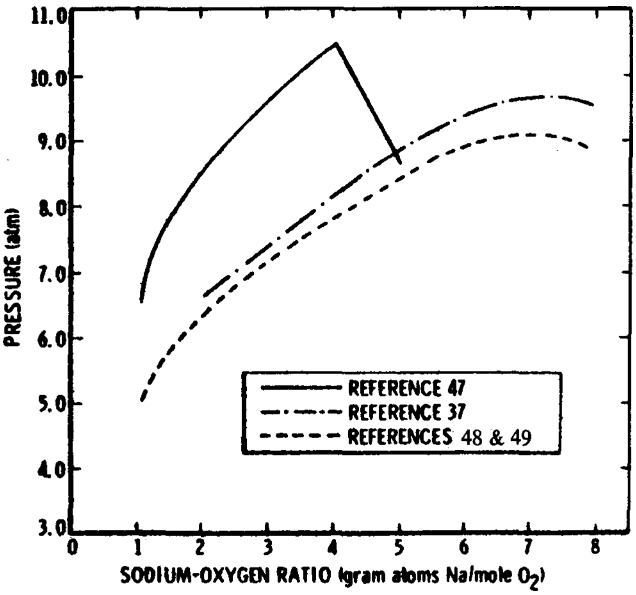
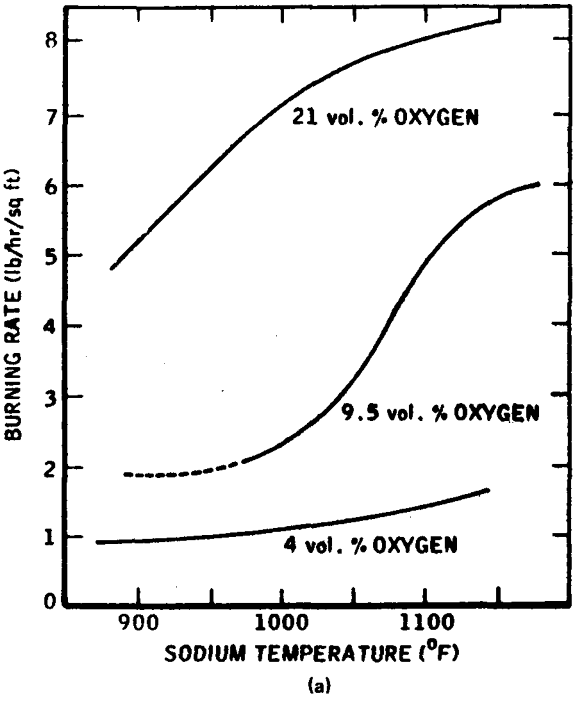
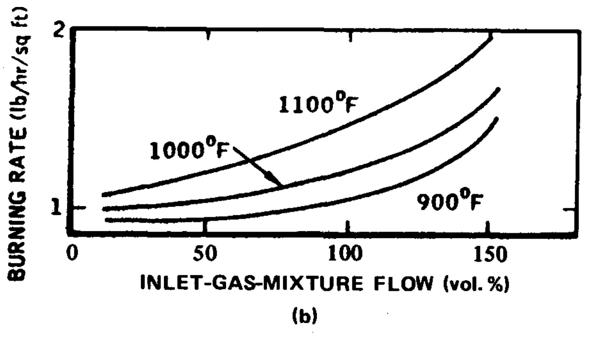


Fig. 2.6 Calculated equilibrium adiabatic pressures for the sodium-air reaction.



(a)



(b)

Fig. 2.5 Sodium pool, 2 ft in diameter and 0.8 ft deep, burning in forced-flow ventilated 45-cu ft enclosure. (a) Burning rate vs. inlet-gas flow rate for 4 vol.% oxygen at 900, 1000, and 1100°F. (b) Burning rate vs. sodium temperature for 4, 9.5, and 21 vol.% oxygen at a gas flow rate of 90 scfm.

TABLE 2.11 - Comparison of Small NaK and Sodium Fires

Characteristics	NaK	Na
Oxide smoke	White	Yellow within 1 in. of fire; white above that
Maximum temperature	1620°F	1660°F
Intermediate products	None apparent	Grey, hard mixture of sodium and sodium oxide
Burning mechanism	Incandescent nodules in black, oily mass	Incandescent nodules in crumbly residue
Flame	About 1/4 to 1/2 in. covering glowing nodules	Same as NaK; flame and burning slightly more vigorous

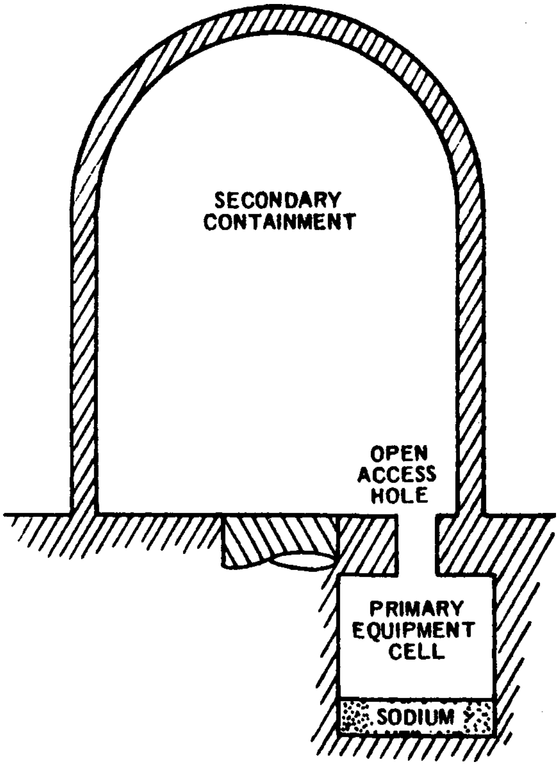


Fig. 2.7 Schematic of reactor containment following sodium spill in open primary equipment cell.

which heat is released in the Na-O_2 reaction zone and the rate at which heat is transferred away from the spill by convection to the secondary volume, by conduction to the floor, and by radiation to the surrounding walls. The sodium temperature gives rise to temperature gradients in the system (cell and secondary volume), which, in turn, provide the driving force for a fresh supply of oxygen flowing from the secondary volume to the cell volume.

One method of calculating the various heat losses from the Na-O_2 reaction zone and the rate of oxygen influx has been reported [52]. Table 2.12 shows the effect of several system parameters on the resulting pressure rise in the secondary containment volume for a pool fire in an open cell. Results of calculations for a fire in a single compartment (closed cell) with different initial oxygen contents are also listed in Table 2.12, along with the pressure rise in the reactor building of the EFAPP fast reactor estimated for a large sodium fire on the operating floor [37].

Factors contributing to the reduction of equilibrium sodium burning rates, system overpressures, and fire duration, which should be given consideration in system design for acci-

TABLE 2.12 - Pressure Rise in Containment Systems Caused by Pool Fire

Volume of primary vault (V_1), cu ft	Volume of secondary containment (V_2), cu ft	Vault opening area, sq ft	Sodium spill temp., °F	Sodium spill quantity, lb	Sodium spill area, sq ft	Maximum pressure rise, psig	Time to maximum ΔP, hr	Heat-absorbing mass in bldg., 10^5 lb	Remarks
	0.33×10^5		800	$\sim$10,000	3800	25.8	0.175	4.1	Initially 16.6 vol.% O_2; fire on operating floor
10,000			1200	25,000	$\sim$600	14.0	0.1	0	Closed cell, 4 vol.% O_2
10,000			1200	25,000	600	19.0	0.1	0	Closed cell, air
10,000	1×10^6	28.3	1200	25,000	600	7.7	4	0	
10,000	1×10^6	100	1200	25,000	600	10.4	2.8	0	
10,000	1×10^6	28.3	1200	25,000	600	6.3		5.0	
10,000	1×10^6	28.3	950	25,000	600	7.6	4	0	

dent mitigation are (1) increased heat-transfer rates from the vault and secondary volume atmospheres to additional heat-absorbing masses, (2) the use of vault and secondary volume ventilation and cooling systems, (3) vault geometries that reduce the surface area of the sodium pools following a spill, (4) use of vault construction materials with poor insulating properties, and (5) reduced oxygen environments.

2-4.6 *Sodium-Fire-Control Design Considerations*

(a) *Physics of Sodium Fire Aerosols.*

(1) *Sodium Oxide Aerosol Release Rates and Compositions.* The release rate of the combustion products of sodium is a function of the oxygen concentration and the burning rate. The release fraction of sodium oxide when nitrogen containing 4 vol.% O_2 is swept across a 3-sq-ft pot of liquid sodium at flow rates of about 100 cfm is approximately 60%, but the release fraction in air for the same conditions is only 20%. The burning rate is proportional to the oxygen concentration; it decreases as the oxygen is consumed in a closed system and as air expands out of a partially closed system during a fire. Burning rates in cells connected to an air environment by small openings (e.g., a 3- to 8-ft-diameter manhole) rapidly decrease as oxygen is depleted and are sustained only by diffusion of oxygen back into the cell via the openings. The final burning rate is a small fraction of the initial burning rate.

Water vapor reacts rapidly with Na_2O to produce NaOH, which, in turn, reacts with CO_2 to form sodium carbonate. The aerosol aerodynamic properties are essentially unaffected by the chemical composition since the densities are all between 2.25 and 2.5 g/cm^3.

(2) ^{131}*I Release from Sodium Fires.* The release fractions of Na^{131}I from sodium fires are reported in Ref. 53. For small-area burnpots the release fraction of Na^{131}I was twice that of the sodium oxide when all sodium was oxidized (i.e., with 20% oxide released, 40% of the volume was released). It was shown that the specific activity of the released sodium was twice that in the liquid pool. No elemental iodine is produced when ^{131}I exists as NaI in the liquid sodium before burning.

(3) *Initial Size.* The initial particle-size distribution above a pool of burning sodium is log normal with a mass median diameter, D, that varies with the mass concentrations above the pool. If the mass concentration, ρ, is expressed in micrograms per cubic centimeter, the relation is

$$D = 0.74(\rho)^{0.23} \tag{2.29}$$

The geometrical standard deviation, σ, of the initial distribution is always between 2 and 2.4.

For air fires D is 1.0 μ, and σ is 2.1 [54]. About 95% of the mass released from an air sodium fire exists as particles with diameters greater than 0.3 μ. Agglomeration makes the mass fraction less than this size negligible in a very short time [see Sec. 2-4.6 (a)(4)].

(4) *Agglomeration and Growth.* If the released oxides from a sodium fire are allowed to accumulate in a relatively leaktight enclosure, the particle sizes of the aerosol increase in time because of agglomeration. Higher mass concentration causes larger particles to be produced in a given time. The relation between the mass concentration, ρ_R, introduced into a closed chamber in a given time and the approximate maximum mass median, r, to which the particles grow [32] is

$$r = a\rho_R^b \tag{2.30}$$

where a varies from 1 to 2 and b from

0.4 to 0.5.

(5) *Plating and Settling Characteristics.* When the particles become airborne and agglomerate, several removal mechanisms cause further decrease in the number of particles. These mechanisms are settling, plating, and removal by air filters connected to the ventilation system.

Settling is proportional to the diameter squared for particles larger than 1 μ, and plating is proportional to the diffusion coefficient, D, which is proportional to $1/r$.

Plating and settling are important removal mechanisms following the accidental release of sodium and fission products. The sodium does not remain available for leakage from the containment building; its airborne concentration continues to decrease, and thus eventually it is unavailable for release. High concentrations are reduced by agglomeration, which increases the size of particles. Large particles are readily removed by filters. High concentrations increase the load requirements of the filters, but, again because of the size of the particles, the prefilters' efficiency is increased, and the load on the high-efficiency filter can be controlled.

(6) *Models and Codes.* The following equation essentially describes the fate of monosized airborne sodium:

$$V\frac{dn}{dt} = -v_s n A_f - \frac{D}{\Delta} n A_w - Qn + S \qquad (2.31)$$

where

n = concentration of airborne sodium (g/cm^3)
Δ = concentration boundary layer (cm)
D = diffusion coefficient (cm^2/sec)
$D/\Delta = v_p$ = plating rate (cm/sec)
v_s = settling rate (cm/sec)
A_f, A_w = area of flow and wall (cm^2)
V = volume of building (cm^3)
Q = flow rate out of building (cm^3/sec)
S = source term (g/sec)

If a distribution exists in the diffusion coefficient or in the local concentration, the equation is solvable only by computers. Computer solutions of Eq. 2.31 for heterogeneous distributions have been reported [53].

(b) *Air-Cleaning Requirements for Sodium Fires.* The AEC-recognized high-efficiency "absolute" filters widely used for air-cleaning filtration require special attention if they are to be useful and effective in the event of sodium fires. Susceptibility of the filters to physical and chemical degradation necessitates frequent testing and careful installation and operation to ensure integrity and efficiency. The filters must be protected from excessive corrosion and excessive loadings of sodium oxide and must be located where they can withstand the heat generated from sodium fires. In typical facilities the large volume of the building and the tortuous path and expansions and contractions of the ventilation duct may be sufficient to reduce the heat from credible fires to a tolerable level at the filters. In a large sodium fire, specially designed prefilter systems are needed to protect the absolute filters.

The amount of sodium oxide the prefilters and absolute filters are required to collect must be minimized to maintain the reliability of a filter system used to control the release of fission products from an installation. The sodium oxide aerosol produced from burning liquid sodium in air consists of particles easily filtered by the absolute filter (95% of the mass is greater than 0.3 μ in dilute concentrations near μg/cm^3.

Several high-load filters can remove a large fraction of the aerosol before the final absolute filter is reached; these units are:

1. Cloth-bag filter with reverse air jets of automatic shakers.
2. Cyclone separators with exhaust filters.
3. Wet scrubbers.
4. Electrostatic precipitators with wash-off plates.

The cloth-bag filter, one of the few commercial systems tested for efficiency for filtering sodium oxide, was evaluated by Atomics International [55]. Its efficiency was greater than 99% for high loadings (15 to 30 grains/cu ft). Water scrubbers associated with bubblers or agitators have measured efficiencies greater than 99% for sodium oxide at concentrations up to 80 μg/cm^3 (about 35 grains/cu ft), according to unpublished Atomics International results.

(1) *Pressure-Drop Effects*

Loading effects on pressure. Selected filter media contemplated for use in Hanford Atomic Products Operation (HAPO) reactor-building exhaust ventilation systems [56] were subjected to accelerated life-loading tests to determine the most desirable filter arrangement that would predispose to long life and economical operation. The primary filtration system consisted of high-efficiency, fire-resistant filters.

One of the test dusts was natural settled dust accumulated in the attic space of a project building over a number of years and was readily collected in sufficient quantity by vacuum cleaning.

The high-efficiency fire-resistant filter paper tested, that commercially available at the time, was an all-glass-fiber medium. Tests were performed on this medium using aerosols of three different sizes. In the initial tests the filter was exposed to the 5.5 μ of dust directly from the chamber. In another series of tests the selected prefilter was placed upstream of the high-efficiency medium. Size analyses of the dust passing the prefilter indicated it had a mass mean size of about 2.0 μ. The average concentration of this prefiltered dust was 40 mg/m^3. A third series of tests was run using a sodium chloride fume having a mass mean size of about 0.5 μ. The results of loading tests on the high-efficiency filter can be seen in Fig. 2.8, in which the increase in pressure drop is related to (1) a loading of the natural test dust, (2) a loading of the prefiltered dust, and (3) a loading of the NaCl fume. As expected, for a given dust loading the pressure-drop increase is considerably greater with prefiltered dust of a selectively smaller size. This was more apparent with the NaCl fume.

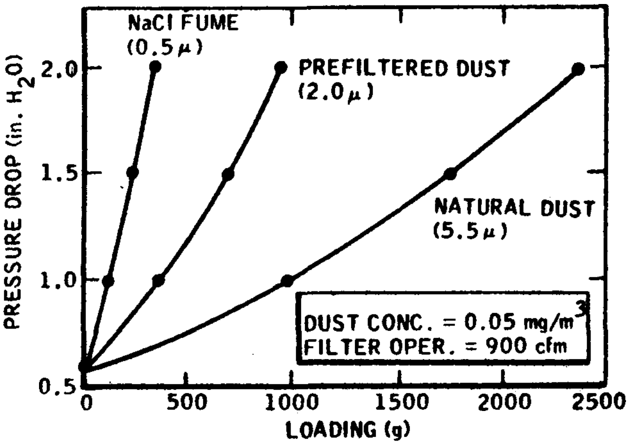


Fig. 2.8 Effect of particle size on loading of high-efficiency media.

The particulate concentrations to which filters would be exposed in the reactor ventilating systems under assumed sodium-fire conditions were measured in several instances. Because of sampling difficulties, however, only limited data were obtained. The concentrations varied between approximately 0.05 and 0.005 mg/m^3. If the loading pressure-drop relations shown in Fig. 2.8 are applied to an estimated airstream loading of 0.05 mg/m^3, the anticipated life expectancy of the high-efficiency filter units can be projected. This is seen in Fig. 2.9 for the three aerosols previously discussed. If the actual dust is assumed to be in the size range of the chamber test dust, the life expectancy of these filters is

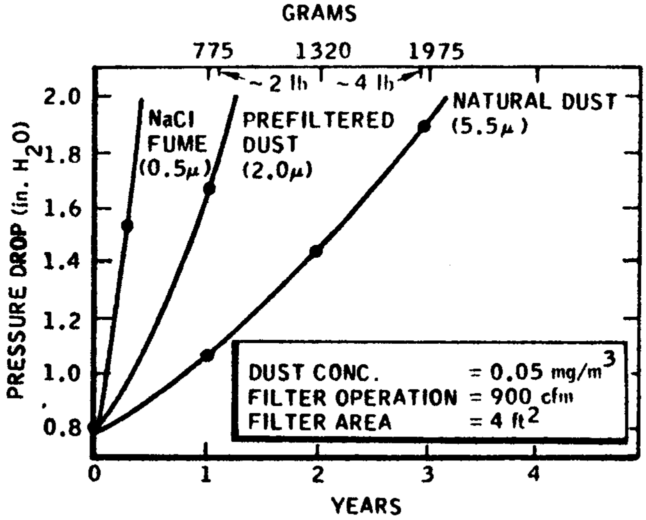


Fig. 2.9 Effect of particle size on life of high-efficiency filter units.

about three years if the maximum permissible pressure drop is 2.0 in. water.

It can be seen from Fig. 2.9 that loadings of 1.2 to 5 lb per filter would readily clog the filters. If 100 lb of oxide were airborne in a 1 million cu ft building with a ventilation rate of 10^4 cfm, then 1 lb/min or 60 lb/hr would arrive at the filter. Since there is a flow of 10^3 cfm through each filter, the load per filter is 6 lb/hr. Therefore a 2-in. or greater pressure drop occurs in 1 hr.

Pressure-drop effects on efficiency. Loading of filters can also affect their efficiencies. Figure 2.10 presents the results of experimental work performed in France [57] which shows that efficiency can either increase or decrease depending on the particle size distribution of the aerosol.

(2) *Filter Media*

Types of filters. A filter medium is a porous material designed to separate suspended or dispersed particles from the gas or liquid that passes through it. The term "filter medium" is often used to distinguish this material from the materials used in the construction of other components of an assembled filter (frame, separators, adhesive, gaskets, etc.)

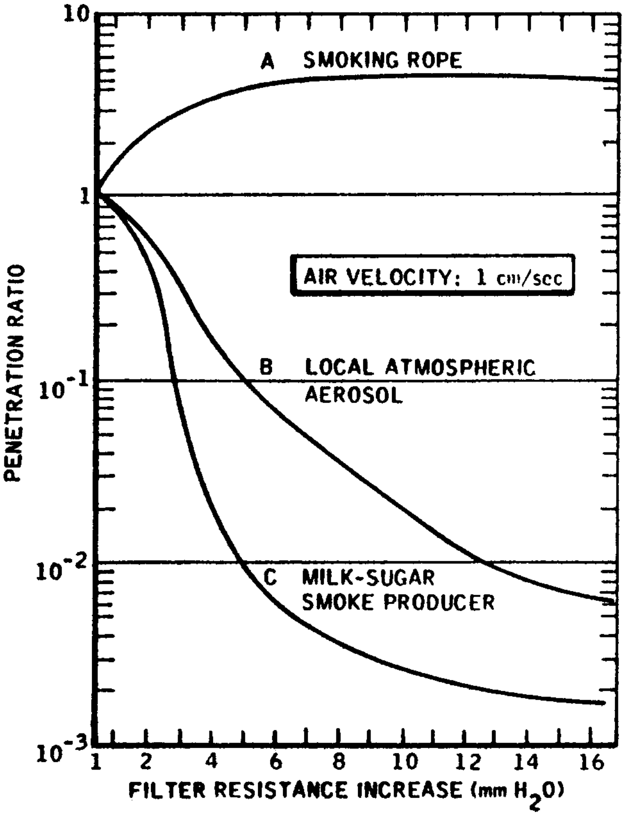


Fig. 2.10 Filter efficiency and clogging.

The filter medium should have good resistance to heat and caustics and should retain its strength when exposed to moisture. Filters of glass fiber and asbestos have the advantage of being nonreactive in NaOH. Glass-fiber filters have greater strength and relatively high efficiencies. New fireproof filters with metal frames and separators and glass-fiber filter materials are available.

Special filter studies for sodium and NaK aerosols. A minimal amount of research has been performed to determine characteristics of high-efficiency, high-loading, nonreactive filters for Na-NaO aerosols.

Some early work was done by Harvard Air Cleaning Laboratory [58] on the evaluation of single-layer fibrous filters for the removal of NaK fumes and oxides.

Included in the design of HNPF [38] was a high-loading high-efficiency "dry scrubber" to remove the Na-NaO fume produced during a major primary- or secondary-coolant fire. This scrubber is actually a vertical bag filter of siliconized glass fabric with a reverse air jet to the bags. The system is designed to operate at 500°F with a flow of 5000 cfm at 6-in. maximum pressure drop. The efficiency of the filter media is specified at 98.5%. The use of multiple-bag units with automatic switching and cleaning gives this type of unit a very high loading factor.

Further work was completed by Harvard Air Cleaning Laboratory [59] on the use of multilayer deep-bed filters for Na-NaO fumes generated during a large sodium fire. Most of the work was performed with sodium fumes but some sodium oxide studies were included. No difference was found in the filtering characteristics of these aerosols. The median diameter of the sodium-fume aerosol mass averaged 1.5 μ with a deviation greater than 2.0. This study concluded that a deep-bed filter consisting of 2-in.-deep beds of 1000-, 500-, 250-, 125-, and 60-μ stainless-steel-fiber media packed to 4 to 5 lb/cu ft, followed by two 2-in.-deep beds of 30- and 15-μ glass-fiber media packed at 1.5 lb/cu ft and then followed by a pleated absolute filter, could collect 0.75 lb of sodium and sodium oxides per square foot for a 20-in. water pressure drop at the equivalent flow of 40 cfm. It is evident that higher flow rates would cause excessive pressure drop, and therefore a prefilter should be considered for use in such a filtration scheme. Filtered sodium fumes (nonoxidized) produce a highly reactive and explosive package because of the potential reaction of water vapor with the finely divided condensed sodium.

(3) *Fission-Product Release and Removal.* Unless fission products are released from fuel directly into air during or before a sodium fire, no molecular iodine or organic iodides are present in the atmosphere. The preponderant quantity of sodium oxide aerosol produced during the burning of sodium scavenges all particulate fission products released from liquid sodium. The resulting agglomerate of fission products and Na_2O aerosol will plate out, settle, or will be removed by filters as if it were only oxide.

Because of the possibility that sodium fires will occur after unassociated fuel-element-cladding ruptures have released fission products to the sodium, the ventilation design must provide an efficient removal mechanism to prevent overloading of the high-efficiency air filters and/or the charcoal filters. Several schemes are available:

1. Use of cyclone separators (high-load capacity, no clogging).
2. Use of bag filters with collector hoppers (continuous removal by shaking).
3. Use of primary containment vessel with recirculating cleanup system (this still requires a high-load filtering system).
4. Using no ventilation during most of time that air concentration is high (contains release but contaminates building).

(4) *System Design* [57]

Codes governing designs (AEC Installations). All design effort for AEC installations is governed by the AEC *Manual* and its local interpretations. Instructions in this manual require compliance with local codes as well as certain other nationally recognized codes in the interest of constructing safe facilities and providing for their safe operation.

For design references, see AEC *Manual* (Design Criteria), Chap. 6306, Heating, Ventilating and Air Conditioning; *The National Fire Codes*, National Fire Protection Association (NFPA), that pertain to fixed extinguishing equipment; and state and local codes for the location under consideration.

The designer must make himself thoroughly familiar with all applicable codes during early planning of any work. Radiation safety features and control do not always remain compatible with the usual interpretation of NFPA fire codes. For this reason the designer must arrange systems for maximum compliance with both considerations. The American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. (ASHRAE) *Guide and Data Book* [60] should be used as a basic guide in all ventilation work. (See Refs. 61 and 62 for additional information.)

Arrangement of system components. The arrangement of components is paramount to the success of an exhaust system. The order of sequence of components varies with different types of systems; therefore features such as shielding, containment of contaminants, and access must be studied and evaluated before the design is completed [60]. Special considerations in design include:

1. Maintaining all ductwork and other components under a negative pressure during system operation. (Fan power will thus be situated near the terminus of the system, i.e., before release to the atmosphere or stack.)
2. Considering pressure loading in the arrangement of components since ductwork under negative pressure is subject to collapse.
3. Arranging for physical separation of roughing filters from high-efficiency filters, a factor of importance in minimizing the spread of fire [60].
4. Controlling and monitoring pressure.
5. Evaluating maintainability, accessability, and testability.
6. Planning for both normal and off-normal conditions.

Filtration. If chemically neutral exhaust gases are to be handled, particulate filtration is best achieved by a method that does not entail secondary wastes such as washing solutions, water, or oil additives. Dry-type filter units serve this requirement better than other devices. If particulate loading in the airstream is low (i.e., < 0.05 grains/1000 cu ft), high-efficiency filter life can be expected to be more than twelve months' continuous usage. Prefilters increase filter life when a significant part of the particulates measure over 1 µ. If high air concentrations of NaO are handled, prefiltering is mandatory.

Exhaust streams containing chemically active ingredients present a formidable hazard to filtration equipment, both to the frame and the filter medium. All constituents to be encountered by the filtering devices must be predetermined. Systems arranged to serve multiple sources of effluent from operations perhaps unrelated present an even more difficult filtration problem. Costs soar as a result of attempting to design one system to meet complex disposal demands for incompatible effluents. It is advisable to provide separate filtration facilities for each basic effluent and, if necessary, to combine the effluents downstream from filtering points in the system. This permits filtration to be best suited to the particular needs of each exhaust source.

The construction of most filters, especially high-efficiency filters of the absolute type, requires precautions in application and use to guarantee the integrity of the installation throughout the filter life.

In the absence of exact data concerning the gradation by size and weight of particulates to be expected in exhaust streams, the following are suggested for initial design:

1. Prefilter [up to 35% National Bureau of Standards (NBS) efficiency, or equivalent]. Provide for pressure drops at normal flow that are at least three times the initial resistance (clean) or 0.5 in. water gauge, which-

ever is the greater value.

2. High efficiency (from 35 to 95% NBS). Provide for pressure drops at normal flow that are at least three times the initial resistance (clean). Never exceed the manufacturer's recommended limit for pressure drop since this may exceed the strength of the frame.

3. High efficiency, absolute type [99.95%, or better, per dioctyl phthalate (DOP) 0.3 μ smoke testing]. Provide for pressure drops at normal flow that are at least three times the initial resistance (clean), except where preceded by a filter bank of equal efficiency. In such event a resistance allowance of 1.25 times the initial resistance for the second stage of filters affords reasonable life insofar as particulate pickup is concerned.

Sealing faces for filter gaskets must be prepared initially as flat, smooth surfaces accessible for cleaning and inspection. Crack leakage must be eliminated at the sealing face; this is done best by welding all joints with continuous seal welds.

Fan selection. Fan selection must be finalized after all other features of the system are designed and carefully analyzed to anticipate system characteristics. The fan (or fans) must be chosen to match the load and flow characteristics of the system; oversize can be as critical to good system performance as undersize. Designers must respect the importance of proper fan selection to suit both normal and maximum system demands.

REFERENCES

1. W. Milich and E.C. King, *Underwater Disposal of Sodium with EB Nozzle*, MSA Technical Report 40, Mine Safety Appliances Co., 1955.

2. Manufacturing Chemists Association, Inc., *Chemical Safety Data Sheet, SD-47*, 246 Woodward Building, 15th & H Streets, N.W., Washington, D.C., 1952.

3. Frank A. Patty (Ed.), *Industrial Hygiene and Toxicology*, 2nd rev. ed., Vol. II, Interscience Publishers, New York, 1963.

4. *Threshold Limit Values*. American Conference of Governmental Industrial Hygienists, 1014 Broadway, Cincinnati, Ohio.

5. *Documentation of Threshold Limit Values*, rev. ed., American Conference of Governmental Industrial Hygienists, 1014 Broadway, Cincinnati, Ohio, 1966.

6. F. L. Mangold and R. A. Tidball, *Report II on Sodium Leak Detection and Thermal Insulation Tests*, Technical Report 17, Mine Safety Appliances Co., Nov. 1, 1952.

7. W. Milich and E. C. King, *Sodium Leak Detection in Vertical Piping*, Technical Report 34, Mine Safety Appliances Co., Nov. 18, 1954.

8. W. Milich, R. C. Andrews, and E. C. King, *Performance Tests of Thermal Insulation for Sodium Piping*, Memo Report 72, Mine Safety Appliances Co., Dec. 31, 1954.

9. AEC Press Release K-172, General Design Criteria for Nuclear Power Plant Construction Permits, July 10, 1967.

10. M. A. Salmon, *Effects of Tube Leaks in Sodium-Heated Steam Generators*, USAEC Report NAA-SR-8140, Atomics International, Apr. 15, 1963.

11. H. Etherington (Ed.), *Nuclear Engineering Handbook*, 1st ed., McGraw-Hill Book Company, Inc., New York, 1958.

12. David T. Goldman and J. R. Roesser, *Chart of the Nuclides*, Knolls Atomic Power Laboratory, Ninth Edition, July 1966.

13. J. C. Roy and J. J. Hawton, *Table of Estimated Cross Sections for (n,p), (n,α), and (n,2n) Reactions in a Fission Neutron Spectrum*, Canadian Report CRC-1003, December 1960.

14. Brookhaven National Laboratory, *Neutron Cross Sections*, USAEC Report BNL-325 (2nd ed.)(Suppl. 2), Vols. I, IIA, IIB, IIC, III.

15. P. Speigler, *Sodium-24 Specific Activity in HNPF U-Mo and U-C Reactor Systems*, USAEC Report NAA-SR-Memo-3830, Atomics International, May 21, 1956.

16. S. L. Rosen, *Argon Generation in NaK-Cooled Reactors*, USAEC Report NAA-SR-11303, Atomics International, Nov. 10, 1965.

17. Theodore Rockwell III (Ed.), *Reactor Shielding Design Manual*, USAEC Report TID-7004, Division of Reactor Development, Naval Reactors Branch, AEC, March 1956.

18. R. S. Hart and C. T. Nelson, *Fission-Product Retention Characteristics of Sodium at High Temperatures*, USAEC Report NAA-SR-Memo-8712, Atomics International, June 1, 1964.

19. R. J. Begley, Liquid Sodium Absorbs Gaseous Iodine, *Nucleonics*, 20(10): 100 (1962).

20. W. P. Kunkel, *Fission-Product Retention in Sodium: A Summary of Analytical and Experimental Studies at Atomics International*, USAEC Report NAA-SR-11766, Atomics International, Aug. 8, 1966.

21. G. L. O'Neill, J. Duffy, D. B. Sherer, J. C. Gilbertson, and F. W. Knight, *A Technical and Economic Evaluation of Vented Fuel for Sodium-Cooled Fast Ceramic Reactors*, USAEC Report GEAP-4770, General Electric Company, May 1965.

22. A. W. Castleman et al., Fission Product Behavior in Sodium Systems, in *Alkali Metal Coolants*, Symposium Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1967, (STI/PUB/143).

23. A. W. Castleman, Jr. and I. N. Tang, *Thermodynamics of Fission-Product Sodium Solutions*, USAEC Report BNL-11611, Brookhaven National Laboratory.

24. W. P. Kunkel, B. D. Pollock, J. Guon, G. B. Zwetzig, M. Silberberg, and S. Berger, *LMFBR Fission-Product Contamination and Control Studies: A Status Report*, USAEC Report AI-AEC-12687, Atomics International, June 30, 1968.

25. J. Saroul, Investigation of Behavior of Fission Products in Sodium and Argon - PIRANA Experiments, *Proceedings of the International Conference on the Safety of Fast Reactors, Aix-en-Provence, Sept. 19-22, 1967*, G. Denielou (Ed.), Report CONF-670916, Commissariat à l'Energie Atomique, 1967.

26. W. S. Clough, *A Summary of Research and Development Work Carried Out in 1966 in Health and Safety Departments of UKAEA*, British Report AESB-(RP)-M-46, September 1967.

27. R. S. Hart, *Distribution of Fission Product Contamination in the SRE*, Report NAA-SR-6890, Atomics International, March 1962.

28. A. I. Leipunsky et al., Five Years Operating Experience with Reactor BR-5 in *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 6, pp. 51-61, United Nations, New York, 1965.

29. R. E. Mueller et al., Results of Fission-Product Analysis to Determine Extent of Fuel Failure in Fermi Accident, *Trans. Amer. Nucl. Soc.*, 10: 334 (1967).

30. R. R. Mathews, J. L. Phillips, K. J. Henry, R. H. Allardice, D. M. Donaldson, and H. E. Tilbe, Performance and Operation of the Dounreay Fast Reactor, in *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 6, pp. 23-32, United Nations, New York, 1965.

31. J. C. Clifford et al., Behavior of Fission Products in Sodium, in *Alkali Metal Coolants*, Symposium Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/143).

32. Atomics International, *Quarterly Technical Progress Report*, AEC Unclassified Programs, October-December 1967, USAEC Report AI-AEC-12638.

33. J. D. Gracie and J. J. Droher, *A Study of Sodium Fires*, USAEC Report NAA-SR-4883, Atomics International, Oct. 15, 1960.

34. H. C. Cowen and H. Vickers, *The Oxidation of Sodium. A Review of Progress from Apr. 1, 1954 to Dec. 31, 1954*, British Report FRDC/P-105, Apr. 15, 1955.

35. P. B. Longton, *Alkali-Metal-Gas Reactions. Part IX, The Influence of Moisture on the Reaction of Sodium with Oxygen*, British Report IGR-TN/C-535, April 1957.

36. Atomics International, *Annual Technical Progress Report. AEC Unclassified Programs, Fiscal Year 1963*, USAEC Report NAA-SR-888 (Sec. I), p. 144, Apr. 1, 1964.

37. E. Garelis, *Sodium-Air Accident Study for a Sodium-Cooled Reactor*, USAEC Report AECU-4161, Atomic Power Development Associates, Inc., Apr. 6, 1959.

38. Atomics International, *Final Summary Safeguards Report for the Hallam Nuclear Power Facility*, USAEC Report NAA-SR-5700, Apr. 15, 1961.

39. G. N. Lauben, *Initial Experience with Large Sodium Fires Experiments (LF-1)*, USAEC Report NAA-SR-12041, Atomics International, Aug. 1, 1966.

40. Atomics International, *Annual Technical Progress Report. USAEC Unclassified Programs, Fiscal Year 1965*, USAEC Report NAA-SR-11450 (Sect. 7), Nov. 10, 1965.

41. H. H. Gott and G. Flook, The Dounreay Fast Reactor, *Engineering*, pp. 280-282, Aug. 26, 1956.

42. G. N. Lauben and C. L. Larson, Characterization of Source Terms for Aerosol Transport During Sodium Fires, in *Proceedings of the Ninth AEC Air Cleaning Conference, Boston, Sept. 13-16, 1966*, USAEC Report CONF-660904, Vol. 1, pp. 28-48, January 1967.

43. Atomics International, *Quarterly Technical Progress Report. AEC Unclassified Program, January-March 1968*, USAEC Report AI-AEC-12680.

44. H. A. Morewitz, R. L. Koontz, et al., Sodium Burning, Aerosol Generation, and Control of Fission Product Release During an Accident, Part II, *Proceedings of the International Conference on Safety of Fast Reactors, Aix-en-Provence, Sept. 19-22, 1967*, G. Denielou (Ed.), Report CONF-670916, Commissariat à l'Energie Atomique, 1967.

45. F. L. Mangold and R. A. Tidball, *Sodium Fires Studies*, USAEC file No. NP-3812, Mine Safety Appliances Co., Apr. 23, 1952.

46. E. Hines, A. Gemant, and J. K. Kelley, How Strong Must Reactor Housings Be to Contain Na-Air Reactions? *Nucleonics*, 14(10): 38-41 (1956).

47. J. R. Humphreys, Jr., Sodium-

Air Reactions as They Pertain to Reactor Safety and Containment, in *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958*, Vol. 11, pp. 177-185, United Nations, New York, 1958.

48. Argonne National Laboratory, *Reactor Development Program Progress Report, June 1966*, USAEC Report ANL-7230, p. 70, July 27, 1966.

49. Argonne National Laboratory, *Chemical Engineering Division Semiannual Report, January-June 1966*, USAEC Report ANL-7225, Section IV, p. 164, Reactor Safety, November 1966.

50. Atomics International, *Quarterly Technical Progress Report. AEC Unclassified Programs, October-December 1963*, USAEC Report NAA-SR-9339, p. I-C-29, November 15, 1965.

51. S. J. Rogers and W. A. Everson, *Extinguishment of Alkali Metal Fires*, Report APL-TDR-64114, Mine Safety Appliances Co., October 1964.

52. Atomics International, *Quarterly Technical Progress Report. AEC Unclassified Programs, October-December 1966*, USAEC Report NAA-SR-12296, p. 55, Oct. 25, 1967.

53. Atomics International, *Annual Technical Progress Report. AEC Unclassified Programs, Fiscal Year 1966*, USAEC Report NAA-SR-12010, Aug. 31, 1966.

54. Atomics International, *Annual Technical Progress Report. AEC Unclassified Programs, Fiscal Year 1967*, USAEC Report NAA-SR-12492, June 30, 1971.

55. R. L. Koontz et al., *Interim Report FFTF Containment Cleanup and Ventilation Exhaust Filtration Studies*, Report NAA-SR-Memo 12498, in preparation.

56. Division of Reactor Development, AEC, and Harvard University, *Seventh AEC Air Cleaning Conference, Oct. 10-12, 1961, Brookhaven National Laboratory, Upton, N.Y.*, USAEC Report TID-7627. (See especially F. E. Adley and D. E. Wisehart, Life-Loading Tests on Certain Filter Media, pp. 116-126.)

57. B. H. Kornegay, D. K. Jamison, and J. M. Morgan, Jr. (Eds.), *Eighth AEC Air Cleaning Conference, Oct. 22-25, 1963, Oak Ridge National Laboratory, Oak Ridge, Tenn.*, USAEC Report TID-7677, U. S. Atomic Energy Commission.

58. R. Dennis, E. Kristal, and L. Silverman, *Fibrous Filters for NaK Fume Removal*, USAEC Report NYO-4811, Harvard University, May 1, 1960.

59. P. Himot, F. J. Viles, Jr., J. Sullivan, and M. W. First, Sodium Aerosol and Its Filtration, in *Proceedings of the Ninth AEC Air Cleaning Conference, Boston, Sept. 13-16, 1967*, USAEC Report CONF-660904, Vol. 2, pp. 887-904, January 1967.

60. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., *Guide and Data Book*, Vol. 1, Fundamental and Equipment, New York, 1963.

61. G. Humphrey and J. H. Palmer, *Inspection, Storage, Handling, and Installation of High-Efficiency Particulate Air Filter Units*, USAEC Report TID-7023, U. S. Atomic Energy Commission.

62. United States of America Standards Institute, *Fundamentals Covering the Design and Operation of Local Exhaust Systems*, A2A-29.2, 1960.

Chapter 3

Handling

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3-1 INTRODUCTION

The use of sodium or NaK as a heat-transfer fluid necessitates the development of special precautions and procedures since both sodium and NaK react violently with moisture, oxygen, and a variety of other chemical compounds. This chapter reviews the methods developed for handling sodium and NaK from procurement to disposal.

The sections of this chapter are developed on the assumption that personnel performing the various operations are familiar with the hazards involved in handling sodium and NaK. Liberal reference is made to sections of Chap. 2 on special hazards, clothing requirements, and training, but repetition is avoided. Chapter 2 should be consulted for familiarization with (1) hazards associated with handling sodium and NaK, (2) training requirements, and (3) protective clothing.

3-2 PROCUREMENT AND SHIPPING

3-2.1 *Sodium Procurement*

Sodium is produced commercially by the electrolysis of molten sodium chloride admixed with calcium chloride to lower the melting point of the mixture. (See Refs. 1 to 3 for a detailed description of the process.) Sodium is presently manufactured by E.I. du Pont de Nemours & Co., Inc.; Ethyl Corp.; and National Distillers & Chemical Corp. [4]. The American production rate has increased from 18 million pounds in 1941 to 327 million pounds in 1966 [4,5].

Sodium is manufactured in two standard grades, regular and a special reactor grade. The principal difference between the two is that the reactor grade has a lower calcium content. Typical and maximum impurity levels are presented in Table 3.1. The price of sodium dropped steadily from \$29/lb in 1860 to 16¢/lb in 1937. Since 1937 the price has remained relatively firm at 17 to 21¢/lb plus freight [5,6]. Reactor-grade sodium, which is filtered through porous metallic filters and blanketed in argon all the way from the electrolytic cell in which it is produced to the container in which it is shipped, costs about 4¢/lb more than regular-grade sodium.

TABLE 3.1 - Chemical Analysis of Commercially Available Sodium

Impurity	Typical levels, ppm		Maximum levels [10], ppm	
	Ref. 8	Ref. 9	Reactor grade	Regular grade
Aluminum	8	1 to 4		
Antimony			<10	
Barium	2	-		
Beryllium	1*	-		
Bismuth	10*	-		
Boron	4	0.1 to 2.0	<1	
Cadmium	1	<0.05	<2	
Calcium (reg.)	190	200		<400
Calcium (reac.)	-	2 to 8	<20	
Carbon			<30	30 to 50
Cerium	2	-		
Cesium	5	5	<15	
Chlorides	30	30	<50	<50
Cobalt	2	0.11 to 0.21	<1	
Copper	2	-	<10	
Dysprosium	-	-	<0.02	
Europium	-	-	<0.2	
Gadolinium	-	-	<0.02	
Gold	-	<2		
Indium	2	7 to 13	<25	
Iron	2		<10	
Lead	1	≤1	<7	
Lithium	17	<0.06 to 0.36	<5	
Magnesium	5	-		
Manganese	2	-	<5	
Mercury	4*	-	<35	
Molybdenum	2*	-		
Nickel	2	-	<5	
Nitrogen	-	<3		
Oxygen			<100	150 to 250
Palladium	5*	-		
Phosphorus	10	<1		
Potassium	100	86 to 180	150	
Rare earths	-	4		
Rhenium			<100	
Rhodium			<30	
Samarium			<0.2	
Silicon	5	-		

TABLE 3.1 - Chemical Analysis of Commercially Available Sodium (Continued)

Impurity	Typical levels, ppm		Maximum levels [10], ppm	
	Ref. 8	Ref. 9	Reactor grade	Regular grade
Silver	1	<2	<15	
Strontium	5	-		
Sulfur	14	1 to 6	<100	
Tantalum			<5	
Tin	10*	≤1		
Titanium	10*	-		
Tungsten	-	3 to 7		
Uranium	5	-		
Vanadium	4	-		
Zinc	-	2 to 5		
Zirconium Hafnium	-	2		

*Analyses made but none detected. Values given are limit of sensitivity of method used.

Various other grades and purities are available from the three manufacturers named and from a number of other chemical companies who purchase sodium from one of these three and further purify it for resale.

3-2.2 *NaK Procurement*

Sodium-potassium alloys are produced commercially by the distillation of the reaction products of potassium chloride and sodium [7]. The term "NaK" (pronounced "nack") is widely used to designate these alloys. The percentage composition of NaK is normally given in terms of potassium, the more expensive metal; i.e., NaK-78 is 78% potassium and 22% sodium. The only manufacturer presently producing NaK is the Mine Safety Appliances Company at their MSA Research Corp. Two grades of NaK are available, commercial and high purity.

Commercial-grade NaK is available in any composition desired. It has a purity of 99+% and a composition tolerance of ±1%. Heavy metals are present in the low parts-per-million range. Oxygen, carbon, and calcium may be present as impurities in hundreds of parts per million. A composition phase diagram for NaK is included in Vol. I, Chap. 2.

High-purity NaK is available in only one standard composition, 78% K-22% Na. Other compositions are available on a batch basis. The specifications for high-purity NaK are:

Potassium	Eutectic NaK: 78 wt.% with +0, -1 wt.% tolerance Other NaK alloys: ±1 wt.% tolerance
Oxygen	<50 ppm
Carbon	<50 ppm

3-2.3 *Shipping Regulations*

Shipping regulations classify sodium and NaK as "nonexempt flammable solids." Therefore the transportation of sodium and NaK in interstate commerce by land or water is subject to the "Dangerous Articles" regulations of the Interstate Commerce Commission (ICC). The ICC does not issue separate regulations applying specifically to shipments of sodium or NaK (or to any other commodity). The complete regulations covering the packaging, labeling, and transportation of dangerous articles are published in Title 49, Parts 71 to 78 and 190 to 197, *Code of Federal Regulations*. Amendments subsequent to the most recent revision can be obtained from the daily issues of the *Federal Register*.

The ICC regulations are also published by the

Bureau of Explosives of the Association of American Railroads
T.C. George, Agent
63 Vesey Street, New York, N.Y. 10007

under the title, Tariff 19, Publishing Interstate Commerce Commission Regulations for Transportation of Explosives and Other Dangerous Articles...
and by the

Tariff Bureau of the American Trucking Associations, Inc.
F.G. Freund, Agent
1616 P Street, N.W., Washington, D.C. 20036

under the title, Motor Carriers' Explosive and Dangerous Articles Tariff No. 12.

Transportation of sodium and NaK in civil aircraft is regulated by the Federal Aviation Agency (FAA). Applicable regulations are published in Title 14, Part 103, *Code of Federal Regulations*. Part 103, Transportation of Dangerous Articles and Magnetized Materials, is published separately. In addition to FAA regulations, individual airlines further restrict the conditions under which they will accept sodium and NaK for transportation. A compilation of these restrictions is issued as Official Air Transport Restricted Articles Tariff by

J. Aniello, Agent
Air Traffic Conference of America
Washington, D.C.

Air transport is presently restricted to solid sodium or NaK in quantities of 25 lb or less in nonpassenger aircraft.

Transportation of sodium and NaK by water is subject to regulations prescribed by the Commandant of the U.S. Coast Guard. Current regulations applicable to sodium and NaK appear in Title 46, Parts 146 to 149, *Code of Federal Regulations*, as amended. The coast guard regulations covering transportation, storage, or stowage of dangerous articles on ships are also published by T.C. George as a Water Carrier Tariff. The transportation of sodium or NaK in the U.S. mails is presently prohibited by the *U.S. Postal Guide*.

The regulations issued by the coast guard and FAA embody the packaging and labeling requirements of the ICC.

Intrastate shipments of sodium and NaK are not subject to ICC regulations, but they must meet the requirements of any state or local regulations. Persons desiring to export sodium or NaK should determine what regulations apply to such shipments in the countries to which they are made.

The ICC, FAA, and coast guard regulations cited apply to radioactive as well as nonradioactive sodium or NaK. In addition, the U.S. Atomic Energy Commission (AEC) has issued regulations governing: (1) the transportation of high-level radioactive materials and (2) the transportation of radioactive materials when the shipments are not subject to ICC regulations. These regulations are published in Title 10, Part 71, *Code of Federal Regulations*, for AEC licensees and in Chap. 0529 of the AEC *Manual* for AEC contractors.

The International Atomic Energy Agency (IAEA) established regulations for the international transport of radioactive materials [11,12]. All aspects of these regulations have not been adopted yet, however, and exporters must verify what regulations apply in the country where the shipment is to be made.

3-2.4 *Shipping Containers*

The first requirement of any shipping container is that it meet the ICC regulations. The various suppliers have adopted a variety of standard containers capable of meeting these requirements.

Commercial- and reactor-grade sodium is shipped in 80,000-lb-net tank cars; in 230- and 420-lb-net returnable drums; and in 290-lb-net returnable barrels packed with 1-, 2 1/2-, 5-, or 12 1/2-lb bricks.

The tank cars are filled under a nitrogen, helium, or argon blanket with liquefied sodium and are equipped with coils used to fuse the sodium prior to shipment and to remelt the sodium at its destination. The sodium is unloaded by vacuum or pressure.

The drums are filled with liquefied sodium under nitrogen or other specified inert-gas blanket. The sodium solidifies when it cools, and the drums are unloaded by using an electric drum heater to melt the sodium, and gravity, pressure, or vacuum to drain it.

Smaller quantities of commercial- and reactor-grade sodium are shipped in wooden cases of 100 lb net (ten 10-lb tins each containing four 2 1/2-lb bricks), 50 lb net (two 25-lb-net steel pails of 2 1/2- or 1-lb bricks), and a variety of smaller sizes down to 1-lb hermetically sealed cans.

Commercial- and high-purity-grade NaK is available in standard containers of 3, 10, 25, and 200 lb. High-purity NaK is shipped in the stainless-steel containers shown in Fig. 3.1 with a nitrogen or helium cover gas. These containers are equipped with bellows-sealed valves, fill caps, and special fittings to minimize the possibility of contamination during filling, shipping, and discharging. Commercial-grade NaK is shipped in similar mild-steel containers. Ampoules of NaK are also available.

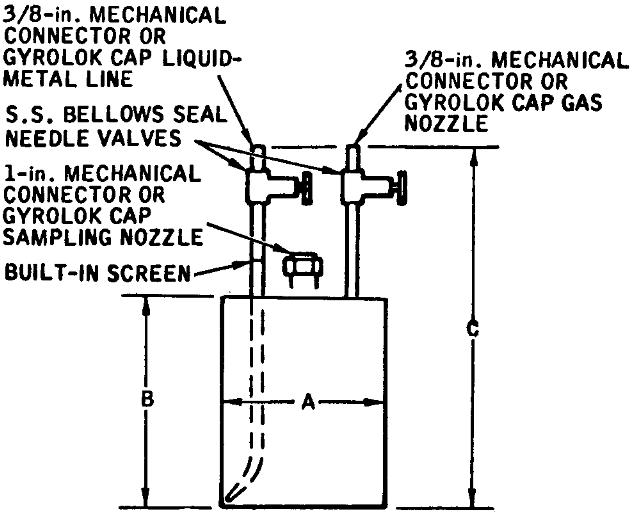


Fig. 3.1 Shipping container for high-purity NaK.

Capacity, lb	Dimensions, in. A	B	C	Shipping weight, lb
3	$6\frac{1}{8}$	8	$14\frac{1}{2}$	25
10	$8\frac{1}{8}$	10	$16\frac{1}{2}$	35
25	$10\frac{1}{8}$	15	$21\frac{1}{2}$	70
200	21	$29\frac{5}{8}$	$34\frac{1}{2}$	425

All grades of sodium and NaK are available from the various suppliers in nonstandard quantities. Nonstandard quantities are shipped in partially full standard containers or in special containers. Any special containers must meet ICC regulations.

3-3 STORAGE

3-3.1 *Introduction*

Sodium and NaK are commonly stored in their shipping containers until they are used or transferred into a system. Proper safety precautions for the storage of these containers minimize the possibility of fire and resultant injury to personnel, damage to equipment, and loss of the valuable liquid metal. Precautions for the storage of bulk quantities of sodium or NaK in barrels and tins are discussed in Sec. 3-3.2. Tank-car storage is discussed in Sec. 3-3.3, and provisions for storage in liquid-metal systems are discussed in Sec. 3-3.4.

3-3.2 *Bulk Storage*

Areas used for the storage of barrels and tins of sodium and NaK should offer isolation, moisture and fire protection, and provisions for removing any hydrogen that may be generated.

(a) *Isolation*

Sodium and NaK should be stored in isolated areas. Liquid-metal-storage areas should not be used for storing anything other than liquid metals and liquid-metal containers awaiting cleaning or return to the supplier. Isolation can be obtained by providing, in order of decreasing preference:

1. An isolated building.
2. A separate room - preferably with no doors into the main building and with fireproof walls separating the storage area from other areas.
3. A separate area in a room; fireproof partitions or yellow lines on the floor are advisable for isolating the area.
4. A separate flammables-storage cabinet with appropriate markings.

Sodium and NaK should never be stored in the vicinity of water, oxidizing agents or other substances that react with sodium.

(b) *Moisture Protection*

Moisture protection should be provided to minimize the possibility of a sodium fire and resultant hydrogen generation. The building should be waterproof, and there should be no sprinkler system, water pipes, or steam lines in the storage area. The floor should be elevated, with steps at the doorways, to prevent water from entering, and all openings should be leakproof. The building or room should be heated with nonopen-flame heaters to prevent the condensation of water due to changing atmospheric conditions. Metal covers should extend a few inches down the side of the container to prevent condensing or leaking water from dripping on the contents of the container.

Drums containing sodium or NaK should be raised off the floor on blocks or grates to allow visual checks for leaks and corrosion. Drip pans are also advisable to catch and keep dripping sodium or NaK off a concrete floor. Burning sodium has been known to react with and spall concrete, further spreading the fire.

(c) *Fire Protection*

Fire extinguishers suitable for liquid-metal fires should be provided in the area. Provisions should be included to keep dry-powder extinguishants dry. Notices should be conspicuously posted warning that sodium and/or NaK are stored in the area and that water, carbon dioxide, carbon tetrachloride, and acid-type fire extinguishers are not to be used. Extinguishers of these types should be excluded from the storage area.

(d) *Hydrogen Considerations*

Provisions must be incorporated to prevent hydrogen explosions if water does react with the sodium or NaK. Continuously operating power ventilators should be provided to remove hydrogen if it is generated. Smoking and open flames should be prohibited or restricted in the area. All lights, switches, motors, and other electrical equipment should be explosion proof to prevent possible arcing and a resulting explosion if hydrogen does accumulate.

3-3.3 *Tank-Car Storage*

Sodium received in tank cars is stored in the cars until it is transferred into a system. Tank cars are also used as system storage tanks in many applications. Provisions for storage in tank cars are quite similar to those for barrel storage.

Tank cars containing sodium should be isolated as much as possible and should not be stored near bulk supplies of water, oxidizing agents, or other materials that react with sodium. Tank cars offer considerable moisture protection, but, if they are to be used as system storage tanks or are to occupy an area on a regular basis, protective covers are desirable. Sprinkler systems, water pipes, and steam lines should be excluded from tank-car storage areas. The fire protection provisions mentioned in Sec. 3-3.2 apply in their entirety. Smoking and open flames should also be prohibited in tank-car storage areas. The use of tank cars as storage tanks allows all transferring operations to be performed with permanent piping under an inert atmosphere.

3-3.4 *System Storage Provisions*

Provisions for storing sodium or NaK in system storage tanks are very similar to those for bulk storage in drums. Large-scale storage of sodium in outdoor heated tanks is acceptable, but in most cases indoor or protected storage is preferred. In addition to the storage provisions outlined previously, an inert cover gas must be employed in a system storage tank.

If the storage tank is connected to a radioactive-sodium or -NaK system, additional provisions are required. Storage tanks in radioactive systems must be shielded to protect personnel from the highly radioactive sodium or potassium isotopes. Storage tanks for radioactive sodium and NaK are commonly placed in special metal-lined concrete vaults. Inert, moisture-free atmospheres are maintained in these vaults, and the vault exhaust is usually routed through shielded, high-efficiency filters. The concrete provides the shielding necessary to protect personnel; the inert atmosphere minimizes the fire danger and potential spread of radioactive contamination; and the filters stop most of the contamination resulting from any spills or leaks.

3-4 COVER GAS

3-4.1 *Introduction*

Cover gases are commonly used to protect sodium and NaK from exposure to the atmosphere. This section deals with the selection and handling of cover gases.

Nitrogen, argon, and helium are normally used as cover gases for sodium and NaK systems. Table 3.2 gives a brief listing of the physical properties of these gases [13]. The other rare gases are acceptable but are more expensive and less readily available. Carbon dioxide or carbon monoxide should not be used since at high temperatures they react with the alkali metals.

3-4.2 *Contaminants*

The impurities of concern in cover-gas applications are oxygen, hydrogen, water vapor, hydrocarbons, and, to a lesser extent, carbon monoxide and carbon dioxide. The permissible amount of each contaminant in the cover gas is determined by system design, system application, and the quantity of gas used.

The most common and troublesome contaminant is oxygen. As discussed earlier, oxygen causes corrosion and increased oxide plugging. In determining the allowable oxygen content in the cover gas, the following factors must be considered: (1) the more gas used, the more highly purified it must be, and (2) a system with a cold trap or high allowable oxide content can tolerate a lower purity gas.

Hydrogen is of concern because of

TABLE 3.2 - Physical Properties of Normally Accepted Inert Gases for Sodium Service*

Property	Helium	Nitrogen	Argon
Molecular weight [14]	4.003	28.007	39.948
Density			
0°C and 760 mm Hg (g/liter)	0.1785	1.25049	1.785
70°F at 1 atm (lb/cu ft)	0.01034	0.07246	0.1034
Melting point (1 atm)			
°C	-227.1	-209.9	-189.2
°F	-457.8	-345.8	-308.5
Boiling point (1 atm)			
°C	-268.92	-195.81	-185.86
°F	-452.06	-320.46	-302.55
Critical temperature			
°C	-267.95	-147.16	-122.46
°F	-450.31	-232.89	-188.39
Critical pressure (atm)	2.261	33.5	48.0
Specific heat (cal/g or Btu/lb)			
70°F (C_p)	1.248	0.2477 (60°F)	0.1252
60°F (C_v)	0.752	0.1765	0.075
Thermal conductivity			
cal/(sec)(cm^2)(°C/cm)†	339. × 10^{-6}	60.4 × 10^{-6}	38.4 × 10^{-6}
32°F Btu/(hr)(sq ft)(°F/ft)	0.082	0.01462 (60°F)	0.00928

*Data from The Matheson Co., Inc., *Matheson Gas Data Book*, 4th ed., East Rutherford, N.J., 1966.

†Converted from following: conversion factor 4.1336 × 10^{-3}[cal/(sec)(cm^2)(°C/cm)]/[Btu/(hr)(sq ft)(°F/ft)].

the formation of sodium hydride, which has a limited solubility in sodium and can plug small openings (i.e., orifices, filters, etc.). In reactors where the flux spectrum is above the thermal energy level, excessive sodium hydride can cause unwanted reactivity excursions by acting as a neutron moderator. In general, however, hydrogen is not present in large quantities in the gases used for cover-gas applications.

Water vapor is of concern since it is a source of both oxygen and hydrogen. The sodium (or potassium) hydroxide formed breaks down to give sodium oxide and the hydride. As such, the impurity content can usually be determined on the basis of the individual impurities.

The presence of hydrocarbons in the cover gas is undesirable since they "crack" at high temperature. Such cracking adds carbon and thus carburizes structural materials. Hydrocarbons are present in very minute quantities in commercial gases and would be of concern only in a system with thin members subjected to cycled strains.

For systems with critical limitations on impurities, high-purity gases are recommended. In these gases, which are supplied by most gas producers, total impurities are limited to approximately 50 ppm, the bulk being oxygen.

In general, high-purity gases are

"water pumped"; i.e., the compressor is water lubricated rather than oil lubricated. This type of compression is advantageous since as an impurity water is easier to detect and remove than are hydrocarbons. For the rare cases requiring gases of higher purity, the gas purification equipment should be part of the system. Gases of ultrahigh purity (<10 ppm) are obtainable [14] but are difficult to handle and transfer without adding undue atmospheric contaminants. (Consult Sec. 3-4.4 for purification techniques.)

There have been some developmental efforts to relax gas-purity requirements [15-18]. Sodium systems were operated with cover-gas oxygen impurity levels of 2%. The results of these tests indicated that operating with high impurity levels is impractical. The difficulties caused by the impurities generally outweigh the gas-handling simplifications possible with the lower-purity cover gas.

3-4.3 *Advantages and Disadvantages of Different Gases*

The choice of the proper inert gas for a particular system is not always clear-cut. Nitrogen is the least expensive and thus the most commonly used cover gas. However, the desirability of using nitrogen as a cover gas is uncertain (see Vol. V, Chap. 2). There is no positive evidence that high-purity nitrogen will nitride stainless steel, but there is evidence that impure nitrogen will do so [16]. Nitrogen reacts with lithium and zirconium at elevated temperature [18-20] and forms nitrides [21] with titanium, cobalt, chromium, molybdenum, and many other elements. The full effect of nitrogen on stainless steel is unknown at present. This uncertainty limits the use of nitrogen as a cover gas in high-temperature systems.

Helium is considered inert under all conditions with all structural materials, but it is expensive. Helium is considerably lighter than oxygen or air and as a result is not a particularly good cover over open pools of sodium. The small size of the helium atom, coupled with its buoyancy, also increases leakage in a helium cover-gas system. Increased leakage increases usage and further amplifies cost differential between helium and the other gases. Because it does not become radioactive and is completely inert, helium has been chosen as the cover gas for the Sodium Reactor Experiment (SRE), the Hallam Nuclear Power Facility (HNPF), and several SNAP reactors.

Operation of the SRE revealed a "period spike" phenomenon attributed to the presence of gas bubbles in the sodium [22]. Although it was never positively verified, the cause was believed to have been temperature-induced differential solubility effects. The cover gases under study (N_2, He, Ar) are not particularly soluble in sodium, but, as solubility increases with decreasing atomic weight, helium is considerably more soluble than argon [23]. Therefore argon may be preferred to helium.

Argon is also considered inert to structural materials at all temperatures but does become quite radioactive in a reactor system. Nitrogen-15 also becomes radioactive, but it is not very abundant, has a very short half-life (7.1 sec), and presents little radiological problem. Table 3.3 lists briefly the nuclear properties of the subject gases.

Radiological considerations necessitate the use of a gas holdup system and an appropriate monitoring system for a reactor cover gas. The possibility of fuel-element leakage or the use of vented fuel elements with the resulting release of fission-product gases necessitates a holdup system in reactor cover-gas systems. Therefore, for the radiological considerations involved in handling cover-gas leakage, the fact that argon is used does not increase the system complexity. Since the density of argon is greater than the density of oxygen or air, it tends

TABLE 3.3 - Nuclear Properties of Normally Accepted Inert Gases for Sodium Service [24]

Isotope	Abundance [25], %	Absorption	Cross-section scattering, barns	Total, barns	Neutron energy, ev	Remarks
Helium	100		2.0		0.025	
^{3}He	1.3×10^{-4}	5327 barns			thermal	(n,γ) reaction to ^{4}He
^{4}He	∿100	<50 mb				(n,p) reaction to ^{3}H
Nitrogen	100	1.85 barns	10.5	12.3	0.025	
^{14}N	99.63	1.89 barns			thermal	(n,γ) reaction to ^{15}N (n,p) reaction to ^{14}C
^{15}N	0.37	0.08 mb			thermal	(n,γ) reaction to ^{16}N
Argon	100	0.63 barn	0.75	1.4	0.025	
^{36}Ar	0.337	5.5 mb			thermal	(n,γ) reaction to ^{37}Ar
^{38}Ar	0.063	0.8 barn			thermal	(n,γ) reaction to ^{39}Ar
^{40}Ar	99.6	0.61 barn			thermal	(n,γ) reaction to ^{41}Ar

to form a cover over a pool of sodium in the presence of air or oxygen. This allows the removal of components or equipment from a sodium or NaK system with a minimum of contamination to the system. Cover-gas leakage (and gas usage) are lower with argon than with helium or nitrogen because of the large physical size and lower mobility of the argon atom. Argon has been selected as the cover gas for the Experimental Breeder Reactor No. II (EBR-II) and the Enrico Fermi Atomic Power Plant (EFAPP).

Specific system and nuclear reactor considerations must be known before it can be determined which gas is preferred and what gas purity levels are required.

3-4.4 *Purification*

Helium, argon, and nitrogen are purchased to the guaranteed purity levels reported in Table 3.4. These specifications exceed those required for most cover-gas applications and for transferring liquid-metal charges between loop components. Argon and nitrogen are manufactured to a higher purity than is reported in Table 3.4 by liquefaction and rectification of air. Some of the newer plants handle the products as liquids that do not require further drying. If water-lubricated pumps are required in filling high-pressure containers, the gas is usually dried by passing it over activated

TABLE 3.4 - Commercial Guaranteed Specifications* for Helium, Argon, and Nitrogen

	Helium	Argon	Nitrogen
Purity, min. %	99.995	99.995	99.98
Impurities, ppm			
Oxygen	<5	<1	<15
Hydrogen	<1	<1	<1
Nitrogen	<14	<3.2	-
Carbon†	<0.03	<0.04	<0.03
Methane	<1	<2.1	-
Carbon dioxide	<1	-	<1
Krypton	<0.02	<0.8	<1.3
Argon	<2	-	-
Moisture	<2	<1	<1.5
Total gas impurities, max. %	0.005	0.005	0.02

*Data from The Matheson Co., Inc., *Matheson Gas Data Book*, East Rutherford, N.J., 1966; and from Air Reduction Co., Inc., Vernon, Calif., April 1967.

†All forms other than those listed.

alumina at high pressure.

Purification is usually required if the inert gas is to be used in sodium- or NaK-sampling operations or if the gas has become contaminated during shipping. Purification may also be required if the operating system is not relatively clean. Numerous purification techniques are available. One common technique uses the gettering characteristics of NaK to remove oxygen and water vapor [20,26,27] from the cover gas. The cover gas is passed through NaK purification towers operating at 600 to 700°F. Alternate approaches bubble the gas through a hot tower operating at ∿350°F and a cold tower operating at ∿70°F. Vapor and entrainment traps are required to prevent carryover of NaK into the pure-gas system. Bubbling gas through calcium-packed tubes operating at ∿600°C is also a common technique [20,28,29] for oxygen gettering. Temperature control is sensitive in this process owing to operation near the melting point of calcium (810°C). Commercial desiccants for water-vapor removal and heated copper or uranium metal turnings for oxygen removal are also common [30]. Adequate water-vapor capacity is usually a problem with commercial desiccants for large systems. The use of uranium metal turnings presents a slight radiological hazard.

If drying is required, passing the gas over activated alumina at atmospheric or high pressure easily lowers the moisture content to below a dew point of -76°F. Liquid-nitrogen-cooled traps are sometimes used as gas dryers in small cover-gas systems.

Systems are also available for providing extremely high-purity gases. Activated synthetic Zeolite systems are capable of reducing moisture content to less than 1 ppm [31]. The Zeolite is also very effective in removing carbon dioxide and some hydrocarbons. Zeolite is regeneratable and has a relatively high capacity for water vapor, ∿2% by volume. Purification towers containing titanium sponge and operating at ∿1525°F are very effective in removing the reactive gases (i.e., oxygen, nitrogen, carbon monoxide, and light hydrocarbons) from helium or argon. They are, of course, useless in a nitrogen system but are capable of providing very pure helium or argon [31].

Extremely high-purity gases or purification systems capable of providing extremely pure gases are almost worthless if system cleanliness is ignored. Maintaining gas purity rests with the system. If system cleanliness is ignored during design, fabrication, and operation, gas purity cannot be maintained. The designer must select materials that can be easily cleaned and degreased [31]. Fabrication practices and cleanliness must be consistent with the end-result purity requirement. Operation must be such as to prevent contamination of the system.

3-4.5 *Gas Sampling*

Gas sampling is required on at least an occasional basis in any cover-gas system to ensure that the desired gas-purity level is really being achieved. Gas sampling can be performed with on-line instrumentation or by removing a sample for chemical analysis. Obtaining and encapsulating gas samples for subsequent chemical analysis is the subject of this section. On-line gas sampling and the chemical analysis of cover-gas samples once they have been obtained are discussed in Vol. I, Chap. 2.

The importance of obtaining a representative sample cannot be overemphasized. A nonrepresentative or contaminated sample makes subsequent analysis worthless. The three common techniques for collecting gas samples are liquid displacement, flow through, and vacuum expansion.

(a) *Liquid-Displacement Samplers*

Liquid-displacement techniques are relatively simple. A typical liquid-displacement sampling system is shown schematically in Fig. 3.2. The cover-gas sample is obtained by using cover-gas system pressure to displace a portion of the liquid in the jar. Contamination of the sample is prevented by sealing the jar before removing it from the tank. Mercury is the preferred displacement liquid. Water and many aqueous solutions are also used, but their use should be avoided in accurate work because of the possibility of preferential dissolution of gas impurities. It is also advisable to purge the sample hose thoroughly before initiating sample collection.

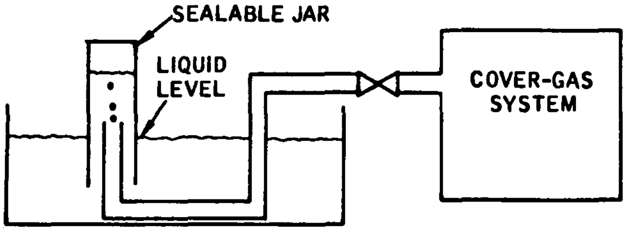


Fig. 3.2 Schematic diagram of liquid-displacement sampler.

(b) *Flow-Through Samplers*

A schematic diagram of a flow-through sampler is shown in Fig. 3.3. When a sample is desired, all the sample system valves are opened, and the cover gas is allowed to flow through the sample container to thoroughly purge out any re-

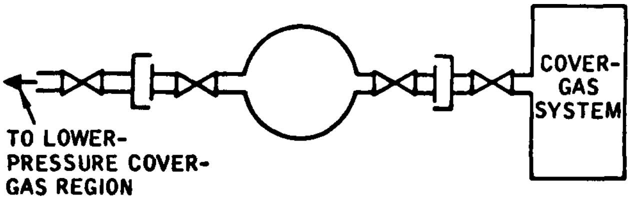
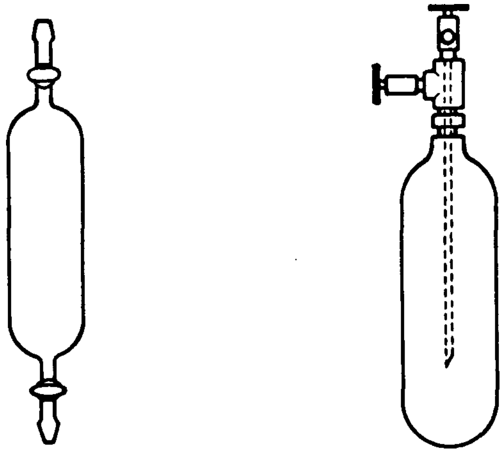


Fig. 3.3 Schematic diagram of flow-through gas sampler.

sidual gases. Ten to fifty volume changes are generally sufficient; but this should be determined from the sample container volume, gas flow rate, and desired accuracy. After adequate purging is completed all valves are closed, and the sample container is removed for analysis. Flow-through sample containers are usually made of glass or metal with valves at both ends, but metal containers with reentrant tubes may also be used (see Fig. 3.4). Care must be exercised in the choice of containers to be sure they are absolutely clean and the valves do not leak. Materials that absorb gases should be avoided in the selection of container and valve materials, lubricants, and packings. If the cover-gas system is operated at a negative pressure or at so low a pressure that sampling requires an excessive time to purge the container, a vacuum pump or gas compressor can be used to increase the flow rate.



FLOW-THROUGH GAS SAMPLE TUBE

STEEL GAS SAMPLE VESSEL EQUIPPED WITH RE-ENTRANT TUBE

Fig. 3.4 Flow-through sample containers.

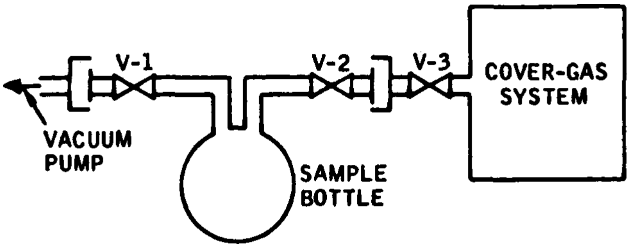


Fig. 3.5 Schematic diagram of vacuum sampler.

(c) *Vacuum-Expansion Sampling*

The vacuum-expansion technique is shown schematically in Fig. 3.5. Valve V-3 is closed, and valves V-1 and V-2 are opened to obtain a sample. After the sample bottle is evacuated, valve V-1 is closed and V-3 is opened. A short time, ∿2 min, is allowed for filling, and then valves V-2 and V-3 are closed, and the sample is removed for analysis. Modifications of this procedure include multiple inert-gas-vacuum purges or heating of the sample bottle to drive off gases before taking a sample. Sample containers are usually made of steel. Container valves must not leak, and the container must be carefully cleaned before use.

Of the three sampling techniques, flow through and vacuum expansion are generally preferred for system cover-gas sampling. These two techniques (1) are more adaptable to the use of metal containers and permanent plumbing installations, (2) do not require an extra fluid, and (3) are adaptable to sampling a low- or negative-pressure system. Purging of the sample container and sample-system plumbing is also simpler with the latter two techniques. Any of these procedures is adaptable to sampling radioactive gases if the exhaust gases are routed back into the system or into a holdup system.

3-4.6 *Liquid Storage*

The preceding development is based on storage of inert gases as gas in high-pressure cylinders. Inert gases can also be stored as liquid and then converted to gas for use as required. Storage of argon and nitrogen as liquid for use in cover-gas systems is quite common. Liquid storage of helium for cover-gas applications is not practical because of the extremely low temperature required (∿0°K) and the costs incurred in helium liquefaction, shipping, and storage. When liquid storage systems are used, liquefied gas is purchased in tank-truck quantities and stored under moderate pressure in double-walled tanks connected to the cover-gas system (see Fig. 3.6). On an as-required basis the gas is vaporized and pumped or pushed into the cover-gas piping. In high-pressure cover-gas systems, compressors are used to pump new gas into the system. In low-to-moderate-pressure systems, the storage tank is maintained at a higher pressure than the system, and this differential can be used to push new gas into the system. Liquid storage presents certain advantages over high-pressure gas storage:

1. Liquefied gases are considerably cheaper than bottled gases.
2. The physical handling of large quantities of gas is simplified with liquid storage.

3-4.7 *Availability*

Liquid and gaseous argon, nitrogen, and helium are widely available commercially throughout the United States. Until 1961 the government restricted the production of helium, the Bureau of Mines being the sole supplier in the United States [32]. Since 1962 private industry has been allowed to produce helium. Principal producers [32] are the Bureau of Mines, Amarillo, Tex.; Kerr-McGee Chemical Corp., Navajo, Ariz.; and Air Reduction Co. Inc., Otis, Kans. Helium gas is shipped in tank-car quantities directly to the consumer or to wholesalers who transfer it to smaller cylinders and stockpile it according to customer requirements. Most wholesale suppliers of argon and nitrogen also furnish helium procured from the principal helium producers. Liquid helium is also available, generally from the same sources, but its use is still rather specialized.

3-4.8 *Inert-Gas Generators*

Inert gas produced by so-called inert-gas generators can be used instead of commercial bottled or liquefied gas. Commercially available inert-gas generators use the liquefaction and rectification process used in manufac-

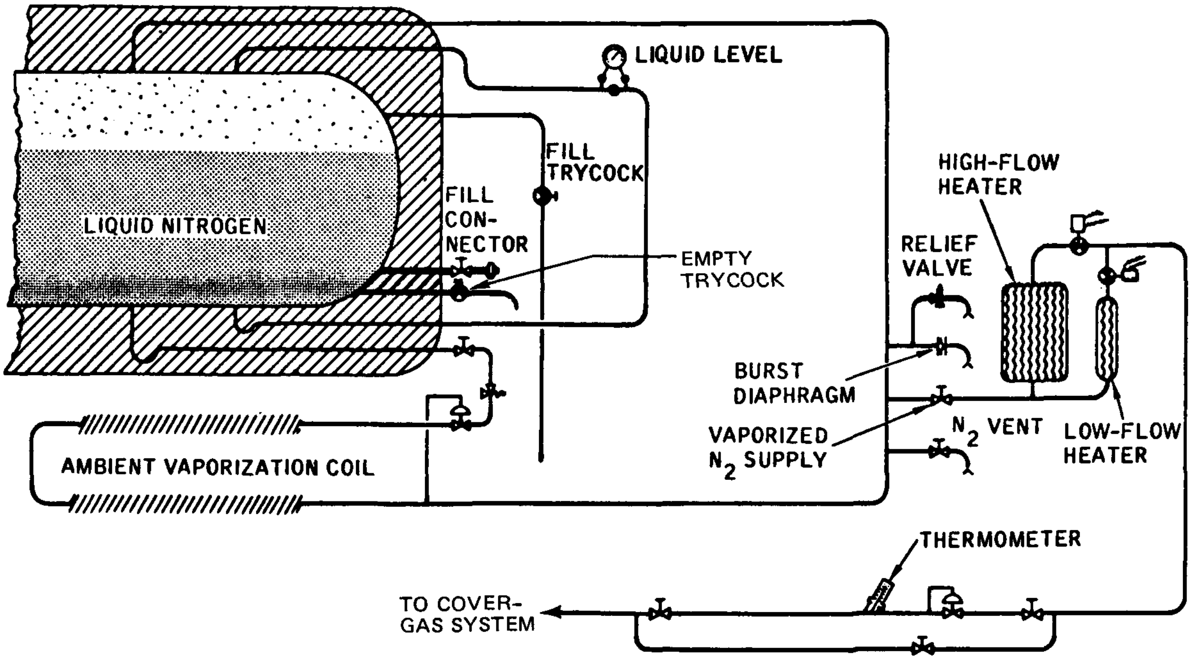


Fig. 3.6 Schematic diagram of liquid-nitrogen system.

turing commercial bottled gas. These units are capable of producing gas (argon and nitrogen) of any desired purity. Inert-gas generators that burn natural gas or fuel oil in air and then purify the resulting gas by absorbing carbon dioxide and moisture are also available. The resulting gas is primarily nitrogen but contains other inert gases present in air.

Commercial units that meet the following specifications are available:

	Nitrogen generator [33]	Inert-gas generator [34]
Nitrogen (and argon), minimum purity	99+%	85+%
Oxygen	<15 ppm	<0.02%
Hydrogen	0.5 max.%	0.6 max.%
Carbon dioxide	<20 ppm	<12.5%
Carbon monoxide	0.5 max.%	0.6 max.%
Moisture, dew point	-80°F	-80°F

After purification in the carbon dioxide scrubbing tower, the inert gas is generally dried by an activated alumina or silica-gel tower.

Inert gas of any required purity can be obtained from these inert-gas generators depending on the balance between initial cost, size, weight, operating cost, and capacity.

3-5 MATERIAL-EXPOSURE FACILITIES

3-5.1 *Introduction*

Removable samples of structural or other system materials are frequently installed in sodium or NaK systems to permit early evaluation of corrosion or mass-transfer rates or effects. These may be especially useful in nuclear reactor systems where material failures can lead to the complete loss of equipment and require expensive decontamination of entire facilities. The samples are exposed in a specially provided side loop where temperature and flow conditions can be controlled to simulate the actual environment seen by the material or structure concerned. Material samples can be reclaimed from the exposure facility on a periodic basis. Any attack by the coolant should be reflected by the condition of the material samples.

Material exposure facilities designed for sodium systems are described in Secs. 3-5.2 and 3-5.3; these can be adapted to NaK systems. The pre- and postexposure handling of samples is discussed in Sec. 3-5.4.

3-5.2 *Existing Material-Exposure Facilities*

Figure 3.7 is a schematic diagram of the tab exposure facility used at the SRE [35]. Sodium at 1200°F was continuously circulated past the tabs during an exposure run. A frozen sodium seal cooled by vault atmosphere with a kerosene-cooled backup section was provided for the tab extraction shaft. A freeze-off section was also provided on the inlet and outlet lines to be used as a backup for the shutoff valves during the tab-extraction operations. The facility was installed in the hot-trap loop, and the hot-trap and the line heaters were used to provide the required elevated temperature. For tab removal, flow was stopped in the loop, and the line freeze-off section was placed in service. A seal valve and gas lock were installed over the extraction tube, and the extraction shaft and tabs were removed to a shielded container. The advantages of this method are the on-line installation and the relatively simple method of replacing tabs. The major disadvantages are the shaft freeze seal and its accompanying cooling systems. The shaft freeze seal failed during flow and pressure changes. A proposed modification would add a metal-to-metal primary seal (see Fig. 3.7 insert) to protect the freeze seal from pressure surges.

At the HNPF a combination material

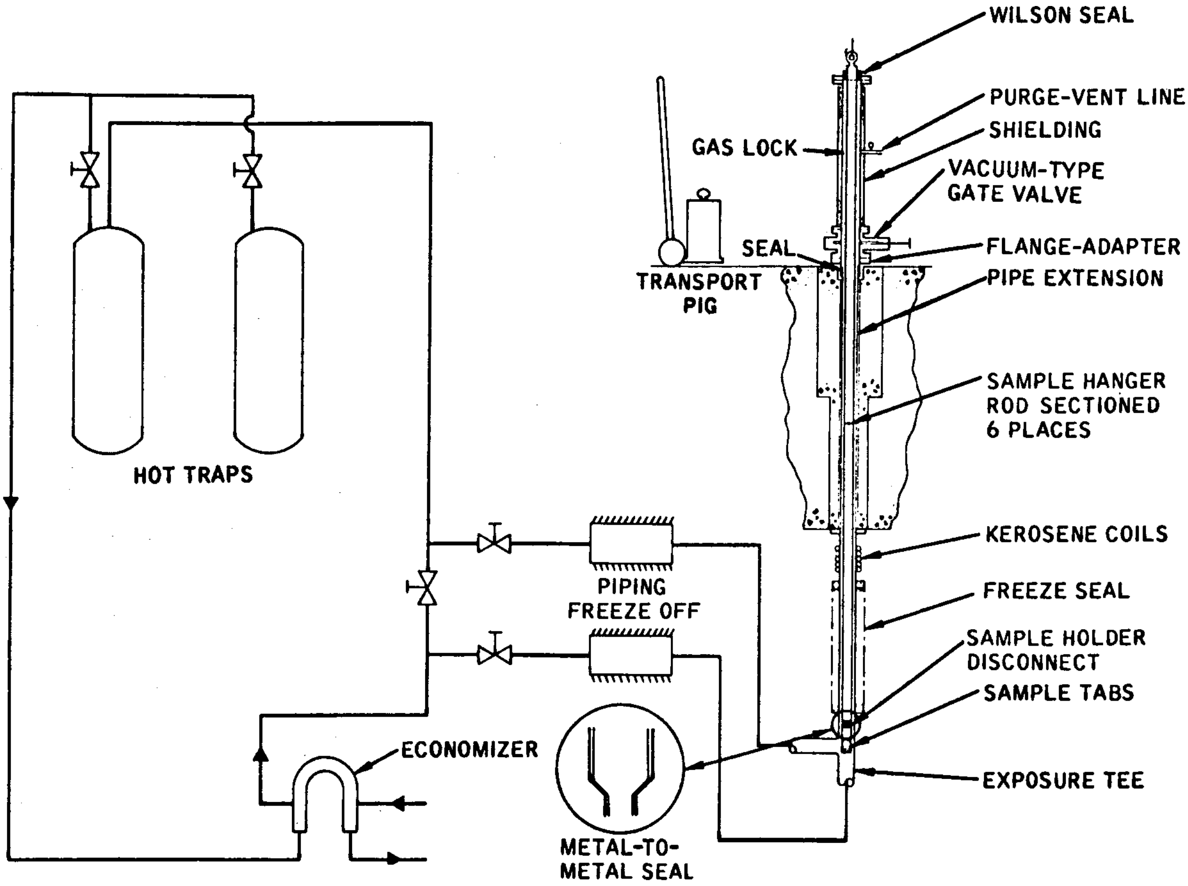


Fig. 3.7 Schematic diagram of hot-traps tab-exposure facility.

sample holder and sodium sampler was incorporated in the piping at the entry and exit to the carbon trap (see Fig. 3.8). The installation provided flow-through exposure for multiple-material samples and a flow-agitated sodium sample. The unit consisted of a cap, position rod, tab sample holder, and sodium sample cup. The sample device was removed after cool-down and decay of the hot trap by removing a high-temperature ring joint, and the exposed element was replaced with a new unit. Removal and packaging was accomplished under an inert atmosphere. A similar tab holder might be placed anywhere in an operating system.

3-5.3 *Proposed Material-Exposure Facility*

A conceptual layout of a material-exposure facility for the Fast Flux Test Facility (FFTF) is shown in Fig. 3.9. The chamber has inlet and outlet valves, a freeze trap, a fixed sodium-level probe, sample-mounting provisions, and an electric heater and controller. The inlet and outlet valves are provided for isolation and flow control. Filter and filter-bypass provisions can be incorporated if the elimination of particular matter is desired. An inert-gas supply and a freeze trap are mounted at the top to purge the chamber. The gas supply can also be used to vary the sodium level in the container to allow for thermal expansion during

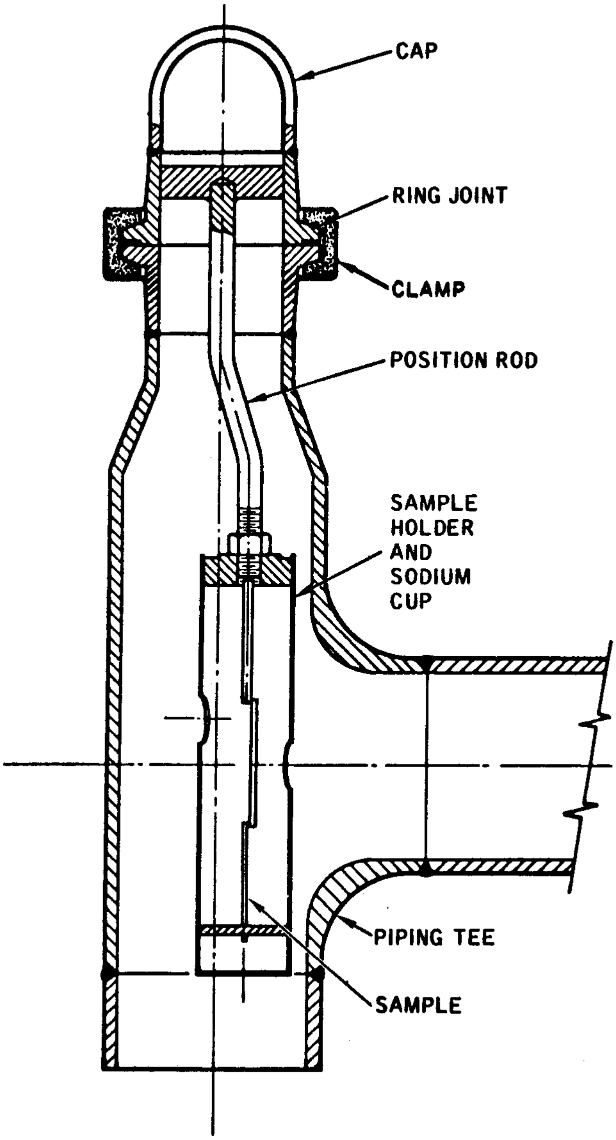


Fig. 3.8 Schematic diagram of Hallam Nuclear Power Facility sample holder.

heatup or to remove the majority of the sodium during sample retrieval.

Similar chambers can be used at several places in an operating system.

3-5.4 *Material-Sample Handling*

For representative results the material samples must be carefully chosen to be truly representative of the materials in the system. Samples fabricated from the same materials used in the system are preferred. Samples should also receive the same heat treatment and finishes that are applied to similar material in the system.

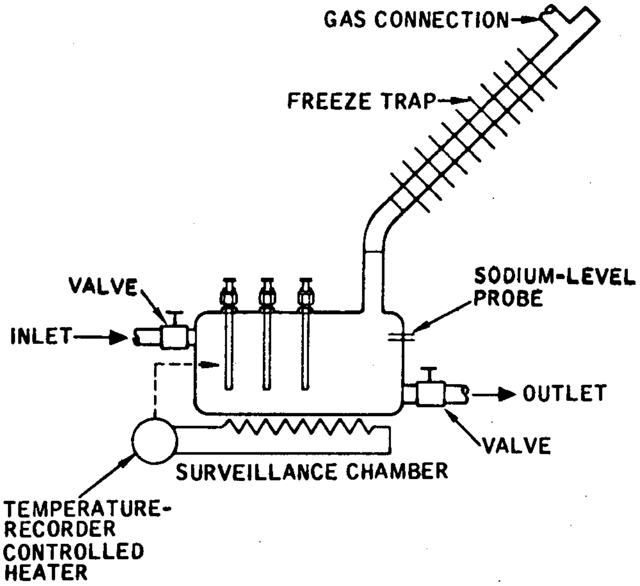


Fig. 3.9 Proposed material-exposure holder for the Fast Flux Test Facility.

After fabrication the samples are thoroughly cleaned by procedures appropriate to the material and then are weighed, measured, and photographed, and any desired metallurgical measurements are performed. It is advisable to retain a sample of each material for postexposure comparison. After being cleaned, the samples should be handled with care and stored in sealed containers in an inert or vacuum atmosphere until installed in the sample holder.

When the exposure period is completed, all sample transfers must be performed in an inert or vacuum atmosphere until the samples are cleaned. Samples should be cleaned in an alcohol bath according to procedures outlined in Sec. 3-9. The wash solution is retained for future analysis if corrosion products are present in it. After cleaning, the samples are weighed, measured, and photographed, and metallurgical measurements are repeated.

3-6 SODIUM AND NaK SAMPLING

3-6.1 *Introduction*

The maintenance of any sodium or NaK system necessitates monitoring coolant impurity levels. Two general techniques used to determine impurity levels are: (1) chemical analysis of coolant samples removed from the system and (2) the use of on-line instruments that measure the level of total impurities. On-line instruments are discussed in Vol. V, Chap. 1. The removal of samples from the coolant for analysis is the subject of this chapter. The chemical analysis of the resulting samples is discussed in Vol. I, Chap. 2.

Sodium and NaK sampling presents many difficulties because of the extreme reactivity of these substances with atmospheric gases and moisture at room temperature and their reactivity with containment materials at elevated temperature. Sampling must be performed in a high-purity inert atmosphere (argon or helium) or under a hard vacuum to prevent any contamination. (See Sec. 3-4 for information on high-purity inert atmospheres.) Preevacuated sample receivers (10^{-4} torr or better) [36,37] can also be used to withdraw a sample from a low-pressure system without pumps or other complications. Reaction between containment materials and sodium or NaK can be prevented by selecting for sample containers materials compatible at the sampling temperatures. Glass or quartz, each of which is attacked by sodium above 250°C, cannot be used above this temperature unless oxide or glass constituents are unimportant. If samples are being taken for metal concentrations, the bucket or sample-line materials must be considered. If a sample line is used, the material should be the same as the system or should be completely compatible with all phases of the eventual chemical analysis. For example, a nickel bucket must be used to sample for iron because during the chemical analysis the bucket is etched with acid to remove plated-out iron. If a stainless-steel bucket is used, the iron that precipitates as the sample cools cannot be etched off since the bucket material contributes to the iron concentration. For high-temperature sampling systems stainless-steel tubing has been used successfully. Sampling lines must be maintained at or slightly above system temperatures. A common mistake is to sample from a surge tank at a lower temperature than the loop. A sample that is to be removed from the sampling apparatus is cooled rapidly to minimize impurity segregation and migration.

The sampling equipment must also be clean and dry. All oxides must be removed from metals to be used for sampling, and porous surfaces must be thoroughly degassed. The preferred cleaning agents are acetone, distilled water, and alcohol. Chlorinated hydrocarbons must not be used. After cleaning, the sampler is oven dried in vacuum or hydrogen fired for at least 1 hr at 350°F. It should then be protected from contamination by placing in closed and preferably desiccated storage until used. Care should be exercised to prevent contamination by handling from final cleaning to insertion of sampler into the sodium or NaK.

The numerous techniques available for obtaining sodium and NaK samples can be grouped into the following categories: (1) flow-through samplers, (2) retort samplers, (3) thief-tube samplers, (4) dip-bucket samplers, and (5) other sampling techniques. Adaptations of the various techniques are discussed in the following sections. The probability of success decreases in about the order listed.

3-6.2 *Flow-Through Samplers* [38,39]

Numerous flow-through samplers have been used in sodium and NaK sampling. A typical arrangement incorporates a special sample section in a small bypass loop (Fig. 3.10). When a sample is desired, flow is established and maintained in the bypass loop for several hours to flush out any impurities and obtain a representative sample. Flow is stopped, and the loop is allowed to cool. After cooling, the sample section is pinched off, the bypass loop is isolated, the sample section is removed from the system, and a new sample section is installed in its place. A combination welding and pinchoff tool is advisable to seal NaK sample sections to prevent leakage.

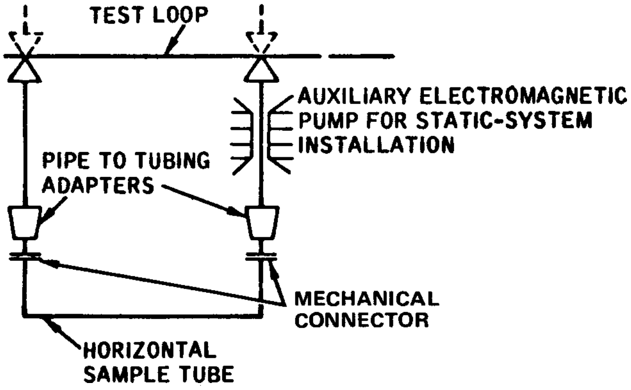


Fig. 3.10 Schematic diagram of a typical flow-through sampler.

A typical sampling procedure is:

Sample tube cleaning

1. Immerse in acetone or alcohol.
2. Rinse with distilled water.
3. Immerse in a nitric acid bath - 50% nitrate and 50% distilled water - for approximately 1 hr (for 300-series stainless steel only).
4. Rinse with distilled water.
5. Flush inner surface with hexane.
6. Bake in an oven at 130°C for 12 hr.

Sample procedure

1. Install sample section.
2. Insulate both the heating element and the piping.
3. Helium leak check all fittings and evacuate sample tube to a pressure of 5 μ, then close the evacuation valve. During evacuation, preheat the sampling piping to within 10°F of the loop temperature using a heating cable or tubular heater.
4. Open the inlet and outlet valves.
5. Circulate the sodium for 1 hr minimum and for 4 hr if possible.
6. Close the outlet valve, remove the insulation, and allow the sample tube to cool.
7. When the sample tube cools to a temperature of approximately 300°F, crimp the tube 1 in. from the mechanical connectors. A combination crimping-welding tool is preferred for the crimping operation.
8. Close the inlet valve and allow the sample to cool to below 150°F.
9. Remove sample and cap both ends.
10. Install new sample section or cap ends leading to system.

If ample time is allowed to flush out impurities in the bypass loop, flow-through samples are quite representative of the sodium content. Some heterogeneity is introduced into the sample during cooling, and, if only a portion of the sample is analyzed, this heterogeneity may introduce a significant error. The error can be minimized by remelting sodium and analyzing the total sample or by quick-freezing the sample to minimize heterogeneous effects. Quick-stripping insulation, forced-circulation cooling, and even quenching arrangements have been proposed for quick-freezing the sodium sample.

3-6.3 *Retort Sampling* [37,38,40]

Retort sampling is another common technique for obtaining sodium or NaK samples. The major components of a typical retort sampler (shown in Fig. 3.11) include an evacuated bottle, bottle-isolation valve, and system-drain valve. When the valves are opened, the system pressure quickly fills the evacuated bottle with sodium or NaK, and then the valves are closed. After sufficient time for the sample to cool, the bottle is removed for analysis, and

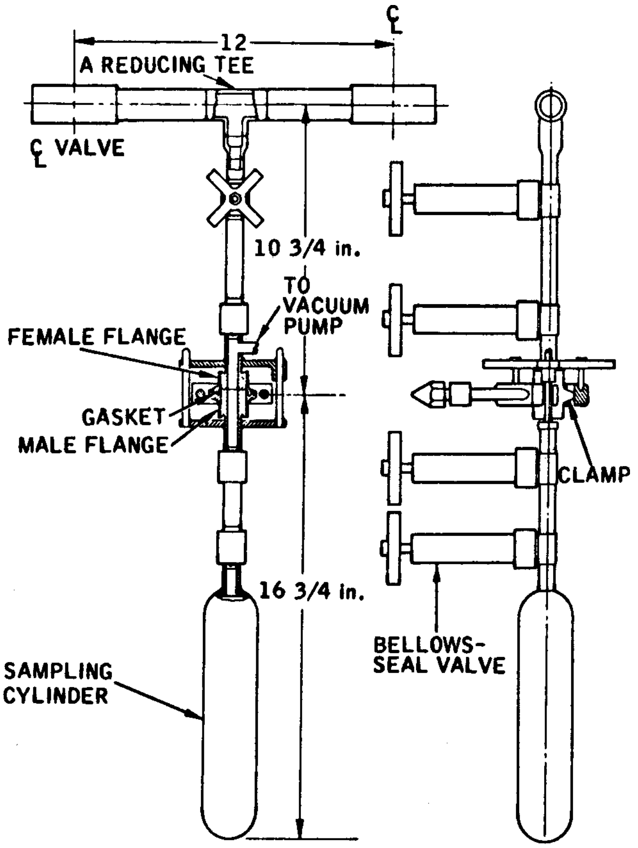


Fig. 3.11 Typical retort sampler.

a new preevacuated bottle is installed in its place. Various modifications to this system include: (1) multiple system or bottle valves to minimize chances of leakage; (2) provisions for evacuating the bottle and connecting lines after installation; and (3) provisions for remote-handling installation, sampling, and removal. The system shown in Fig. 3.11 is designed for remote-handling operation.

The system is subject to error if great care is not exercised in its design and operation. The connecting piping must be small in comparison to the bottle size to minimize the fluid trapped between valves. Fluid trapped during a previous sample will contaminate follow-on samples. Valves must be chosen with a minimum volume for trapping impurities, and the orientation and position of the drain valve must minimize the possibility of the drain line acting as a cold finger for trapping oxides and other impurities.

Figure 3.12 is a schematic diagram of a modified retort sample system designed to eliminate these errors. This system incorporates a special sample section in addition to the evacuated bottle. When the drain valve is opened, sodium or NaK flushes through the various valves and the sample section and into the evacuated bottle. The sample section is then pinched off in the same manner described in the flow-through sampler. If the evacuated-bottle volume is equal to or larger than the drain line and sample lines, any impurities present in the lines should be flushed into the evacuated bottle and the sample section should contain a representative system sample. After it is pinched off, the sample is removed for analysis, and a new sample section is installed in its place.

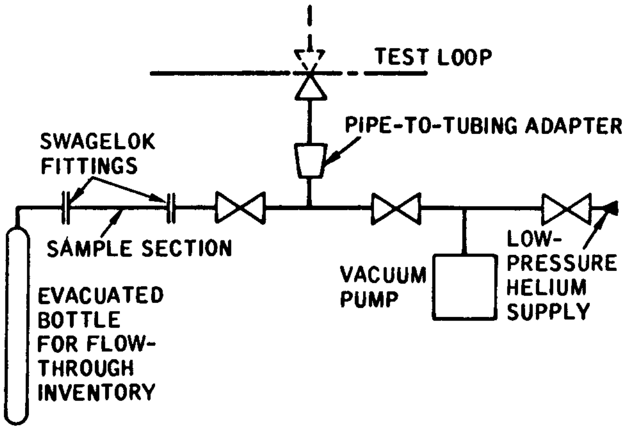


Fig. 3.12 Modified retort sampler.

3-6.4 *Thief-Tube Samplers* [36,41]

Glass thief-tube or pipetting techniques are commonly used for sampling molten sodium. Thief-tube techniques have been used to take samples from systems operating at 950°F [5,41], but they are generally limited to approximately 250°C because of the attack on glass by sodium. Glass thief tubes can be used for high-temperature applications if oxide content is unimportant, or metal thief tubes can be used. Metal capillary tubes are difficult to outgas, however, and thus their use has been limited.

Figure 3.13 shows a Pyrex thief tube developed by General Electric Company [41] for use in sodium sampling. This thief tube is evacuated and sealed during fabrication. The end of the capillary tube is formed so that it can be easily broken off when sampling is desired. In the sampling operation the glass tube is inserted into a metal holder (also shown in Fig. 3.13) and the holder and tube are inserted into the chamber from which the sample is to be taken. Prior to sample taking, the thief tube and its holder are thoroughly cleaned to remove all contaminants and residue from previous samplings. The tube and holder are then rinsed with acetone and dried. When a sample is to be taken, the tube and holder are preheated to near sodium temperature with a propane torch and are slowly inserted into the tank to be sampled. When the thief tube is completely inserted, its breakable tip is below the surface of the sodium in the tank. A sodium sample is obtained by breaking off the glass tip. The vacuum in the thief tube forces sodium to fill the bulb. When this is completed, usually in a few seconds, the tube and holder are removed and allowed to cool to room temperature. The sodium tank being sampled is normally open to the atmosphere during the sampling operation. The tank is pressurized slightly with inert gas to prevent air from entering during this time.

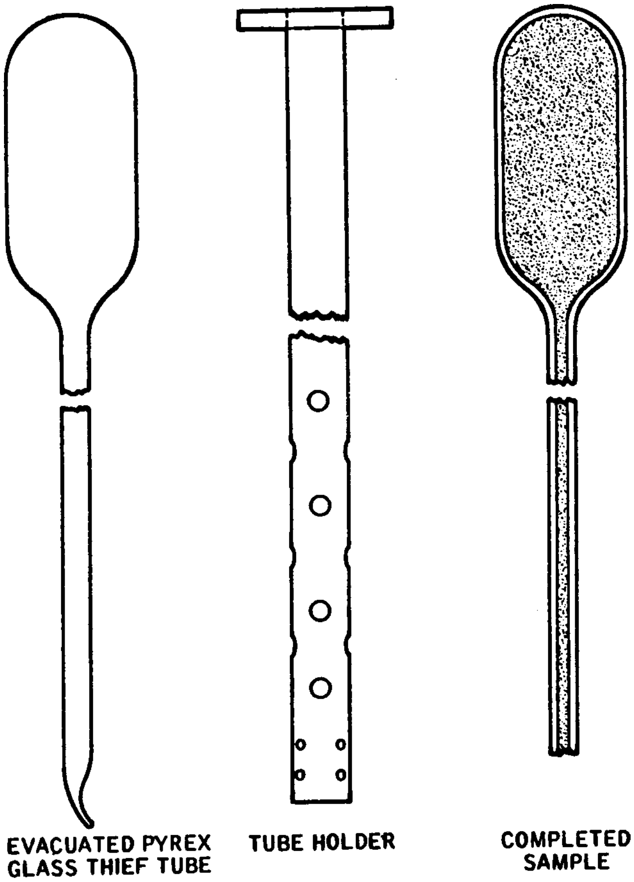


Fig. 3.13 Pyrex thief tube with holder and completed sample.

After the sample cools to room temperature, the capillary is sealed and removed for analysis. During analysis the lower end of the capillary, which may be exposed to the atmosphere during filling and cooling, is usually discarded.

Thief tubes can also be used for NaK sampling, but, since the NaK is usually liquid at room temperature, the capillary end must be sealed after filling.

3-6.5 *Dip Techniques*

The SRE incorporated a dip sampling technique [22,35,38] that could be used with the reactor operating. The core sample cup was a 3/4-in.-diameter, 12-in.-long (75-ml capacity) cylinder connected to a long shaft. The cup, shaft, associated seals, and necessary shielding were mounted in one of the shield-plug locations in the top shield (Fig. 3.14). A removable extension rod, gas lock and seal, and two 6-in. valves complete the assembly (Fig. 3.15).

To take a sodium sample, one attaches the extension rod to the sample-cup hanger rod, rotates the inner plug over

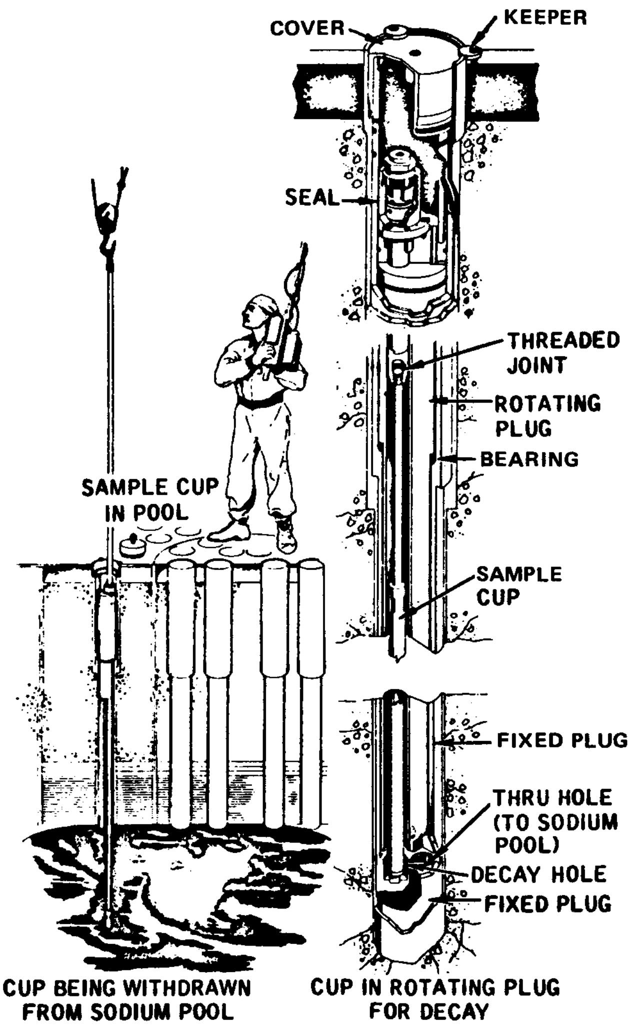


Fig. 3.14 Core sodium sampler.

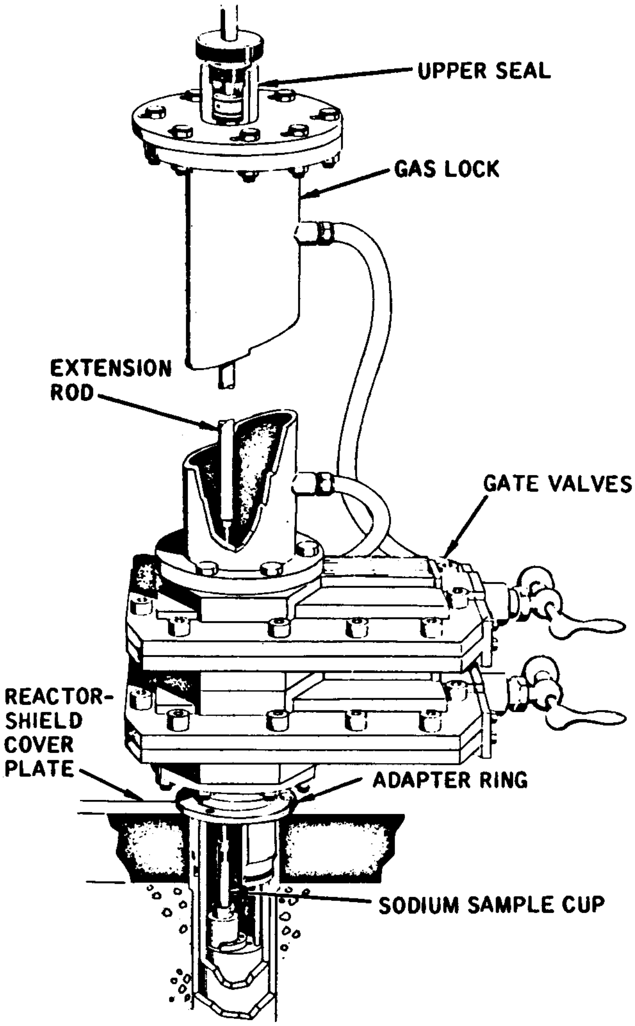


Fig. 3.15 Sodium-sampler gas lock.

the "thru hole," and lowers the sample cup into the reactor. After the sample cup is raised to the normal position, the inner plug is rotated over the "decay hole," and the extension rod is removed from the hanger rod. The sample remains in the decay hole for 10 to 14 days (sufficient time for radioactive decay) and is then removed by using the gas-lock and 6-in. valve assembly. The gas-lock assembly is required to maintain the gastight integrity of the reactor during this operation. The extension rod is inserted through the seal on the gas lock and through the lock and the two valves and then attached to the sample. The gas-lock assembly is purged, and an inert atmosphere established. Finally, the sample is removed, and a new, empty sample cup is placed in the sampler.

The primary error associated with dip sampling techniques is surface contamination. Sodium pools normally have a film of oxides and other contaminants floating on the surface. Dip cups passing through the surface pick up a disproportionate amount of this surface film. The top of or opening into the cup "sees" the surface layer before it sees the total pool. Surface-layer contaminants may fill a small cup before it reaches the bulk sodium pool. This might be overcome by remotely open-able lids or windows that open at prescribed levels.

3-6.6 *Other Sampling Techniques* [36,42]

Sodium and NaK samples have also been obtained by syphon techniques [42] involving opening the sodium reservoir, inserting a tube below the liquid surface, and sucking a sample through the tube and into a sealed sample reservoir. The sample reservoir may be preevacuated or may contain provisions for purging with inert gas and evacuation. This technique is very similar to the retort sampling technique mentioned previously. A schematic diagram of a typical syphon system is shown in Fig. 3.16. Rubber-stopper glass flasks and glass tubing can be used for low-temperature sampling.

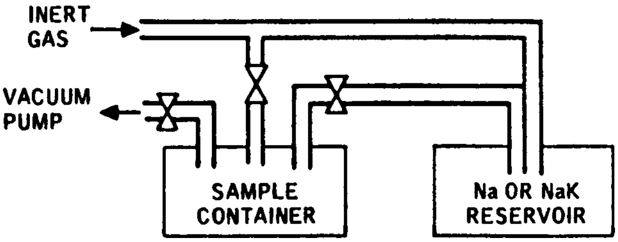


Fig. 3.16 Schematic diagram of a syphon sampler.

Solid sodium can be sampled by coring or cutting off segments, but this technique is subject to severe error because of the segregation of impurities in the sodium during freezing and the formation of an oxide layer on the surface. Coring is not recommended.

3-7 OPERATIONAL HANDLING

3-7.1 *Introduction*

Preparations for storage-tank filling, and operation of sodium and NaK systems involve procedures that are unique. The procedures developed for preparing and filling a system are discussed in Secs. 3-7.2 to 3-7.7. Section 3-7.8 reviews the unique features of the operation of sodium and NaK systems.

3-7.2 *System Cleaning* [5]

During fabrication of systems all components should be installed free of grease, dirt, oil, and other foreign materials that can (1) plug up small passages, pumps, or valves with particulate material, (2) react chemically with the liquid metal in the system, or (3) form plugs due to the limited solubility of certain constituent materials in sodium and NaK. Since all metals are normally coated with a layer of oil or grease during fabrication and since hydrocarbons carburize structural materials at high temperatures, some form of degreasing must be applied. Pickling solutions, degreasing solutions, and detergent compounds have been used successfully to remove these organics from metal surfaces. In pickling, care must be taken to choose a solution compatible with all materials used in fabrication of both the system and its components. Most systems are basically unimetallic, but other materials may be present in instruments and special items of equipment. All traces of the pickling solution must be removed after use to prevent contamination of the liquid metal.

Degreasing solutions are satisfactory; but again, care must be taken to remove all traces of the solution to guard against the presence of halogenated hydrocarbons that could react chemically with the sodium or NaK and hydrocarbons that could carburize the materials of construction.

One of the more effective methods is to flush the components with a nonsudsing detergent in hot water. After the system is thoroughly flushed, it is rinsed with hot water to remove all traces of detergent and then completely dried under a vacuum and/or a flowing inert gas. The rinsing and drying operation is very important in sodium and NaK systems because of the chemical activity of these metals. It is very important that chemical cleaning solutions be completely flushed from the system, especially from thin-walled members such as heat-exchanger tubes. Failure to remove cleaning solutions completely has caused expensive failures in several liquid-metal systems. Drying is usually carried out by heating the system with hot, flowing, inert gas or system heaters to above 250°F and then evacuating to a pressure below the vapor pressure of water at the lowest system temperature. This procedure is normally repeated two or three times to remove all residual water, and then the system is left in an evacuated state.

Hot sodium or NaK flushes are also an excellent cleaning technique for high-purity systems. After completion of the cleaning and drying procedures noted above, the system is filled with sodium or NaK; flow is established and maintained for several hours; and then the system is completely drained. Circulating and dumping the sodium or NaK at or near operating temperature is recommended if all system components can withstand the thermal stresses involved. Circulating at or near operating temperature may require fill-system heaters to attain the required temperature for reactor systems or other systems whose primary heat sources are not operating during filling. Sodium and NaK are excellent solvents, and flushing a system with either of these materials, as appropriate, will remove almost all residual contamination. The sodium or NaK used in the initial charge may be disposed of or may be purified for reuse. Commercial-grade metals are usually used in the initial charge if it is to be disposed of, and then a reactor- or high-purity-grade metal is used for the final charge.

3-7.3 *Leak Testing* [1]

During component fabrication and after the system is complete, leak tests must be carried out to ensure tight joints. If sodium or NaK systems are to be operated for long periods of time at high temperature, care must be taken in leak testing. The most widely used methods of inspection are radiographic examinations, dye-penetrant testing, and helium leak detection by mass spectrometry.

Radiographic examination of welds is recommended wherever possible. On multipass welds the first pass should be checked with dye penetrant, and the final weld should be radiographed. Faults not detected by other techniques, which could later develop into a leak, should be uncovered.

Mechanical joints and any weld joints that cannot be radiographed are generally inspected with a mass-spectrometer helium leak detector. A common specification for a mass-spectrometer leak test is 0.01 μ/cu ft/hr helium leakage with a vacuum in the vessel and helium in a tent around the vessel. If it is not possible to evacuate the system or to enclose it in a tent, it can be pressurized with helium and the joints scanned with a mass-spectrometer probe. When it is impossible to use a mass-spectrometer leak detector or when it is felt that this requirement is too stringent, the organic-halide leak detector can be used. However, organic halides should never be used where they might contact sodium or NaK (bulk or residue), because of potential reactions (see Vol. I, Chap. 2). If used in a clean system or component, organic halides must be completely removed before filling with sodium or NaK.

System pressure tests and tests with soap solutions on the exterior surfaces of welds and joints are useful preliminary leak tests, but they should be followed by helium leak tests. Leaks missed with the soap-bubble (wash soap from pipe prior to use) or pressure tests may appear during service in liquid metals at elevated temperatures.

3-7.4 *Purging or Evacuating a System*

Before a system is filled with sodium or NaK, air and moisture must be removed. This may have been done as part of the cleaning operation if filling is to follow cleaning (see Sec. 3-7.2), but the procedure must be repeated if there is a significant time lag between cleaning and filling or if a system is to be refilled and no cleaning was required. The simplest technique is to use the hot-gas purge-evacuation procedure discussed in Sec. 3-7.2. After the final drying cycle, the system is left evacuated and can then be filled with sodium or NaK.

Large systems that cannot support a high vacuum because of excessive leakage (at pump-shaft seals) or any system that includes tanks or delicate components not designed for vacuum service can be purged with hot inert gas (>250°F) until the oxygen and moisture content are reduced to acceptable levels (this usually takes several hours for large systems). The acceptable oxygen and moisture content of the system depends on the temperature of operation, the purpose of the system, and the system capability for removing oxides from the sodium or NaK (see Vol. V, Chap. 1).

3-7.5 *Sodium (NaK) Preparation* [5]

Liquid metals frequently must be purified prior to charging into a heat-transfer system. Commercial sodium is available in three forms, cast bricks, solid-cast drums, and tank cars. (For further details, see Sec. 3-2.1.) During the casting operation the brick sodium becomes coated with sodium oxide and organic materials such as the kerosene used to grease the molds. These impurities should be removed before or while charging to decrease the cold trapping required in the heat-transfer system and to prevent metallurgical damage.

The organics are removed and thus carburization of the components is prevented by heating brick sodium to 500°F or higher and holding for several days to vaporize any hydrocarbons. It is then cooled to 250°F and passed through porous metal filters with hole sizes of 15 μ or less to remove sodium oxide and any organic residues.

Fused sodium and NaK are of a higher purity than brick sodium; therefore the need for purification is not as great. Most large systems include purification equipment that can be used to clean up the sodium or NaK after charging. Regardless of the purification equipment in the system, it is good practice to filter the sodium or NaK stream during the charging operation. Filters are usually installed with bypass provisions to allow replacement between charging operations. Micrometallic filters saturated with sodium or NaK are highly pyrophoric and are very difficult to clean completely. Replacement is cheaper and considerably safer.

3-7.6 *Preheating Considerations*

Before charging, the sodium system and the sodium to be introduced must be preheated to above 208°F (usually 300 to 350°F) to prevent solidification of the sodium in the piping and components during the charging operation. NaK systems do not require preheating unless the system temperature is below the melting point of the particular alloy.

Care must be taken to ensure complete heating during preheat operations to prevent solidification of sodium in small passages and to heat at a controlled rate to prevent excessive thermal stresses in such components as pumps, valves, and tube sheets. The allowable heating rate of equipment is sometimes controlled by the thermal stresses set up during heating in a dry condition. Some equipment can be operated successfully under transient thermal conditions at several hundred degrees per minute when filled with sodium but must be heated in the dry condition at a much slower rate to avoid excessive thermal stresses.

During the preheating of a system full of frozen sodium, great care must be taken to avoid rupture or damage of delicate components such as bellows and diaphragms. The volumetric expansion of sodium as it melts is approximately 2.7%. Heating is started at a free surface and progresses a section at a time. Valves are opened when they are heated to >250°F to allow sodium to expand as the preheating progresses. Delicate components, e.g., valve bellows, must not be heated until the adjacent pipe is hot and a liquid-metal path is established back to a gas space. Bellows-seal valves are especially subject to failure when operated with sodium frozen in the bellows.

3-7.7 *Charging (Filling) Systems*

Excluding the melting and preheating requirements necessary for sodium systems, the charging procedures are very similar for both sodium and NaK. The commonly used alloys of NaK are liquid at ambient temperature and generally require no melting or preheating.

Three techniques are used for inducing flow during loading: gravity, pumps, and differential pressure. Gravity loading is usually restricted to laboratory systems operating at or near atmospheric pressure. Most systems use a combination fill-and-drain tank positioned at the low point in the system for emergency draining. Positioning the fill-and-drain tank at the low point in the system or operating the system much above atmospheric pressure prohibits gravity charging and necessitates the use of pumps or differential pressure to fill the system. Pumps are used occasionally, but the commonest technique is to induce flow by creating a differential pressure between the fill tank and the system.

The differential pressure required to induce flow can be created by (1) pressurizing the fill tank, (2) evacuating the system (vacuum loading), or (3) a combination of 1 and 2. NaK systems are not normally preheated prior to loading, and water condensed in the NaK piping would not necessarily be removed by purging with inert gas. As mentioned in Secs. 3-7.2 and 3-7.4, the simplest technique for drying a system in preparation for filling is to purge with inert gas, evacuate, and then leave the system evacuated for filling.

The advantages of vacuum loading are: (1) The system is dry; (2) if a leak is present or develops in the system during loading, sodium or NaK is not sprayed into the atmosphere; and (3) venting of trapped gases at the high points in the system is greatly simplified. If a leak develops when pressure is used to induce flow during loading, sodium or NaK is sprayed into the atmosphere, but, where vacuum loading is used, leakage is into the system. Leakage into the system and any subsequent reactions reduce the differential pressure between the system and the fill tank and stop the flow. Any reactions are primarily confined to the sodium or NaK system where, in spite of the leak, containment is superior. Evacuating the system before filling greatly reduces the venting of gases during the filling operation. Venting of system high points for sodium systems is complex. Sodium-system high points must be equipped with venting provisions and freeze traps (see Vol. IV, Chap. 2) to prevent sodium liquid or vapor from entering and freezing in the vent lines. To vent a high point, it is necessary to melt the freeze trap, vent the gas, and refreeze the trap. Freeze traps are not normally used for NaK systems, but high-point venting is required. Preevacuating the system reduces the venting of gases as the sodium or NaK advances into the system.

During charging, the sodium or NaK in the fill tank must be maintained within ±50°F of the system-preheat temperature to prevent thermal stresses.

In sodium or NaK systems, small lines or passages in the system must be maintained at or above the sodium or NaK temperature to prevent oxide precipitation and plugging at these points. A tank or drum of sodium or NaK should never be completely emptied during filling, so that heavy residue lying on the bottom of the container and oxides and lighter residue floating on the top of the liquid surface are left in the fill tank, the fill-tank outlet lines should be positioned to prevent removal of residue on the bottom of the tank, and the liquid level in the tank should be monitored during filling to suspend the operation when the surface layer is about to reach the outlet line.

Typical arrangements used to melt sodium and provide flow from sodium tank cars and drums of fused sodium are shown in Figs. 3.17 to 3.19. All three figures are for sodium transfer, but similar arrangements excluding the heating provisions, would be used for removing NaK from supplier drums. Sodium tank cars are equipped with channels welded to the exterior of the tank shell through which hot oil can be circulated. The heating system is shown in the cutaway sketch in Fig. 3.17. The contents of the tank car can be melted in about 12 hr. When melted the sodium is transferred to the nearest receiving point by vacuum or pressure. As sodium is withdrawn the tank car is filled with nitrogen or argon. Procedures for melting sodium and removing it from tank cars are available from the prime sodium manufacturers. In addition, assistance is available for planning and installing bulk-storage and tank-car handling equipment. Drums of sodium are cradled or wrapped with band

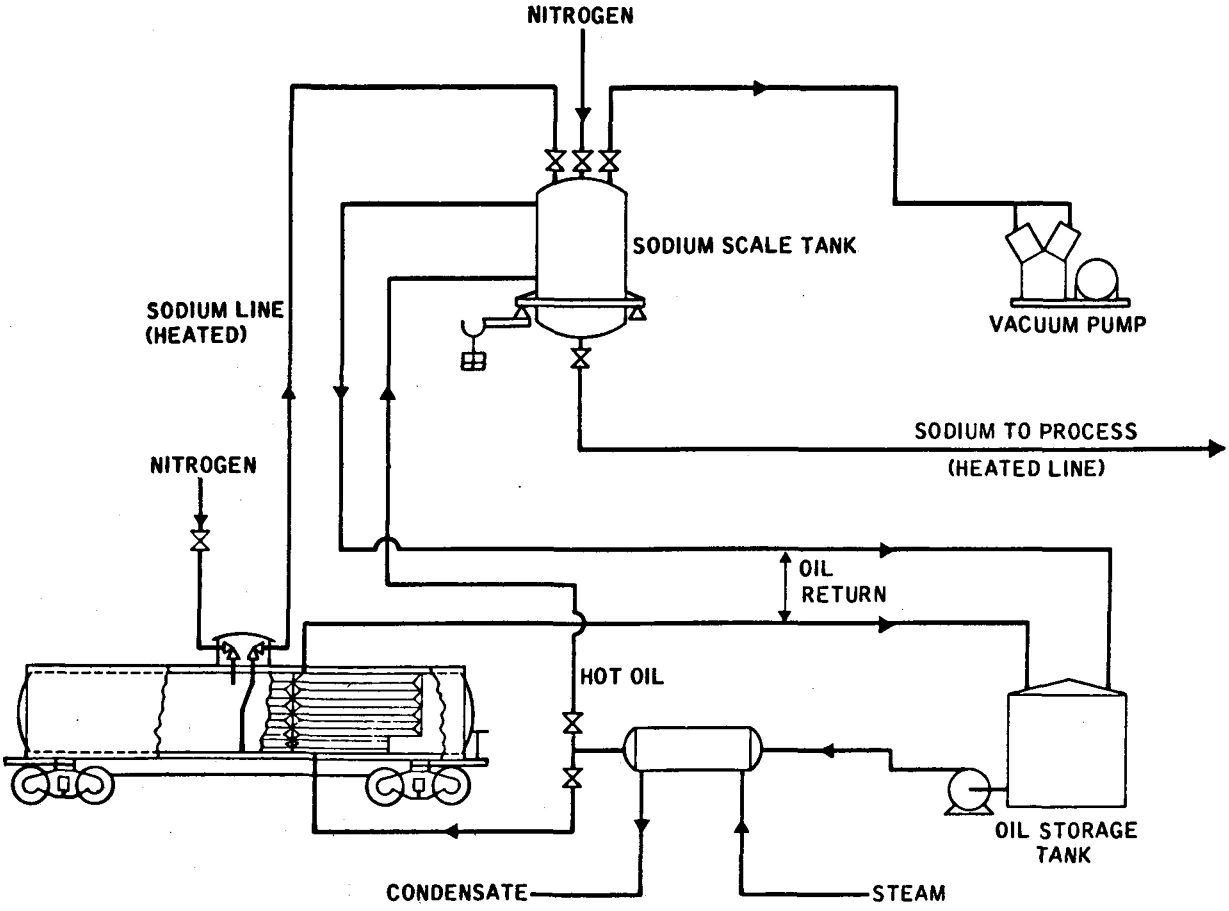


Fig. 3.17 Sodium tank-car unloading system.

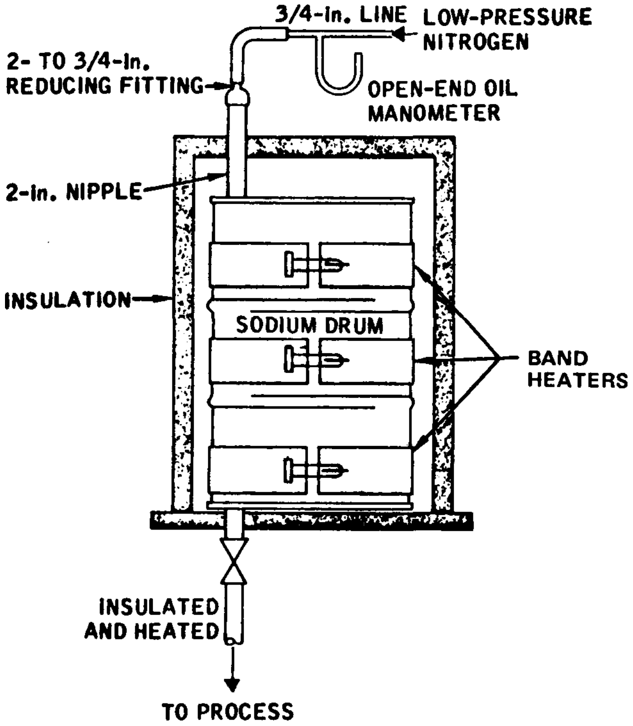


Fig. 3.18 Melting sodium for unloading.

heaters as shown in Figs. 3.18 and 3.19. After melting, the sodium is transferred to the system by vacuum or very slight (inches of water) pressure. Open-end oil manometers are recommended to minimize pressure in the drum. As with tank-car transfers, inert gas, nitrogen or argon, is used to replace the sodium.

A typical fill-and-drain system [43] is shown in Fig. 3.20. The system fill-and-drain tank (dump-storage tank) is filled from vendor containers; the sodium is purified by circulation through the cold-trap loop; and then the system is filled from the fill-and-drain tank.

3-7.8 *Operations* [8]

The operation of liquid-metal systems is quite similar to the operation of any circulating liquid system, but there are some distinctive differences involving:

1. Inert cover gas.

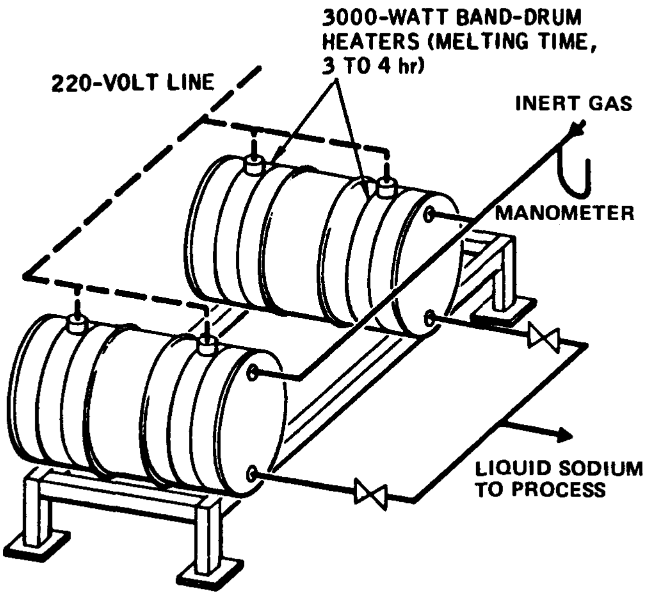


Fig. 3.19 Liquid-sodium fill system.

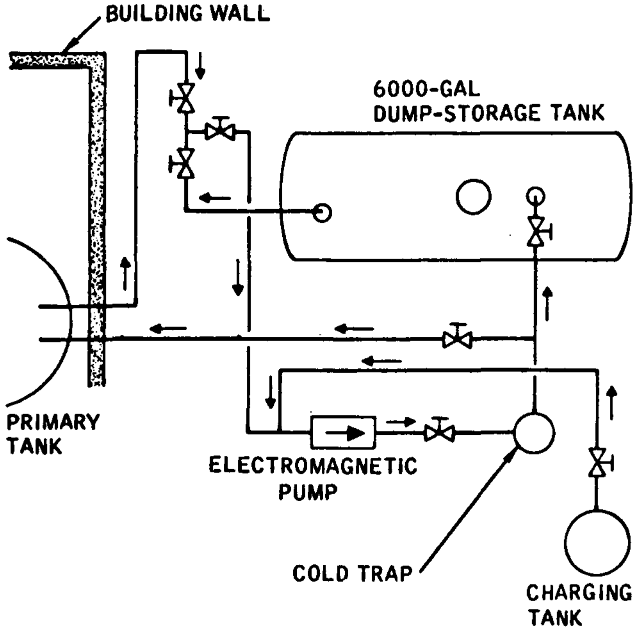


Fig. 3.20 Schematic diagram of sodium-transfer system. (From F. Smith, Sodium Handling at Argonne National Laboratory, in *Handling and Uses of Alkali Metals*, Advances in Chemistry Series, No. 19, American Chemical Society, New York, 1957.)

2. Sampling techniques
3. Coolant purification.
4. Close control of transient temperature conditions.
5. Auxiliary heating of static lines.

(a) *Cover Gas*

(See Sec. 3-4.) A cover gas must be maintained over the liquid metal at all times to prevent a chemical reaction between the alkali metal and the atmosphere. The cover gas also maintains the desired suction pressure on liquid-metal pumps to prevent cavitation (pump suction pressures of 10 to 15 psig are usually sufficient).

The purity requirements for the cover gas must be determined for each specific system. Helium, argon, or nitrogen is generally used and with proper techniques can be made very pure. Since corrosion of most construction materials is accelerated by the presence of sodium or potassium oxide in the metal, it is important to keep the oxygen level quite low for longtime operation. The main source of oxide contamination is the leakage of air into the cover-gas system. For this reason a tight cover-gas system is necessary to restrict the entrance of oxygen. Commercially available gases may contain impurities that will react with the liquid metal, forming oxides and hydroxides. These impurities and any impurities leaking into the system can be removed successfully by the addition of purifying equipment in the cover system (see Sec. 3-4). The selection of the proper cover-gas purifying equipment for any application depends on the purity required and the quantities of gas to be used.

(b) *Sampling*

(See Secs. 3-5, 3-6, and 4-5.) The liquid-metal system should be sampled periodically to determine the level of undesirable impurities. This can be done either by physically removing a sample from the system and analyzing it chemically for oxygen and dissolved metals (see Sec. 3-6), or by using one of the on-line sampling devices discussed in Sec. 4-5. Material effects are evaluated by the use of material-exposure facilities that provide information on the rate at which the coolant and its impurities are reacting with the system structural materials (see Sec. 3-5).

(c) *Purification During Operation*

(See Vol. V, Chap. 1.) Impurities can be removed from the liquid-metal system by a variety of techniques, but the most common are cold trapping, hot trapping, and filtering. Two types of cold traps have been used successfully. The natural-convection cold trap, which operates continuously, can remove oxides from a system when the oxides appear slowly and there is no need for rapid decontamination. However, if the impurities enter the system in large quantities or if fast purification is necessary, a forced-convection (circulating) cold trap is commonly used.

The two types of hot traps commonly used are a hot trap for carbon removal which uses stainless-steel mesh as a getter and a hot trap for oxygen removal which uses zirconium as the getter material. Hot traps normally operate in bypass loops that may also include cold traps or filtering provisions. Filters are generally of the sintered-metal type. Provisions should be made for bypass valving to allow filter replacement with little or no interruption in normal operation.

(d) *Thermal Transients*

Compared with other liquids, sodium and NaK have very low thermal resistances. Therefore the temperature of the inner wall of the container body immediately follows transient thermal conditions in the flowing fluid. And, since the heat-transfer coefficient between sodium and the metal wall is higher than the thermal conductivity of the wall itself, high thermal stresses can be set up during transient conditions. Therefore the maximum allowable rate of temperature change of the system should be determined, and during operation care should be taken to see that this rate of temperature change is not exceeded.

(e) *Miscellaneous*

Auxiliary items such as vent, drain, and instrument lines should be monitored frequently to determine that their temperature is higher than the saturation temperature of the impurities of the system. These blind ends act as diffusion cold traps, and plugging occurs if they are maintained at a temperature below the oxide saturation temperature of the system coolant.

Instrument lines and cover-gas lines connected to the gas phase over free surfaces often become plugged in high-temperature systems because of the condensation of the sodium vapor present in the cover gas. Proper design can minimize these difficulties, and temperature control of these lines near the nozzles to the system assists in preventing plugging.

Liquid metal can be removed from or added to the system during operation as required. In very large systems liquid metal is occasionally withdrawn from the system during normal heating operations to reduce the size of the expansion tank required. At times valve-seat leakage in the charge line will cause a slow drainage of metal from the heat-transfer system. The liquid level should be monitored and, if the level in the expansion tank falls, makeup must be added to prevent cover gas from entering the circulating stream and gas-locking pumps or heat-transfer surface.

The charge-tank and expansion-tank cover gases are sometimes connected to maintain equal pressure on the two tanks so that the system may be gravity drained in emergencies by opening a drain valve. The interconnecting gas line should be monitored to ensure that plugs, which could prevent dumping the system, do not form.

3-8 MAINTENANCE

3-8.1 *Introduction*

The use of liquid metal as a working fluid necessitates the development of special maintenance procedures. Equipment contaminated with sodium or NaK must be cut into or removed in a manner that will prevent sodium or NaK reactions with air or moisture. Liquid-metal systems can be maintained safely provided the necessary precautions are taken. Procedures adopted for the maintenance of liquid-metal systems are discussed in the following paragraphs.

3-8.2 *Initial Preparations*

Initial preparations are the key to safe maintenance of liquid-metal systems. Initial preparations for maintenance should be instituted in the design of the operating system. Systems should be designed to permit complete drainage of the liquid metal (see Sec. 3-9). Equipment requiring periodic maintenance or having a high probability of failure should be easily accessible. Equipment to be removed from a system on a routine basis should be designed with provisions for removal while maintaining system cover gas.

In addition to initial preparations during the design phase, the following precautions are appropriate:

1. All maintenance activity should be thoroughly planned. Written procedures are recommended.
2. All equipment, tools, and other accessories should be prepared prior to initiating work.
3. All personnel must be thoroughly familiar with the properties of sodium and NaK, the established handling procedures, and the protective-clothing requirements (see Chap. 2).
4. Liquid-metal fire-fighting equipment must be available in the area. All

extraneous combustible material should be removed from the area.

5. At least two people must be present whenever any maintenance work on sodium- or NaK-containing systems is to be performed. Partially completed work should never be left unattended. If work is interrupted, access openings must be sealed, preferably with normal seals. If the system has been drained, taped-on metal covers are acceptable.

6. It is advisable to have a fireman present if cutting operations are to be performed.

7. If maintenance is to be performed in a vault or gallery that normally contains an inert atmosphere, the atmosphere must be sampled to verify that the oxygen content is acceptable and no combustible gases are present before entering and for the duration of the operation.

8. Containers for the disposal of flammable residue must be provided in the work area (see Sec. 3-9).

9. Dry calcium-carbonate-lined drip pans are also advisable if small quantities of liquid metal may be spilled during the maintenance operation. These are especially useful in NaK systems where it is difficult to drain a system completely and where the residue is liquid. Drip troughs to direct falling metal into drip pans are also useful. In complex pipe arrays where metal troughs cannot be used, heavy asbestos cloth can be substituted.

10. All electrical power to the system must be turned off, and the appropriate breakers must be tagged out.

3-8.3 *Repair Operations*

Before cutting operations are initiated, insulation, line heaters, and instrumentation leads must be removed. Identification of all components and component wiring prior to removal is a very important time-saver during reinstallation. Carefully removed and packaged insulation, heaters, and other wiring can be reinstalled after the repair is completed.

There are three generally used techniques suited for the repair of sodium piping systems. If repair or modifications are extensive and involve many openings of the system, it is generally advisable to remove all traces of sodium and NaK from the system. Thus, after the piping is drained, the residual sodium film is chemically removed. This procedure is both laborious and complex. Its principal advantage is that, once the sodium is removed, the system repairs can take place in a conventional manner; i.e., no inert blanket gas is required. Details of techniques for removing sodium film are described in Vol. IV, Sec. 4-3.4.

The other two repair methods are the balloon technique and the freeze technique. They are generally suitable for all but the most involved and extensive system maintenance operations.

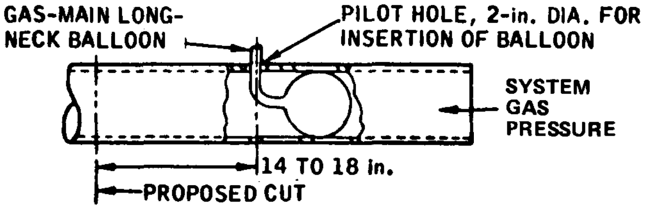
(a) *Balloon Technique* [5]

In the balloon technique the system is prepared by draining the sodium. The empty pipe is allowed to cool to room temperature. The inert-gas pressure is reduced to less than 1/2 psig.

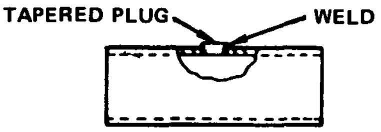
A location is selected for the cut, a 2-in. hole is drilled on the side away from the pipe section to be removed; and an empty balloon is inserted into the hole and inflated (Fig. 3.21).

A balloon pressure 1 to 3 psi above the system pressure will effectively maintain the inert gas in the system and thus prevent oxidation. Balloons of the type manufactured by Safety Gas Main Stopper Co., Inc., have been used satisfactorily. Care should be exercised in drilling the hole to minimize the entry of metallic chips in the system.

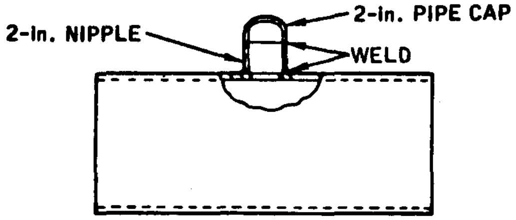
Before the system is rewelded, the weld preparation is made and grinding dust is removed. The oxidized sodium film between the atmosphere and the balloon is removed by wiping with an alcohol-dampened cloth. The repair weld is made and the balloon is de-



(a) BALLOON INSERTION METHOD



2- TO 4-in. PIPE SIZES



OVER 4-in. PIPE SIZES

(b) PILOT-HOLE CLOSURE TECHNIQUE

Fig. 3.21 Balloon technique for repairs in sodium system.

flated and removed. Finally, a plug, shown in Fig. 3.21(b), is inserted and welded in the balloon hole.

The balloon technique is employed primarily for piping runs 4 in. in diameter and larger. Its use is contingent on draining the sodium. Since the sodium is drained, the pipe can be sawed or ground open. The balloon technique is particularly useful where excessive oxygen contamination of the system is undesirable.

For smaller piping, or in systems where oxygen contamination is less critical, the system can be drained, allowed to cool, and opened without resorting to the balloons. An inert-gas purge is maintained during the cutting operation and while the system is open. Rubber stoppers or caps made of masking tape are useful to prevent gross contamination of the system by the atmosphere.

(b) *Freeze Technique* [5]

In the freeze technique of system maintenance, the sodium is not drained from the piping. The seal against atmospheric oxidation is obtained by reducing the system temperature and allowing the liquid metal to solidify in the pipe. System pressure is reduced also. When the pipe is cut, frozen sodium is exposed. Although the surface oxidizes, the solid sodium plug protects the balance of the system from contamination. Artificial cooling is necessary for NaK systems, but it is recommended that these systems be drained if possible.

As the first step in the procedure, the thermal insulation is removed from the region of the cut to shorten the freezing time. Artificial cooling such as forced air and dry ice packs can also be used for this purpose. Heat will be conducted and convected to the frozen region from the sodium piping system. If the heat rate is sufficient, the solid sodium plug may thaw when the system is opened. The sodium must remain frozen at all times during the repair operation. Audible temperature alarms upstream of the cut are advisable to warn of increasing pipe temperature.

The thermal condition mentioned also signifies that high cooling rates are required to freeze large-size piping systems artificially. Thus the practical pipe size limit for the use of rapid cooling for repairing sodium systems is approximately 2 in. in diameter. Larger sodium pipes should be cooled by ambient conditions.

After the sodium is frozen, the pipe can be cut with pipe cutters or power handsaws or by grinding, but thermal cutting methods should never be used. An inert atmosphere is also advisable around the cutting area, but no cutting oils should be employed, particularly in cutting through artificially frozen NaK lines. After the cut is completed, the surface of exposed sodium can be protected from excessive oxidation by liberal use of masking tape.

After the repairs are finished, the

pipe end should be ground in preparation for welding. The sodium is cut back at least 4 to 6 in. (the distance depends on the pipe size and wall thickness). Sodium cutting (with an ordinary knife or chisel) removes the grinding dust and excessive oxidation. After the bulk of the sodium or NaK is cut away, the inside of the pipe should be wiped out with a rag dampened in alcohol or water. This operation prevents sodium or NaK and any other residue from interfering with the welding process. For small lines a drill of the same diameter as the inside of the pipe dampened in butyl alcohol effectively removes sodium. Chill blocks are required during rewelding to minimize the chance of melting the sodium.

A remaining precaution should be exercised in rethawing the system. Although the volumetric change of sodium upon freezing is small, uneven application of heat can cause difficulty. Heating should be gradual and uniform. Particular emphasis is placed on (1) preheating from a surface, (2) avoiding large temperature differences between pipes and large vessels or equipment, and (3) avoiding undue stress on valve bellows.

(c) *Repair Welding*

If it is not necessary to remove a component, welding can generally be done in place. The sodium is drained and the system filled with inert gas. Gas pressure is set at essentially atmospheric. Sodium or NaK film must be removed in the area of the weld. Standard welding procedures can be utilized on the outer system surfaces.

3-8.4 *Equipment Removal* [44-46]

The removal of large pieces of equipment contaminated with sodium or NaK requires special handling to prevent reaction of the sodium or NaK. One technique is to preclean the system before removing the component (see Sec. 3-9). As mentioned in the previous section, this simplifies the repair work, but the cleaning operation is complex and is seldom performed unless extensive repairs are anticipated or other considerations are present.

System cleaning is seldom undertaken if only a single component is to be removed from a system. If a component is to be removed with its sodium and NaK inlet and outlet lines attached, a common practice is simply to cut the component from the system and then cap the lines [44]. A simplified procedure is:

1. Drain the system.
2. Remove insulation, heaters, or instrumentation in the area of any required cuts.
3. Provide support for the component or system piping if support will be lost during cutting.
4. Maintain a slight inert-gas pressure in the system.
5. Cut the inlet line almost but not all the way through with a power hacksaw or pipe cutter.
6. Tape the inlet-line cut.
7. Cut the outlet line completely through.
8. Finish the inlet-line cut.
9. Cap both sides of each cut.

This procedure is usually acceptable unless:

1. Large quantities of sodium or NaK remain in the system after draining.
2. Delicate components are involved which cannot tolerate minor reactions.
3. The system oxide content must be closely controlled.

This procedure can be modified by the incorporation of the balloon technique mentioned previously.

Gas locks can be used to perform component removal operations in a completely inert atmosphere. Surrounding a component in an inert atmosphere allows any required maintenance to be performed with little danger of sodium or NaK reactions. Plastic sheet taped about a component is commonly used as a glove box for work on small components. A continuous bleed flow of inert gas is used to purge air from and maintain an inert atmosphere in the glove box. Care must be exercised in the handling of sodium or NaK in plastic. Hot sodium will burn through the plastic and may even ignite the whole glove box. Fire-retardant plastic must be used in fabricating glove boxes, and small metal drip pans should be used in the glove box to protect the plastic from falling sodium or NaK. Some plastics lose this fire-retardant characteristic with time and exposure to the atmosphere and should be checked before each use. Plastic sheeting and tubing have also been used to provide an inert atmosphere in removing large sodium-contaminated components. On several occasions the HNPF [45] used plastic gas locks to disassemble sodium pumps.

The method used to remove the pump from the casing was:

1. A plastic tube approximately 60 in. in diameter and 25 ft long was prepared from 0.006-in. polyethylene sheet. Masking tape was used to connect the individual plastic pieces and to seal the plastic tube to the pump casing flange.
2. The tube was purged with argon.
3. The pump inner assembly was unbolted and raised into the plastic bag using the building crane. A dynamometer was used to measure the force exerted during the removal operation to prevent damage to the pump internals in the event of binding or mechanical interferences. An argon purge was maintained within the plastic bag during this operation to minimize oxidation of the residual sodium on the pump and to prevent oxygen from entering the system.
4. After the pump inner assembly had cleared the casing flange, the plastic bag was tied in two places and cut between the ties to seal the pump within the bag and also seal off the open pump casing.

Figure 3.22 shows one of the secondary pumps after removal. Note that the clear plastic permits some pump inspection prior to washing and that the sodium has drained fairly well from the pump parts.

Fig. 3.22 Hallam Nuclear Power Facility secondary pump after removal.

As mentioned in Sec. 3-8.2, equipment requiring periodic maintenance or having a high probability of failure should have provisions for removal incorporated in the design of the equipment and maintenance system. The maintenance system should include gas locks for handling this equipment if it is to be removed from the system with sodium or NaK contamination. Common design features for equipment of this type include:

1. Provisions for maintaining an inert atmosphere about the component during and after removal.
2. Provisions for sealing the system during and after component removal.
3. Crane provisions and control capability as appropriate.
4. Provisions for moving the component to a cleaning or maintenance area.
5. Other provisions appropriate to the particular application, e.g., shielding, cooling, etc.

Figure 3.23 [46] is a gas-lock handling apparatus used to remove EBR-II and EFAPP sodium pumps.

Operation of this system for EBR-II applications was as follows [46] :

The pumps were removed into the large cylindrical caisson, which was connected to an adapter section sealed to the pump nozzle (Fig. 3.23). A piston with inflatable silicone rubber seals was attached to the pump to seal the interior of the cylinder from the atmosphere. The adapter section contains a trap door that provides a seal when closed after the pump is pulled into the caisson.

With the sodium at 260°F and the internal space inside the cylinder filled with argon gas, the piston with the pump attached was slowly raised by the building crane. Argon gas was admitted to the cylinder to maintain constant inert-gas pressure. After the pump was removed into the cylinder, the trap door was closed, and the pump was allowed to cool to room temperature. Then the cylinder was disconnected from the adapter and, still containing the pump, was removed to the repair area and cleaned manually. After repair the pump was installed with the same equipment in essentially a reverse sequence of operations.

Very similar techniques and equipment are used for EFAPP applications, except for a different valve arrangement for sealing the enclosures after removal. Two types of sliding valves were employed, one a flat sheet and the other a curtain-type consisting of metal strips covered with plastic. In each case the seal was effected by inflatable seals. A composite drawing of these two alternate valve arrangements is shown in Fig. 3.23.

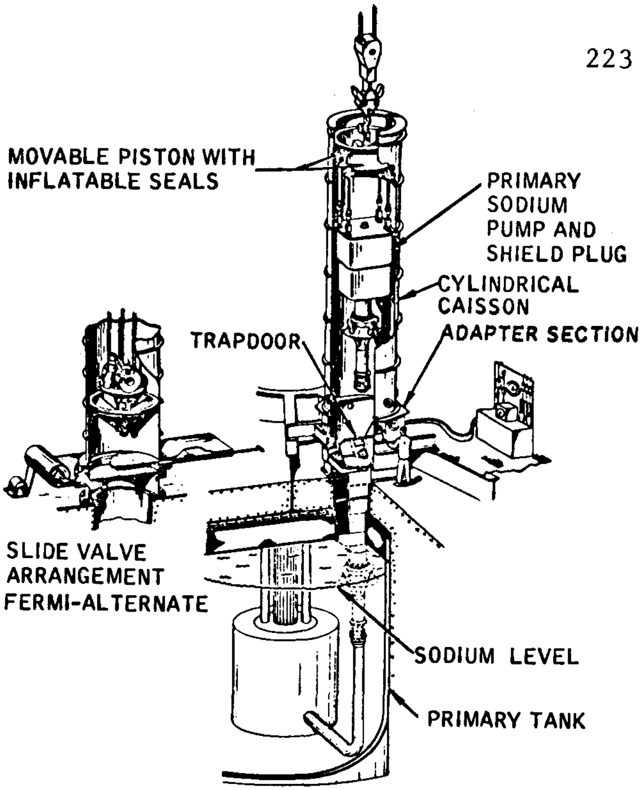


Fig. 3.23 Gas-lock handling apparatus. (From J. L. Koch, F. S. Kirn, G. W. Wensch, C. E. Branyan, and E. L. Alexander, Sodium Cooled Fast Breeder Reactors, in *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 6, p. 37, United Nations, New York, 1965.)

This technique, which is considered very successful, is applicable to the removal of a variety of components from sodium or NaK systems.

3-8.5 *Remote-Maintenance Aspects of Sodium and NaK*

The presence of sodium or NaK complicates the remote maintenance of equipment but does not cause any basic changes. Remote-handling equipment and techniques can be adapted to sodium or NaK systems with only minor changes.

The changes necessary for the remote maintenance of sodium and NaK systems are the topic of this section.

The presence of sodium or NaK necessitates the use of inert atmospheres to prevent sodium or NaK reactions. Most remote-handling facilities (e.g., hot cells, etc.) operate at a slight negative pressure to ensure inflow rather than outflow. Inflow prevents the possible spread of contamination. If sodium or NaK work is to be performed, provisions for maintaining an inert atmosphere must also be added. These provisions necessitate the addition of an inert-gas supply and control and instrumentation system and may require a decrease in facility leakage. Operation at a slight negative pressure and with an inert atmosphere requires excessive gas usage if facility leakage is not relatively low. Leakage would have to be reduced in the design of most remote-handling facilities if they are to handle liquid metals.

The presence of sodium or NaK also requires a more careful selection of materials. Most sodium or NaK systems operate at a high temperature. Remote-handling equipment that remains in place during operation must also be capable of withstanding a high-temperature sodium or NaK environment. This is a difficult environment for the operation of mechanical devices. Sodium or NaK vapors produced at high temperature condense in inopportune places when the temperature is reduced. This can clog passages, jam gears or sliding surfaces, short motor windings, and plate on viewing windows.

Electric motor brush life is also markedly reduced in a dry inert atmosphere. Remote-maintenance facilities and equipment must be fabricated of materials compatible with the environment and must be designed to minimize vapor plating or other effects.

Sodium and NaK are highly radioactive during reactor operation and for a considerable period thereafter (12- to 15-hr half-life). This often necessitates a delay before maintenance can be initiated.

Sodium and NaK are also opaque; this precludes direct viewing. Experience has shown that the manipulation of components under sodium and NaK - and particularly the handling of fuel elements in reactors, where rather high precision is required of the mechanisms - is one of the more difficult aspects of the technology [46-49]. Experience with the EFAPP and EBR-II fuel-handling machines [46-49] reveals a high probability for error in handling equipment in a sodium pool.

Since these operations cannot be visually observed, stringent accuracy and reliability requirements are imposed on the systems. Preoperational tests of EBR-II fuel-handling equipment showed that manual operation of the fuel-transfer arm was needed to permit the operator to feel any interference present. This was achieved by incorporating a system of counterweights to balance the weight of the rather heavy mechanism.

Remote-handling-equipment design must provide "feel" for the operator or provide precise position and limit controls that prevent operator error.

3-9 POSTOPERATION CLEANING AND WASTE DISPOSAL

3-9.1 *Introduction*

The use of liquid metals as a working fluid necessitates the development of special postoperation procedures for cleaning of equipment removed for disposal, repair, or other purposes. Consequently various methods and procedures have been developed for cleaning contaminated equipment and for disposal of waste liquid metal and liquid-metal-contaminated waste.

Cleaning and waste disposal, which involve a potentially greater hazard to operating personnel than any other handling procedure, can be accomplished with safety to personnel and equipment by the proper selection of environment and technique. Cleaning and disposal techniques generally involve reacting sodium or NaK with air, water, or some chemical compound. These reactions are potentially hazardous and require safety precautions and procedures. Personnel doing this work must be cognizant of the cleaning or disposal procedure, precautions, hazards, and emergency procedures before starting the work. Cleaning methods must be compatible with equipment to be reused to avoid such things as heat or corrosion damage. Since most sodium or NaK cleaning and disposal operations involve hydrogen evolution and the production of obnoxious fumes, the work should be accomplished outdoors, preferably in isolated areas or in areas with forced ventilation. Fire-fighting equipment, safety precautions, and protective-clothing requirements for cleaning and waste-disposal operations are discussed in Chap. 2.

The methods used for cleaning sodium- and NaK-contaminated equipment depend on the condition and types of equipment to be cleaned and whether the equipment is to be reused. Various cleaning methods are discussed in Sec. 3-9.2. No definite rules can be established for the selection of one method over another, and a combination of methods is often required to obtain the desired cleanliness.

Procedures for the disposal of sodium and NaK and sodium- and NaK-contaminated waste are discussed in Sec. 3-9.3.

If the sodium or NaK is radioactive or contains radioactive contamination, special material-handling techniques must also be employed. Complications introduced by radiological considerations are included in Sec. 3-9.2 (for cleaning) and 3-9.3 (for waste disposal).

3-9.2 *Postoperation Cleaning*

(a) *Cleaning Techniques*

It is desirable or necessary to clean sodium or NaK systems and components for several reasons. If residue remaining in a system after one test will obscure the results of a future test, the system must be cleaned. If extensive maintenance is to be performed, it is best performed on a system or component completely free of sodium or NaK. If a loop is to be dismantled, it is safer to remove all the sodium and NaK before opening the loop to the atmosphere. If a component is to be repaired or modified, it must be cleaned after removal from a system. Because of these requirements, consideration is given to methods and techniques for cleaning liquid-metal systems and components.

With the exception of liquid ammonia (at low temperatures) and oil, all reagents used for sodium and NaK removal react chemically with the sodium and potassium. The reagents principally employed are water, steam, liquid ammonia, methyl alcohol, ethyl alcohol, and oil. Limited experience has been obtained using the higher alcohols and concentrated sodium hydroxide solutions.

In principle, the reactions for water, steam, and alcohol can be represented by

$$\mathrm{ROH + Na(K) \rightarrow NaOR\ (KOR) + 1/2\ H_2}$$

where ROH is a reagent.

Above 300°C the reaction for ammonia is

$$\mathrm{Na + NH_3 \rightarrow NaNH_2 + 1/2\ H_2}$$

Several considerations result from the cleaning procedure. First, the reaction is exothermic. If the rate of reaction exceeds system heat losses, large temperature rises can result. Further, if pockets of undrained sodium exist, the temperature rises will be uneven. In extremes such uneven heating can cause equipment damage.

Second, the reaction liberates hydrogen gas. Because hydrogen is flammable, it is presumed that the system has been designed to safely prevent hydrogen-oxygen explosions. The more important aspect is the rapidity of hydrogen evolution and the possibility of system overpressure, unless cleaning is done in the open. The principal hazard during cleaning results from this rapid hydrogen-pressure buildup.

The third consideration stems from the possible insolubility of the sodium or potassium reactants in the solvent. If the reaction product tends to be insoluble in the reagent, a buffer layer is set up, preventing complete reaction. This is particularly important because it is impossible to predict reaction completeness. If, for example, water is added to a closed system where a buffer layer has prevented an alcohol from completely reacting all the sodium or NaK, a serious overpressure condition can occur.

These difficulties make it important to design a system with provisions for ultimate water recleaning. Careful consideration during the design phases can save time and considerable money in the event the system or component is recleaned.

The following objectives are important to the design of sodium (NaK) systems [5]:

1. An absolute minimum of sodium (NaK) pockets and traps should remain after drainage. More strict attention should be paid to complete drainage than is normally given to a system or component. For example, horizontal runs of pipe should have slopes of 3° or greater whenever feasible, and unavoidable pockets should be fitted with separate drainage lines.

2. The system or component should have large venting lines or openings to allow rapid hydrogen evolution without pressure holdup. Provisions should also be included to rapidly dilute or burn the hydrogen to prevent hydrogen explosions.

3. As indicated previously, it is difficult to determine when cleaning is complete. It is fairly certain that a straight-through system is cleaned if the cleaning fluid flows through for a reasonable length of time, but this is not true in a parallel-path system. In these systems, undetected plugs can form and cause a serious overpressure on the final water rinse. Parallel paths should be valved whenever possible. Such valving allows assurance that each individual path is open. For parallel paths that cannot be valved (e.g., heat exchangers) utmost caution should be exercised.

4. It is desirable to clean the least-complex arrangement possible. Therefore the system should be kept simple. If at all possible, components or sections of systems should be disassembled and cleaned individually.

Various techniques for system and component cleaning are presented in the following paragraphs. Component and system cleaning procedures are very similar, but the differences will be discussed as they arise.

(1) *Melting and Draining* [20,50]. The first step in any cleaning procedure is a draining operation. Always drain as much sodium or NaK as possible before initiating cleaning procedures. After the bulk of the sodium or NaK is drained, the system (or component) is evacuated and purged several times to dislodge residual pockets of sodium or NaK. The draining of sodium components may require a melting operation to remove the remaining sodium. Unless highly specialized handling equipment is used, NaK systems must always be drained before components are removed from the system. For this discussion we shall assume NaK components have been drained before removal.

A cover gas must be provided over the molten-sodium or liquid-NaK surface during removal of bulk quantities of sodium and NaK. The system cover gas is usually sufficient for system draining, but it is usually necessary to provide a special cover gas during component melting operations. The system or component heaters may provide heat for melting if they are still operable, or externally applied electric heaters, heating torches, or a variety of other heaters can be used depending on the size and configuration of the equipment (see Vol. IV, Chap. 5 for heating techniques). Care should be exercised in heating equipment to prevent overheating or forming localized hot spots.

For system draining or in cleaning facilities, drain tanks are usually provided as part of the system, but they are not normally available for component cleaning. Whenever possible, drainage into sealable drums under an inert atmosphere is recommended. Drums and drain tanks must be equipped with a means for venting residual gas and purging with inert gas. For small volumes drainage into open drums is acceptable provided that (1) the drain pipe extends well below the lip of the open vessel, (2) the vessel has an argon cover gas, (3) the vessel is installed in still air surroundings, and (4) the molten sodium or liquid NaK flows into a dry, compatible fire extinguishant in the vessel. Dry powders are recommended for the fire extinguishant. Sodium carbonate, calcium carbonate, and calcium chloride are commonly used, but all these materials are hygroscopic, and numerous accidents have resulted from their use with sodium and NaK. They are acceptable fire extinguishants only if they are known to be dry and if the material is to be disposed of immediately. Commercially available nonhygroscopic materials (MET-L-X, G-1 Powder, Bedford No. 5 oil, etc.) are recommended for sodium and NaK disposal. During draining into dry extinguishant, it is good practice to periodically add small amounts of extinguishant to keep the sodium covered as much as possible.

In any draining operation the receiving vessel should be leak checked at the temperature involved before use. Vessels with soldered joints are never acceptable for liquid metals. The receiving vessel should also be thermally insulated from any flammable supports to prevent possible ignition of the supports at the draining temperature.

Melting out small volumes of sodium does not normally lend itself to the techniques mentioned, but it can be accomplished by mounting the piece of equipment in a heated vessel with a sodium collection pot. The procedure for this technique is:

1. Mount one or more thermocouples on the equipment and place the equipment on a rack in the heating vessel.
2. Orient the equipment on the rack to afford maximum drainage.
3. Place dry extinguishant in the collection pot.
4. Seal and purge the vessel with inert gas.
5. Heat the vessel until the body temperature of the piece of equipment is ∿350°F.
6. Vent the vessel as required to avoid pressure buildup.
7. After a reasonable soaking period, dependent on configuration and size, reduce the heat and return the vessel temperature to ambient.
8. Control vessel pressure by admitting inert gas as the vessel cools.
9. Open the vessel and inspect the equipment.
10. Proceed to the next cleaning step if no large quantities of sodium remain.

After the draining operation is completed and before any system cleaning operation is begun, the drain tank and any other tanks containing large quantities of liquid metal should be disconnected. If this is not possible, all isolation valves must be closed, and the tank pressure must be carefully monitored during the cleaning operation to verify that cleaning fluid is not leaking into the tank.

(2) *Alcohol Cleaning* [5,29,50-52]. Alcohol is usually used for cleaning small and/or irregularly shaped pieces of equipment that are not adaptable to complete draining. Methyl, ethyl, propyl, and butyl alcohols are commonly used in sodium systems but should never

be used in NaK systems. Alcohols can react with the potassium in NaK to produce a violent potassium superoxide-hydrocarbon reaction. Because of decreasing reaction rates with increasing alcohol molecular size, higher molecular-weight alcohols can be used in NaK cleaning operations. The reduced reaction rate decreases the hazard but increases the postcleaning residue [38,53]. The higher molecular-weight alcohols are less miscible in water, and this complicates the final-stage water flushing. Nonmiscible residue may be left in pockets in a complex system. In addition, the higher molecular-weight molecules may break down in the presence of sodium at the temperatures involved. Atomics International [53] has had considerable success with Dowanol-EB (ethylene glycol monobutyl ether, butyl Cellosolve, 2-butoxyethanol) in cleaning operations. They prefer this alcohol solvent from a hazards standpoint. Kerosene can be added to decrease the alcohol reaction rate, but the addition of hydrocarbons in high-temperature sodium or NaK systems is inadvisable due to carburization.

Alcohol cleaning evolves hydrogen and thus must be done in well-ventilated areas. In general, alcohol cleaning requires mild agitation to ensure circulation of fluid to trapped areas. Since alcohol absorbs moisture from the air, it is important to keep exposure to air at a minimum. This can be accomplished by (1) using a cover gas during the cleaning operation and (2) procuring the alcohol in small containers and using it in batches. The lid of the alcohol container should be promptly replaced after pouring. Alcohol in bottles that have been opened can be saved for use in the near future; if it will not be used soon, it should be discarded. Alcohol that has been removed from the bottle and exposed to the air should never be used.

The major advantages and disadvantages of alcohol cleaning are [5]:

Advantages:

1. The latent heat of vaporization of liquid alcohol serves as a reaction-rate control. If the reaction is too vigorous, the alcohol boils away from the region. The temperature is evenly maintained at the boiling point of alcohol. Large temperature rises are successfully prevented.
2. The mildly reactive higher molecular-weight alcohols can be gradually diluted with lower molecular-weight alcohols or steam. This gradually increases chemical reactivity and minimizes formation of plugs. (This does become more difficult with higher molecular-weight alcohols owing to reduced miscibility.)

Disadvantages:

1. Alcohol flammability requires special handling considerations. A cover gas is recommended for all alcohol cleaning operations except for very small components or for wiping down components.
2. In an alcohol-filled system, there is little room for accommodating rapid hydrogen release, and overpressure may result.
3. The use of large quantities of alcohol is expensive.
4. In systems with large sodium or NaK holdup, thermal cracking and coking of the alcohol may result.
5. Lower molecular-weight alcohols cannot be used with NaK.
6. Alcohols react with potassium superoxides that form during storage of NaK-filled systems.

A procedure for internally cleaning systems or large components is [5]:

1. Completely drain the system, and cool to below alcohol boiling point.
2. Fill the system with nitrogen or other inert gas. Equip high-point vent line with pressure-relief valve. Maintain slight inert-gas bleed.
3. Add enough Dowanol-EB to fill approximately 10% of the system or component volume; allow alcohol to reflux. Other alcohols reacting at a different rate can also be used.

4. Add additional increments of alcohol each time the alcohol temperature falls below the boiling point. Continue until system is completely filled.
5. Circulate or agitate alcohol.
6. Drain.
7. Cut alcohol with 20% ethyl alcohol. Water can also be used in place of the ethyl alcohol if it is known that there are no sodium or NaK pockets remaining in the system.
8. Fill and repeat circulation or agitation.
9. Drain, refill with water, and circulate.
10. Soak and drain.

As a modification to the alcohol or water-dilution process, steam dilution can be used. For this technique, the process is repeated through step 3. After the alcohol refluxing has stopped, steam is added to the alcohol. The combined steam-distillation-type refluxing is continued until all the alcohol has vented from the system (system temperature at steam temperature). Water is then introduced through the steam line and allowed to issue through all vents.

A procedure for components small enough to allow handling and immersion is:

1. Using an open metal vessel, place the piece to be cleaned so that fluid can circulate to all parts requiring cleaning. The piece should be raised off the bottom of the vessel to allow residue space.
2. Carefully fill with alcohol, covering the piece to be cleaned.
3. Provide either continuous or periodic agitation to ensure removal of sodium or NaK.

A heavy compound can be used for the initial fill, and controlled amounts of simpler alcohols can be added periodically to maintain a safe reaction rate. This procedure should be followed either by steam cleaning or by water wash to remove residual deposits. Special procedures can be developed when closed containers are used.

(3) *Steam Cleaning* [5,29,51,52] This method is especially suitable for large complex systems. Compared with the alcohol method it has the advantages of lower cost, nonflammability, and a better chance of complete reaction because the sodium (and NaK) are liquid at the steam temperature.

The advantages and disadvantages of steam cleaning are:

Advantages:

1. There is limited possibility of hydrogen overpressurization since the reactant fluid is a vapor rather than a liquid.
2. Steam is nonflammable.
3. Sodium and NaK are liquid at the steam temperatures. This ensures greater possibility of complete reaction.
4. The rate of reaction may be controlled by the addition of hot inert gas mixed with the steam.
5. Steam cleaning is economical.

Disadvantages:

1. Since the heat capacity of steam is low, large temperature excursions are possible.
2. Limited amount of liquid during the early phases of the operation may permit sodium oxide or sodium hydroxide plugging of smaller lines and trapping of pockets of sodium or NaK. Coating pockets of sodium or NaK with caustic can prevent further reaction and create a definite hazard when water is admitted during the final rinse.

Steam cleaning can be performed in air or in inert atmosphere. An inert atmosphere is preferred if (1) the system or component is heavily contaminated with residual sodium or NaK, (2) it may be damaged by hydrogen-oxygen reactions, or (3) a major portion of or an entire system is to be cleaned. Steam cleaning in air is, however, very useful in cleaning components after the majority of the sodium or NaK has been removed and the component has been removed from the system. The two techniques are described in the following paragraphs.

Steam cleaning in an inert atmosphere

[19,54,55]. The component to be cleaned must be placed in or must be a vessel which can be sealed, vented, and drained and can contain a cover gas and the cleaning steam. For example, the vessel can be a container into which the pieces to be cleaned are placed or the vessel can be a major equipment item, such as a tank or an entire system, which is to be cleaned internally only. In the latter case, free internal passage for steam and gas must be ensured. A pressure-relief system must be provided to remove hydrogen gas generated during cleaning. A continuous inert-gas purge applied during the operation ensures the exclusion of oxygen. The advantage of this method is that because the hydrogen-oxygen reaction potential is reduced, hot spots do not form during the cleaning operation.

The temperature of the vessel, system, or component should be monitored during cleaning operations to detect an excessive temperature rise that may be detrimental to the vessel or the equipment being cleaned. When the permissible temperature is exceeded, the steam supply should be shut off.

A procedure for this operation is:

1. Purge the unit with inert gas.
2. Purge the steam system.
3. Start steam flow into the unit and continue the gas purge.
4. Gradually and carefully admit water to the steam to reduce quality until the effluent is essentially hot water.
5. Continue water washing until the effluent pH is approximately that of the incoming water.
6. Shut off the water supply and heat unit with steam while continuing the purge.
7. Shut off steam supply and continue the gas purge until the equipment is at ambient temperature.

A modification to this process, involving the use of moist inert gas rather than steam, has been shown to be valuable in large, complex systems. The inert gas acts both as a diluent for the steam and as an added absorber of heat. The technique minimizes local over-temperature frequently encountered in steam cleaning.

In practice, a mixture of 5% steam and 95% inert gas (usually N_2 because of cost), obtained by blending the two, is used for the initial reaction. A recirculating blower minimizes inert-gas requirements, which in large systems are excessive. The process is continued with richer steam additions until it is utilizing 100% steam. The remainder of the steps are as indicated.

Steam cleaning in air. The piece to be steam cleaned in air is placed on a tilted metal pan to collect sodium or NaK residue. The pan should be equipped with a drain to avoid condensate collection. The cleaning area should be remote to operating areas. A metal-sheathed concrete pad with side walls is desirable but is not necessary for this operation. Blast-wall protection of personnel is advisable. Before the cleaning operation is begun, it must be ascertained that passages in the unit being cleaned are not plugged. The steam lance should be 6 to 8 ft long. The operator should wear adequate protective clothing and should have a movable splash shield if a permanent blast wall is not available.

The temperature of the component is monitored during cleaning to detect temperature rise, which may be detrimental to the equipment being cleaned or to any enclosure. When the permissible temperature is exceeded, the steam supply is shut off.

A procedure for this operation is:

1. Arrange the equipment on the pan to minimize condensate collection.
2. Purge the steam supply to ensure that the steam is dry before directing the lance at the piece being cleaned.
3. Carefully clean the outside surfaces first to permit heat-up of internal surfaces for reduction of condensation.

4. Carefully direct steam flow to internal surfaces (do not stand in line with any equipment opening).
5. Periodically remove steam lance.
6. Carefully inspect the piece for residual sodium or NaK.
7. Repeat operation until the piece is clean.

(4) *Ammonia Cleaning* [5,28,38,51, 56]. Ammonia cleaning is an alternate method for cleaning sodium- and NaK-contaminated equipment. Since liquid ammonia is one of the true solvents for sodium and potassium, it is a useful tool for cleaning odd-shaped containers and for cleaning surfaces where no chemical reaction is desired. Ammonia is especially useful in cleaning metal samples where other cleaning reagents would obscure the metallurgical interpretation of the sample because of the generation of hydrogen and other reaction products.

Ammonia cleaning must be performed in a closed container capable of containing liquid ammonia. The container can be a vessel into which the pieces to be cleaned are placed, or it can be the enclosure of a system or major item of equipment to be cleaned internally. The pressures required to maintain ammonia liquefaction (114 psi at 70°F) or the necessity for refrigeration generally limit the application of ammonia to small-scale assemblies.

Although ammonia is a solvent for sodium, some caution must be exercised because over long periods of time or at elevated temperatures (435 to 485°F) sodium reacts with ammonia to form sodium amide [57]. This reaction is accelerated by the presence of iron, copper, zinc, water, oxides, and other catalytic materials. The amides can be controlled, but, if the temperature or catalytic materials are not controlled, the reaction may be excessively fast. If the catalytic agents are carefully controlled, the formation of sodium amides may even be used as an aid in cleaning and disposal of sodium residue. This is the basis of a patent on disposal of sodium residue [58].

Liquid ammonia is not a solvent for sodium oxide or hydroxide. Therefore it is necessary to introduce approximately 2 to 5% ammonium chloride in the liquid ammonia to remove Na_2O. Chlorides must not be used in stainless-steel systems if further operation is planned. Ammonium chloride reacts with sodium oxide to form sodium chloride. The latter is soluble to about 3 wt.% in ammonia. Since the ammonium chloride reacts with sodium to liberate hydrogen. it should be introduced only after the bulk of the sodium has been removed by an initial pure ammonia flush. If the ammonium chloride concentration is too high, plugging may occur at points where the ammonia evaporates leaving the solid ammonium chloride salt behind. The major advantage of ammonia cleaning is that liquid ammonia removes alkali metals solely by a solution process; consequently hydrogen is not present to embrittle hydride-forming alloys. The major disadvantages are (1) the formation of poisonous vapors, (2) the necessity for cryogenic or pressurized handling, and (3) its limited ability to remove oxides.

Tests have shown that liquid ammonia is not particularly corrosive to stainless steel and that it can be used to clean sodium- and NaK-contaminated equipment. Ammonia cleaning requires that the entire component or system be filled with ammonia. Ammonia cannot be refluxed as alcohol and water can because the heat transfer is in the opposite direction. The equipment necessary to refrigerate ammonia is quite bulky, and, although ammonia can be used to cool the system, its use requires evaporating some ammonia to the atmosphere.

Ammonia cleaning must be performed in a well-vented area, and any waste release, either liquid or gas, must be carefully controlled. Atmospheric release requires a large dispersal area, and, if condensing sprays are used, they must be large enough to avoid excessively caustic fluid. Personnel performing the cleaning operation must be protected from the ammonia, and self-contained breathing apparatus must be available for use in the event of an ammonia leak.

A procedure for ammonia cleaning is :

1. Purge the equipment with inert gas and pressurize to approximately 25 psig above the ammonia vapor pressure at the equipment temperature.
2. Fill the equipment, venting as required to maintain the desired pressure.
3. Circulate the ammonia if possible.
4. A dark blue color of the fluid indicates that the reaction of sodium and ammonia is complete.
5. Drain the fluid.
6. Repeat the operation until the cleaning fluid is colorless.

(5) *Hot-Oil Cleaning.* Hot-oil cleaning is used for removing frozen sodium from small irregular parts. It can also be used for large components if an oil bath (tank) in which the component can be completely submerged is available. In general, the procedure for cleaning in a hot-oil bath is the same as for alcohol cleaning except that a heat source must be added. The main precautions for this operation are to be sure that (1) the oil is safe for the temperature of operation (approximately 400°F), (2) the oil is dry to prevent water-metal reactions, and (3) an inert gas is present to prevent flashing of the oil. The component to be cleaned is completely submerged in the oil bath, and then the component and bath are brought to the same temperature simultaneously. As the molten sodium pours from the component, the sodium forms a cake on the bottom of the oil bath, and the hydroxide and oxides float to the surface. After cleaning, allow the entire cleaning assembly to cool and allow the sodium to freeze before removing the component or the sodium. Oils can usually be stored and reused if moisture pickup is prevented or if the oil is preheated to boil off any water before introducing any sodium-contaminated equipment.

(6) *NaK Flushes* [59]. A NaK flush can be used as a precleaning tool to remove residual sodium in complex sodium systems. Residual sodium dissolves in the NaK, and this facilitates draining.

(7) *Hand Cleaning.* Small amounts of sodium and NaK residue which are readily accessible can be removed manually by scraping, cutting, gouging, and wiping with scrapers, knives, or damp rags. Removal of residual films prior to welding or following other cleaning operations can be accomplished using rags dampened with either alcohol or water. Materials removed by hand should be placed in metal containers of extinguishant.

After it has been verified that radiation levels are not excessive, hand cleaning of radioactive sodium or NaK from the components can be safely accomplished in controlled work areas.

A minimum of water or alcohol should be used. Soiled cloths or pads must not be redipped into the cleaning solution. Used cloths and pads are usually not cleaned for reuse.

(8) *Sandblasting.* In some instances, in addition to one or more of the previously mentioned methods, it is desirable to sandblast metal surfaces of sodium-contaminated equipment to remove sodium particles locked in the pores of the metal.

Sandblasting of a metal surface, if required, follows the cleaning of the equipment. Dry air and dry materials are used in sandblasting to avoid a reaction with sodium. Except for this specification, the operation is a normal sandblasting procedure.

Equipment that has been exposed to radioactive sodium generally should not be sandblasted. If sandblasting is necessary, it must be done under strict supervision of a health physicist using a double barrier and remote-handling techniques.

(9) *Water Wash.* Finally, it is advisable to end all cleaning operations with a water wash to remove residual deposits and films from surfaces before disposition of the equipment is made. This can be done by spray or immersion. Equipment to be water washed should be visually examined carefully for residual sodium or NaK deposits before starting the wash operation. Any trace of white deposits indicates the possibility of sodium or potassium residue that should be removed before water washing.

(10) *Post-Cleaning Drying* [5,53]. As noted, cleaning procedures are terminated by a final water rinse. The system should not be considered absolutely safe until this water is removed. Removal of the water eliminates one of the two necessary reactants (the other being sodium or NaK).

Since most sodium systems are equipped with pipe heating, removal of water is fairly simple. NaK systems not having heaters should be purged with warm, dry, inert gas. In addition to heating, it is recommended that a vacuum be applied. A single-stage mechanical vacuum pump is normally employed. Either a water separator for the vacuum pump oil or a cold trap is required.

A vacuum of several hundred microns and an overall temperature of 200 to 300°F, are good assurances of the absence of water. The system can then be approached without concern for a delayed sodium- (NaK-) water reaction. Furthermore, the system is dried in preparation for subsequent sodium or NaK filling.

(11) *Fuel-Element Decladding* [19, 60,61]. Sodium-cooled reactor fuels often use sodium or NaK in the annulus between the fuel element and the fuel-element cladding. Safe removal of this sodium or NaK during fuel-element decladding presents a special problem because of the radiological consequences of fires or other reactions involving fuel, especially irradiated fuel. Techniques used in removing this sodium and NaK vary. Decladding has been performed underwater [60], under inert gas followed by disposal of the sodium under water [19], and under a variety of alcohols [61]. Reactants must be chosen with regard to compatibility with the fuel and cladding materials, the quantity of NaK or sodium present in the fuel, and the allowable reaction rate.

(12) *Other Possible Cleaning Techniques* [59]. A process in which ultrasonic vibrations are used to disperse sodium into a light oil carrier has been developed. Since this process is mechanical in nature, it has an advantage over reaction processes in that no heat is generated and no harmful or dangerous reaction products are formed. In addition, the subassembly never leaves the liquid-coolant phase; this is advantageous if gas cooling is a problem. However, this cleaning technique requires an additional process for removal of the oil carrier. The ultrasonic dispersing technique was tested only on small specimens, and further development work is needed to demonstrate the process on large components.

Sodium has been removed from fuel subassemblies by heating them in a vacuum chamber and maintaining an absolute pressure less than the sodium vapor pressure. This process is superior to both the steam reaction and the ultrasonic dispersion in cleanliness, inertness, and process control. Vacuum operation presents a serious obstacle to removal of decay heat from irradiated subassemblies but should be adaptable to nonfuel assemblies.

Both of these procedures should be adaptable to NaK cleaning.

(b) *Requirements for Cleaning Radioactive Sodium- or NaK-Contaminated Equipment* [5,62]

The techniques for cleaning equipment containing radioactive sodium or NaK are similar to those mentioned in the preceding sections, but special precautions are required to prevent the possible release of radioactive material and the exposure of personnel. Radioactive-material-handling techniques must be employed, and all residue, including the primary cleaning fluid, must be collected and handled as radioactive waste.

Special provisions for cleaning radioactive sodium- or NaK-contaminated equipment should be made in the design and construction of the operating facility. A shielded vessel or cell into which radioactive components can be placed and sealed should be provided. If irradiated fuel is to be placed in such a cell, cooling must be available. Provisions for steam, alcohol, ammonia, or whatever other cleaning fluids are to be used should be an integral part of the facility. These provisions should be adaptable to system and component cleaning if system cleaning is considered feasible. Inert-gas and vent-gas handling and holdup systems should be provided. A liquid-waste drainage and holdup system should also be supplied. Sampling provisions are required for the vent-gas holdup tanks and the liquid-waste holdup tanks. Design of vent systems should exclude the infiltration of oxygen or water. Adequate instrumentation for both pressure and temperature is required.

Radioactive equipment can be cleaned in complete safety in a properly designed facility with adequate procedures and health-physics coverage. Any of the cleaning techniques described in Sec. 3-9.2(a) can be adapted to cleaning radioactive equipment. It is advisable to limit the amount of cleaning fluid to minimize the quantities of radioactive waste to be disposed of after cleaning. Facility design may also reduce this problem by providing cleaning-fluid recirculation and filtering systems.

Cleaning of radioactive equipment in general work areas, as opposed to special cleaning facilities, is considerably more hazardous. Care must be taken to eliminate the possibility of rapid chemical reactions that may lead to overpressure conditions and the spread of radioactive contamination. Inert gas must be provided to prevent premature entry of air into a component or system during cleaning. All cleaning fluids must be collected. The cleaning-fluid quantities must be minimized to reduce the quantities of radioactive liquid waste to be handled in temporary facilities. This generally limits the choice of cleaning fluids to alcohol for sodium and to the high-molecular-weight alcohols for NaK. The quantities involved and the containment required for steam generally limit its use to built-in systems, and the containment required for ammonia generally limits its use to very special applications. Alcohol is by no means a perfect solution, but the larger alcohols can be used for NaK and to minimize the initial reaction with sodium if desired. Alcohol reactants - except for the evolving hydrogen - are easily contained, and alcohol can be used several times before final disposal. The alcohol cleaning procedures described previously can be used with only slight modification. The alcohol is normally filtered and reused to minimize the liquid waste.

Sodium [62] or NaK [63] flushes can also be used to aid in decontamination of sodium or NaK systems. Hot sodium or NaK takes residual deposits of sodium into solution for eventual dumping. The expense involved in using liquid metals as a flushing agent is relatively high, but it may be possible to repurify the flushing agent for future use to defray part of the cost.

(c) *Disposal of Cleaning Fluids and Residue*

Bulk quantities of sodium or NaK

drained from a system can be saved in appropriate storage containers or disposed of by one of the techniques described in Sec. 3-9.3. Handling of bulk quantities of nonradioactive cleaning fluids depends on whether all the sodium or NaK has been reacted. If all the sodium and NaK have been reacted, the cleaning fluid can be disposed of as normal industrial waste. If the sodium and NaK are not completely reacted, as might be the case with ammonia cleaning, the liquid should be disposed of by one of the sodium disposal procedures in Sec. 3-9.3. Underwater disposal would probably be preferred. Disposal of bulk quantities of radioactive cleaning fluids would be handled as noted in Sec. 3-9.3.

Solid and semisolid nonradioactive waste material is handled as outlined:

1. As waste is generated, it is placed in metal containers, usually "garbage" cans, painted a conspicuous yellow color with bold lettering indicating that they contain sodium or NaK waste.
2. Fire extinguishant covers the bottom of the container and the individual additions of waste as they are made.
3. The waste is then disposed of by one of the techniques described in Sec. 3-9.3.

A similar technique is usually used to clean up after minor sodium or NaK spills.

The disposal of solid and semisolid radioactive waste material is similar. Differences are:

1. The container is sealable and is packed inside a larger container with fire extinguishant within the annulus between the two drums.
2. Radioactive and nonradioactive waste are segregated.
3. Radioactive waste is disposed of as described in Sec. 3-9.3.

3-9.3 *Disposal*

(a) *Disposal of Sodium and NaK*

Procedures for disposing of sodium and NaK waste are outlined in the following sections.

(1) *Burning* [5,10,51]. Sodium and NaK are best disposed of by burning. Because burning produces heavy, irritating, and corrosive oxide fumes, it is restricted to isolated areas or special burning chambers. If wastes are burned in an isolated area, the burning facility should be positioned so that the prevailing winds carry fumes away from the operators and from occupied areas. Burning chambers equipped with scrubbing and filtering systems can be used to burn liquid-metal waste under all atmospheric conditions without affecting the surroundings. Design details for acceptable scrubbing and filtering systems are available in the literature [10,51], or package systems can be purchased from qualified vendors.

Typically, pieces of waste not larger than 1 lb are burned in shallow steel pans. No more than 50 lb should be burned at one time. Wood kindling or other waste soaked with kerosene is placed in the pan with the sodium or NaK waste (NaK is normally in a partially reacted state or intermixed and covered with calcium carbonate). If the burning rate is too slow, more kerosene can be added; if it is too fast, it can be slowed or stopped by adding dry soda ash or sand. During the burning operation the mass is stirred up occasionally with a long tool. Air jets directed onto the surface of the burning mass speed combustion appreciably [18]. The use of water rather than kerosene to initiate the reaction is also common. After burning is complete, the residue is washed from the pan with a large stream of water applied from a distance of at least 15 ft. Small quantities of waste can be disposed of by using special venturi burners [10] that restrict oxide fumes. Burning in heavy metal dishes under laboratory hoods is also common. Another method of burning is mixing liquid metal with air in a spray nozzle similar to a paint spray gun [10,51]. This method is used in producing sodium peroxide and potassium superoxide. The molten metal is mixed with air, atomized, and burned in a collection chamber. Most of the oxide formed is deposited in the collection chamber, and the balance is trapped by exhaust cleaning devices.

(2) *Underwater Disposal* [10,51,62]. Underwater disposal is an excellent technique for large quantities of sodium or NaK. A typical disposal system, shown in Fig. 3.24, consists of a pressurized supply tank with heating provisions, flowmeter, and submerged nozzle. Systems of this type are capable of disposing of 5000 lb/hr of sodium or NaK. Little smoke is noted at the surface with nozzle depths of 5 and 10 ft [62]. Hydrogen produced during the sodium-water reaction may cause mild detonations and flaming at the surface. These were noted at nozzle depths of 5 ft but not at 10 ft.

(3) *Surface Disposal* [10,51]. Surface disposal has been used for large quantities of sodium or NaK on several occasions. Tanks of sodium or NaK ranging from 500 to 30,000 lb have been floated on the surface of the ocean and ruptured with dynamite detonated by time-delay fuses or by bullets. If large bodies of water are available, this method of disposal offers some advantage. Note, however, that when sodium reacts with water on the surface, hydrogen is evolved, ignition is almost certain to occur, hydrogen-air explosions are likely to take place, and a large quantity of sodium oxide smoke is released.

(4) *Other Disposal Techniques* [5, 59]. Many other water disposal techniques have been used for small-to-moderate quantities of sodium or NaK; these include:

1. Casting sodium in an expendable open-topped can and then catapulting the can into an isolated pond.
2. Floating drums of sodium or NaK on an isolated pond and shooting bullet holes in the cans from a safe distance.

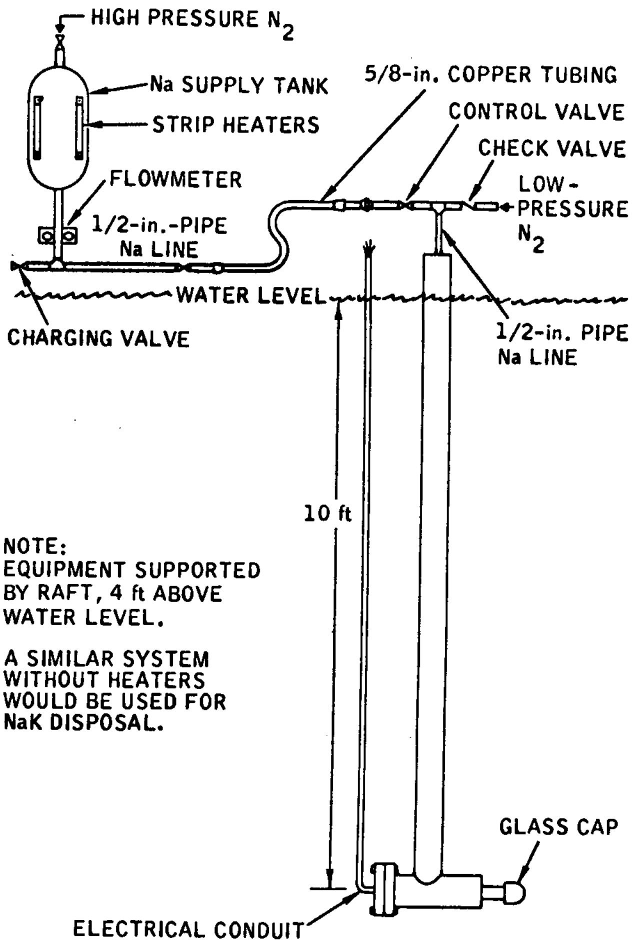


Fig. 3.24 Underwater sodium-disposal system.

3. Pouring liquid sodium or NaK down a chute (trough) leading to a pond. This requires a protective wall for disposal personnel.
4. Spraying water or steam on sodium or NaK contained in suitable containers. Spraying must be performed from a safe distance, and care must be taken to protect personnel from the evolving smoke.

All these techniques involve personnel hazards and must be performed in isolated areas. During waste disposal operations at Oak Ridge National Laboratory (ORNL), carried out in an abandoned quarry pond 2 miles from the laboratory, flames as high as 100 m can be seen; it is a spectacle resembling fireworks [59]. Explosions and fires are common, and containers can be catapulted completely out of a small pond by the liquid-metal-water reaction.

Small quantities of sodium or NaK can be disposed of by reaction with methyl, ethyl, or propyl alcohol. The metal is dropped in a container of the organic, and when the reaction goes to completion, the reaction products are dissolved in water. Owing to the expense of the organic and the fire hazard, this method should be restricted to small quantities of waste.

(b) *Disposal of Alkali-Metal-Contaminated Waste*

Waste materials contaminated with sodium or NaK can be disposed of in a variety of ways. If the waste is combustible, it can be burned; if it is noncombustible or if burning is undesirable, one of the other disposal techniques mentioned previously can be used to react the sodium or NaK, and then the remaining material, if any, can be disposed of as desired. The underwater disposal technique is applicable to liquid-waste disposal only, but the other techniques are equally applicable to liquid or solid material.

(c) *Disposal of Radioactive Sodium and NaK*

Storage is the only presently practiced solution to the problem of disposing of large quantities of radioactive sodium or NaK. The SRE-PEP, HNPF, and EBR-I are the only large liquid-metal-cooled reactors that have been decommissioned. In all three instances the liquid metal is being stored in reactor system tanks. The SRE-PEP sodium and EBR-I NaK are being stored at their respective reactor sites. The HNPF sodium is to be stored at the AEC facility at Richland, Washington (Hanford Site).

Although Na-K activation products are relatively short-lived, the total activity involved and the presence of impurities preclude burning or dumping in the ocean. The concern over eventual leakage of primary containers and fire or explosion precludes burial. Chemical reaction of the sodium and burial of the residue or dilution and dumping of the residue are possible but costly.

Storing sodium or NaK in system storage tanks is inexpensive and relatively safe. The tanks of a decommissioned reactor must be buried if they are radioactive, and, even if they are not radioactive, their scrap value is small. They provide excellent containment for long-term storage. The only costs involved are in value of the land they occupy, the surveillance required, and in shipping charges, if required. Sodium and potassium activation products decay to insignificant levels in from 10 to 40 years, depending on exposure, and it may be possible to reuse the liquid metal in future systems. The cost of sodium does not merit retention for reuse, but the cost and complications of disposal may make it worthwhile. If fission products or other high-level impurities are present in the sodium or NaK, cold-trapping and purification will be required to remove them (see Vol. V, Chap. 1).

Small quantities of radioactive sodium or NaK are normally disposed of by reacting with alcohol or concentrated sodium hydroxide. The resulting product is then diluted and released at permissible levels or concentrated and buried. When impurity levels are too high to safely permit reacting the sodium, it can be frozen in sealed pipes and buried in radioactive disposal areas [5]. Small quantities of radioactive sodium or NaK which are free of long-lived radioactive contaminants decay within a few weeks to levels that allow disposal by nonradioactive disposal techniques.

(d) *Disposal of Radioactive Equipment Contaminated with Sodium or NaK*

Disposal of radioactive equipment

contaminated with sodium or NaK usually involves draining and multiple inert-gas purges to remove as much liquid metal as possible. Sodium or NaK residue remaining after draining is then removed by one or more of the cleaning techniques described in Sec. 3-9.2. After cleaning, the equipment is disposed of as radioactive waste. Cleaning may be omitted if the equipment is to be buried. If this is the case, the sodium or NaK is drained, all penetrations are welded shut, and the equipment is buried.

REFERENCES

1. Gardiner, FIAT-FR-820 (PB-44671), Field Information Agency, Technical, June 20, 1946.

2. D. W. F. Hardie, *Ind. Chemist, 30:* 161-166 (1954).

3. C. L. Mantell, *Industrial Electrochemistry*, McGraw-Hill Book Company, Inc., New York, 1950.

4. B. Petkof, U.S. Bureau of Mines, Department of the Interior, personal communication, May 23, 1967.

5. C. B. Jackson (Ed.), *Liquid Metals Handbook. Sodium-NaK Supplement*, USAEC Report TID-5277, U.S. Atomic Energy Commission, Washington, D.C., and Bureau of Ships, July 1, 1955.

6. E. I. du Pont de Nemours & Co., Inc., personal communication, June 1968.

7. C. B. Jackson and R. C. Werner, The Use of High-Temperature Sodium in Manufacture of NaK Alloy, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955, Vol. 9*, pp. 270-272, United Nations, New York, 1956.

8. C. H. Lemke, N. D. Clare, and R. E. Desantis, Impurities in Commercial Sodium, *Nucleonics, 19:* 78-79 (1961).

9. W. H. Bruggeman, Purity Control in Sodium-Cooled Reactor Systems, *A.I.Ch.E. (Amer. Inst. Chem. Eng.) J., 2*: 153-156 (1956).

10. E. I. du Pont de Nemours & Co., Inc., *Du Pont Sodium Handling and Properties*, Wilmington, Del., 1962.

11. A. E. Shaw, *The Safe Transport of Radioactive Materials. A Key to the 1964 Revision of the International Atomic Energy Agency's Regulations*, British Report TRG-Report-1073, July 28, 1965.

12. *Regulations for Safe Transport of Radioactive Materials, 1964 Revised Edition*, Safety Series, No. 6, International Atomic Energy Agency, Vienna, 1964 (STI/PUB/97).

13. The Matheson Co., Inc., *Matheson Gas Data Book*, 4th ed., East Rutherford, N.J., 1966.

14. The Welch Scientific Company, *Periodic Chart of the Atoms*, Revised, Chicago, Ill., 1963.

15. E. F. Batutis, J. W. Mausteller, and C. A. Palladino, *Nitrogen Containing Two Per Cent Oxygen as a Sodium System Cover Gas*, USAEC file No. NP-5935, Mine Safety Appliances Co., Apr. 10, 1956.

16. R. C. Werner, *The Use of Impure Inert Gas with Sodium*, USAEC file No. NP-6062, Mine Safety Appliances Co., Apr. 14, 1955.

17. W. J. Posey (Ed.), *Progress Report No. 30 for August and September 1955*, USAEC file No. NP-5779, Mine Safety Appliances Co., Oct. 11, 1955.

18. M. Sittig, Safe Handling Alkali Metals, *Ind. Eng. Chem., 48*: 227 (1956).

19. S. Peterson, Metal Gas Reactions, *Nucl. Safety, 5*: 360 (1964).

20. Atomic Power Development Associ-

ates, Inc., *Enrico Fermi Fast-Breeder Reactor Plant*, USAEC Report APDA-115, Nov. 1, 1956.

21. A. G. Hotchkiss and H. M. Webber, Protective Atmospheres in Industry, Part III, *Gen. Elec. Rev.*, *52*(2): 40 (1949).

22. Atomics International, *Sodium Reactor Experiment Power Expansion Program Reactor Safety Analysis Report*, USAEC Report NAA-SR-9516 (Rev.), Nov. 2, 1964.

23. H. Mandel, *Estimated Helium Solubility in Sodium*, Report NAA-SR-10745, Atomics International, Jan. 12, 1965.

24. J. R. Stehn, M. D. Goldberg, B. A. Magurno, and R. Wiener-Chasman, *Neutron Cross Sections*, Vol. 1, Z=1 to 20, USAEC Report BNL-325 (2nd ed.) (Suppl. 2), Brookhaven National Laboratory, May 1964.

25. General Electric Company, *Chart of the Nuclides*, Schenectady, N.Y., November 1966.

26. S. McLain et al., *Reactor Handbook*, Vol. IV, pp. 612-681, Interscience Publishers, New York, 1964.

27. J. R. Dietrich and W. H. Zinn, *Solid Fuel Reactors*, Addison-Wesley Publishing Company, Inc., Reading, Mass., 1958.

28. W. R. Grimes and D. R. Cuneo (Eds.), *High-Temperature Thermometry Seminar, October 1-2, 1959, Oak Ridge, Tenn.*, USAEC Report TID-7586 (Pt. 1), Oak Ridge National Laboratory, August 1960.

29. J. F. Cage, Jr., Sodium Handling Equipment, in *Handling and Uses of Liquid Metals*, pp. 60-66, Advances in Chemistry Series, No. 19, American Chemical Society, New York, 1957.

30. M. E. Smith, J. M. Hansel, and G. R. Waterbury, *An Inert Atmosphere Enclosure for the Preparation of Samples Prior to the Determination of Oxygen*, USAEC Report LA-3344, Los Alamos Scientific Laboratory, May 20, 1965.

31. E. A. Limoncelli, *Use of Helium and Argon as Protective Environments for SNAP-50/SPUR Program*, USAEC Report TIM-824, Pratt and Whitney Aircraft, November 1965.

32. *Minerals Yearbook 1964*, Vol. 2, U.S. Bureau of Mines, Superintendent of Documents, U.S. Government Printing Office, Washington.

33. C. M. Kemp Mfg. Co., *Bulletin No. I-100*, Baltimore, Md., 1955.

34. C. M. Kemp Mfg. Co., *Bulletin No. I-100*, Baltimore, Md., 1963.

35. Atomics International, SRE Opperator Training Manual, unpublished, 1964.

36. K. T. Claxton, Review of Solubility Data for the Liquid Sodium-Oxygen System, *J. Nucl. Energy, 19*, 849 (1965).

37. J. Sannier and R. Vingot, *Sodium Sampling Device on a Circuit for Impurity Analyses*, USAEC Report AEC-tr-6304, translated from a paper presented at the Liquid Metals Colloquium of the European Society of Atomic Energy, Aix-en-Provence, Cadarache, Sept. 30-Oct. 2, 1963 (French), Oak Ridge National Laboratory.

38. Pratt and Whitney Aircraft, *SNAP 50/SPUR Final Summary Report*.

39. Atomics International, *FFTF Materials Surveillance and Sodium Sampling*, Report NAA-SR-MEMO-12317, to be published.

40. W. C. Miller and G. J. Hallinan,

S8DS Fission Product Detection System, Report NAA-SR-MEMO-12087, Atomics International, Oct. 5, 1966.

41. W. W. Sabol and R. W. Lockhart, *Sodium Mass Transfer. VII. Methods for Determining Impurities in Sodium Samples*, USAEC Report GEAP-4178, General Electric Company, September 1963.

42. United Kingdom Atomic Energy Authority, *The Analysis of Sodium Metal and Sodium-Potassium Alloy (Collected Capenhurst Methods)*, British Report IGO-AM/CA-110 (March 1958).

43. F. Smith, Sodium Handling at Argonne National Laboratory, in *Handling and Uses of Alkali Metals*, pp. 42-59, Advances in Chemistry Series, No. 19, American Chemical Society, New York, 1957.

44. R. E. Durand, *Operating Experience with Intermediate Heat Exchangers at the Hallam Nuclear Power Facility*, USAEC Report NAA-SR-9718, Atomics International, June 15, 1964.

45. R. E. Durand, *Operating Experience with Heat-Transfer System Pumps at the Hallam Nuclear Power Facility*, USAEC Report NAA-SR-9717, Atomics International, June 15, 1964.

46. J. L. Koch, F. S. Kirn, G. W. Wensch, C. E. Branyan, and E. L. Alexander, Sodium Cooled Fast Breeder Reactors, in *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 6, pp. 33-44, United Nations, New York, 1965.

47. A. Amorsi and J. G. Yevick, *Progress in Nuclear Energy*, Vol. II, p. 478, Pergamon Press, Inc., New York, 1961.

48. J. R. Dietrich, Sodium Cooled Reactors, *Power Reactor Technol., 8*: 65 (1965).

49. J. L. Koch, Fast Reactor Fuel Handling, in *Fast Reactor Technology. National Topical Meeting, Detroit, Apr. 26-28, 1965*, Report ANS-100, pp. 333-347, American Nuclear Society.

50. Knolls Atomic Power Laboratory, *Guide to Liquid-Metal Handling*, USAEC Report AECU-1273, Mar. 1, 1951.

51. E. I. du Pont de Nemours & Co., Inc., *Du Pont Electrochemicals Bulletin*, Report SP-23-758, Wilmington, Del.

52. W. W. Kendall and J. H. Adams, *Cleaning of 4-inch Sodium Loop at Alplaus Base by Two Methods, Alcohol and Steam*, USAEC Report KAPL-M-WWK4, Knolls Atomic Power Laboratory, May 14, 1954.

53. B. J. Held, Dowanol-EB, Health and Safety Bulletin IH-1, Atomics International, Mar. 29, 1965.

54. H. L. Brinkman and W. Wilson, Steam Cleaning System Liquid-Metal Cooled Fuel Elements, *Proceedings of the Ninth Conference on Hot Laboratories and Equipment, Chicago, Nov. 7-9, 1961*, pp. 295-306, American Nuclear Society, 1961.

55. W. G. Blessing et al., Introduction and Status of Core A, in *Summary of the APDA Fuel Development Programs*, Report APDA-143, pp. 1-6, Atomic Power Development Associates, Inc., April 1961.

56. R. L. Robb, *Ammonia Cleaning of a Sodium Heat Exchanger at the Hallam Nuclear Power Facility*, USAEC Report NAA-SR-8314, Atomics International, May 1, 1963.

57. A. Thorley and A. C. Raine, *Guidance in the Safe Handling of Alkali Metals*, British Report TRG-Report-25, May 4, 1961.

58. N. D. Clare, *Disposal of Sodium Residues*, U.S. Patent No. 2,797,147 to E. I. du Pont de Nemours & Co., Inc., June 25, 1957.

59. H. W. Savage, *Technology of Liquid Metals*, USAEC Report ORNL-tr-854, translated from Italian Report R TI/ING(65)-1 (Italian), Oak Ridge National Laboratory.

60. G. Rey, *NPF Mechanical Cell NaK Disposal and Fume Abatement*, USAEC Report HW-66562, General Electric Company, Sept. 6, 1960.

61. L. Silverman and E. L. Reed, Dissolution of Sodium from Sodium-Bonded Uranium Carbide Fuel Pieces, *Ind. Eng. Chem., Process Design Develop.*, *4*(1): 32-35 (1965).

62. J. W. Mausteller (Ed.), *Progress Report No. 28 for April and May 1955*, USAEC file No. NP-5690, Mine Safety Appliances Co., June 21, 1955.

63. P. E. Bissonnette, *NaK Flushing of Sodium-Contaminated Test Equipment*, USAEC Report KAPL-M-EDL-100, Knolls Atomic Power Laboratory, July 1, 1955.

Chapter 4

Instruments

K. A. DAVIS

4-1 INTRODUCTION

This chapter discusses instruments commonly used to measure process variables, with emphasis on instrument problems and on the types of instruments, primarily the sensors, peculiar to liquid-metal applications. Some techniques established in the broader field of process-variable measurement and in other areas of instrumentation may be applicable, but because of limited usage or apparent suitability in liquid metals, they are not discussed here. The instrumentation literature [1-10], particularly Ref. 1, discusses these techniques.

The use of several systems of units, generally a troublesome practice in any one branch of technology, is much more troublesome in instrumentation involving many branches. In this chapter nearly all data have been expressed in metric (MKS) units. The few exceptions made are clearly identified. Generally, the practice follows that recommended in the *ASTM Metric Practice Guide.**

4-2 FLOW MEASUREMENT

Many techniques of flow measurement used in various industrial and scientific applications are also used in liquid-metal flow measurement. For most applications the electromagnetic flowmeter, whose numerous advantages outweigh its disadvantages, is the preferred instrument. In some applications, however, other measurement techniques, particularly the differential-pressure methods, are used.

4-2.1 *Electromagnetic Flowmeters*

All forms of electromagnetic flowmeters depend on the generation of an electromotive force (emf) in the liquid metal passing through a magnetic field. Shercliff [11] discussed the theory of operation of the various forms.

(a) *Permanent-Magnet Flowmeter*

Most flowmeters in liquid-metal systems use a permanent magnet. The general configuration of components is illustrated in Fig. 4.1. The emf, E, generated in the liquid metal is expressed by

$$E = Bvd \text{ volts} \qquad (4.1)$$

**ASTM Metric Practice Guide*, American Society for Testing and Materials, December 1966.

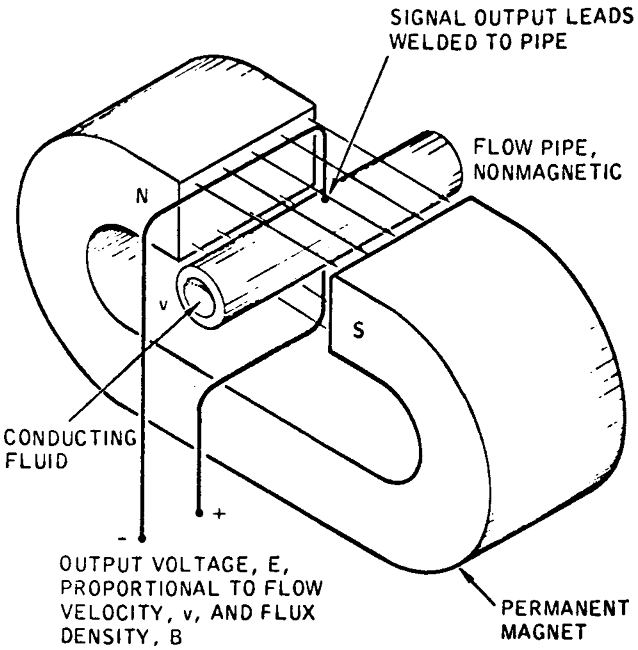


Fig. 4.1 Permanent-magnet flowmeter.

where the vectors, magnetic-flux density, B, in teslas (1 tesla = 10^4 gauss), liquid-metal velocity, v, in meters per second, and duct inside diameter, d, are mutually perpendicular.

In terms of volumetric flow rate, Q,

$$E = \frac{4BQ}{\pi d} \tag{4.2}$$

and is independent of the velocity profile if the profile is axially symmetrical.

The terminal voltage, V, is less than the emf generated, the result of two electrical shunts across the generator. These shunts are:

1. Wall - the shunting due to the conductivity of the duct wall. The reduction factor K_1, dimensionless, is given by

$$K_1 = \frac{2d/D}{1 + (d/D)^2 + (\rho_f/\rho_w)[1 - (d/D)^2]} \tag{4.3}$$

where d = inner-pipe diameter
D = outer-pipe diameter in units consistent with d
ρ_f = resistivity of liquid metal
ρ_w = resistivity of duct material in units consistent with ρ_f

This factor was derived [12] subject to the conditions of (1) negligible interface resistance between the liquid and the wall, (2) axially symmetrical velocity profile, and (3) uniform and infinite magnetic field in the axial direction.

2. End - the shunting due to the conductance through the liquid metal in the end regions where the magnetic field is low. The reduction factor K_2, dimensionless, is given as a function of the aspect ratio [13] in Fig. 4.2.

The terminal voltage, V, is given by

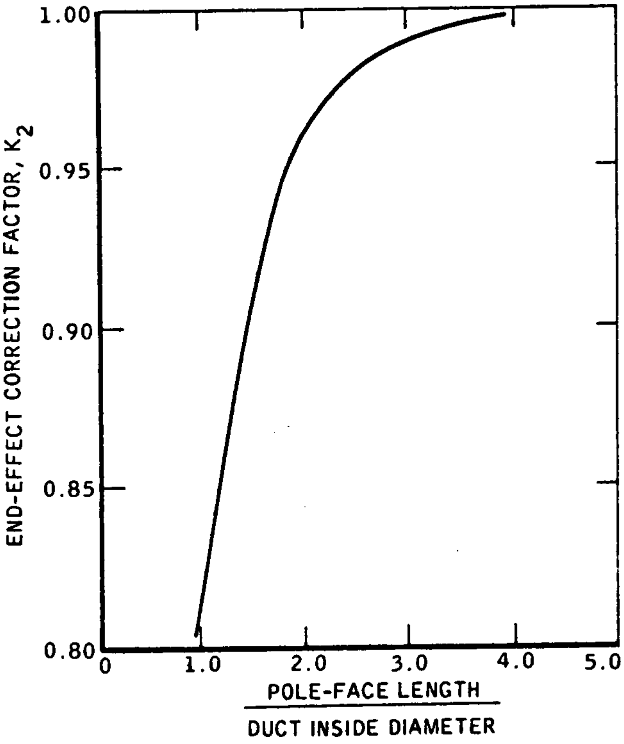


Fig. 4.2 End-shunting correction factor, K_2. [From W. C. Gray and E. R. Astley, Liquid Metal Magnetic Flowmeters, *J. Instr. Soc. Am.*, *1*(60): 17 (1954).]

$$V = K_1K_2E \qquad (4.4)$$

if the values are those at the operating temperature and the geometrical relations and assumed values are maintained.

Magnetic-flux density required can be estimated by use of a graph (Fig. 4.3) based on a flow velocity of 4.57 m/sec (15 ft/sec), a conservative value of maximum desirable flow rate in a pipe. The pipe is sized for the range of volumetric flow rate to provide this velocity. A magnetic-flux density only large enough to provide the emf necessary to operate the indicating instrument is customarily used. Values of 10 to 50 mv are typical. Since the emf is proportional to the duct diameter, large flowmeters provide an adequate output voltage at relatively low flux densities with the consequent benefits of lower magnetic braking pressure loss and smaller magnets.

The top scale shows the duct diameter corresponding to the volumetric flow rate (bottom scale) for a velocity of 4.57 m/sec. The terminal voltage is slightly less than the emf indicated because of the various reduction factors. For purposes of estimation the terminal voltage can be taken as 0.95

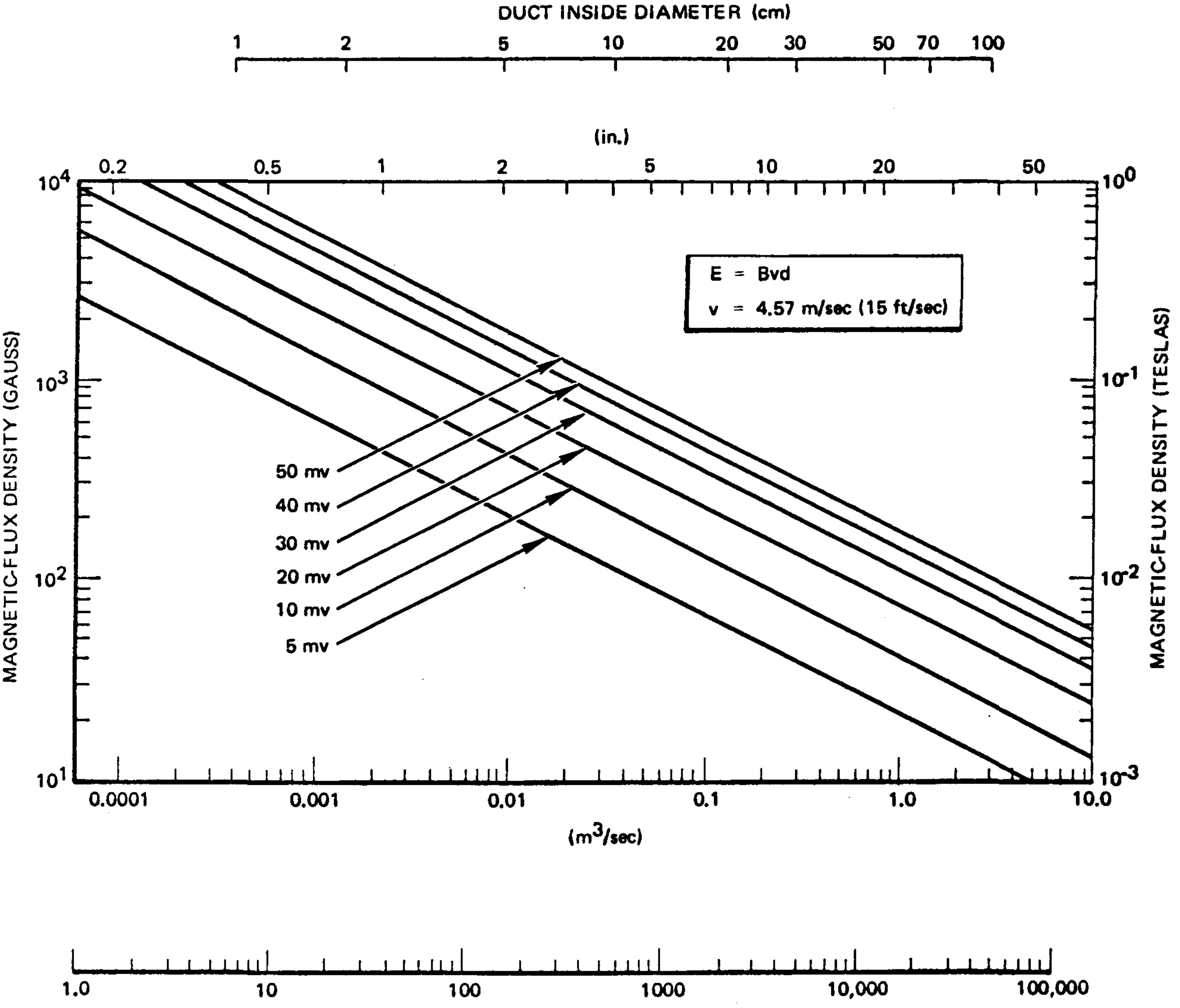


Fig. 4.3 Magnetic-flux density required.

of the emf indicated on the graph.

The duct cross section is ordinarily circular for convenience, low hydraulic loss, and strength. A rectangular-cross-section duct is uncommon but is preferred where an asymmetrical velocity profile is troublesome [11].

The duct material is nonmagnetic to avoid field distortion or shunting of the flux around the liquid metal. Minimum wall thickness and maximum material resistivity consistent with the requirements of liquid-metal containment are used to minimize the wall-shunting effect.

Poor wetting results in erratic voltage indications due to fluctuations in electrical contact and is to be expected during initial operation. Wetting improves with increased temperature and generally is complete after 1-hr operation at 300°C [14,15]. The duct remains wetted after return to room temperature if its interior surface remains covered with liquid metal. Wetting is discussed in Sec. 4-4.1(a).

The electrodes are welded to the duct wall and typically are rods of the same material as the duct to minimize the generation of thermoelectric emf's. (However, if the junctions are at the same temperature and are identical, thermal emf's caused by dissimilarity of materials cancel.) Tests under typical thermal-gradient conditions have shown that the thermal emf's are too small to register on flow recorders [16]. Tests with a 50°C temperature difference between electrodes at a mean temperature of 650°C showed no detectable thermal emf [15]. Measurement at a 25°C temperature difference showed that the thermal emf may be as high as 25×10^{-6} volt, but in most flowmeters tested values of 5×10^{-6} volt or less were typical [13]. Brazing the electrodes to the wall is satisfactory provided careful attention to good brazing practice is observed.

For small flowmeters commercial stock magnets having the required properties, flux density, and air-gap dimensions often are available. For some applications, particularly for large flowmeters, satisfactory stock magnets are not available, and so a magnet must be designed to meet the specific requirements. Permanent-magnet design and performance are treated by Hadfield [17], by Parker and Studders [18], and by design manuals prepared by permanent-magnet manufacturers.

Since the magnet is in close proximity to the duct and usually is connected to it by metallic support, the magnet temperature varies with the liquid-metal temperature. The effect of magnet temperature on the flux is illustrated in Fig. 4.4. The curves shown [19] are for a specific type of Alnico 5.

This flux-density loss must be considered in the magnet selection so that

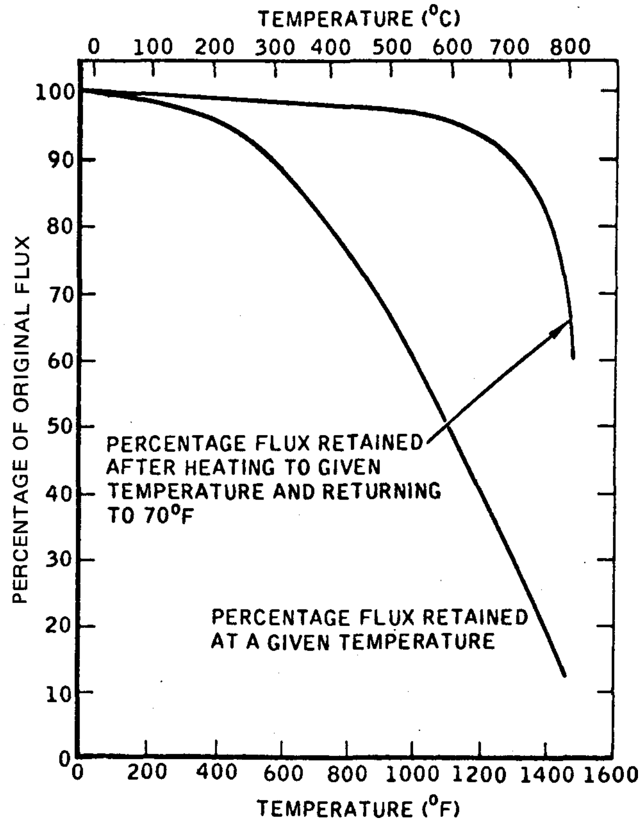


Fig. 4.4 Effect of heat on a specific Alnico 5. [From Thomas & Skinner, Inc., *Permanent Magnet Design*, Bulletin M303, p. 20, Indianapolis, Ind.]

the required flux density is available at the operating temperature. The effect of the loss is to require a larger magnet and, usually more objectionable, a change in the flowmeter calibration with temperature. Accordingly the mounting should provide the minimum thermal conductance from the duct to the magnet consistent with other design factors.

A well-insulated magnet in a flowmeter can be expected to have a temperature below 150°C, even when the liquid-metal temperature is as high as 815°C and the ambient temperature is 82°C [16]. In this magnet-temperature range (below 150°C), the temperature-compensating alloys [20] are effective and can provide a magnetic flux essentially independent of temperature over their operating range [18].

The location of the permanent magnets relative to the air gap and magnetic conductors is a significant design consideration. Figure 4.5 illustrates the preferred arrangement, the magnets being as near the air gap as possible. Equations for calculating the magnetic-flux-leakage factor for various configurations are given in Refs. 19 and 21.

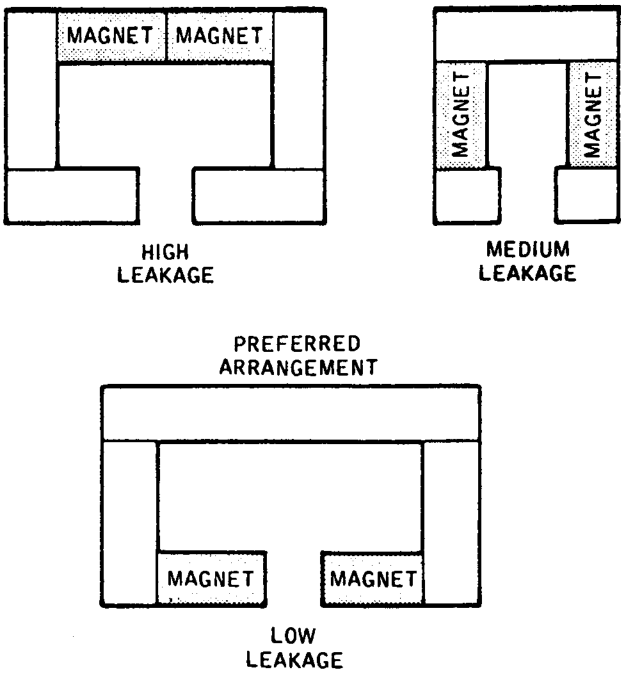


Fig. 4.5 Effect of magnet location on flux leakage.

The selection of the magnet material depends on the specific application. Alnico 5 has been the usual choice [16] on the basis of its high-energy product ($\sim 5 \times 10^6$ gauss-oersteds), stability, high-temperature capabilities, radiation resistance, and availability with relatively few shape restrictions. There is a range of properties of the magnet materials according to composition and manufacturing processes. At least seven forms of Alnico 5 are designated.

High-energy-product materials are preferred to reduce weight or bulk. Typical values of energy product, expressed in million gauss-oersteds, are [22] anisotropic Alnico 5, 5; Alnico 5 DG, 6.5; Alnico V-7 (Columax), 7.5; monocrystalline Alnico 5, 10; and Alnico 9, 10.5. For long-term stability a material having a high coercive force is recommended. Alnico 6 has a higher coercive force than Alnico 5, and magnet stability studies [23] have demonstrated the higher stability of Alnico 6. Test data [23] for stabilized Alnico 6 are shown in Fig. 4.6.

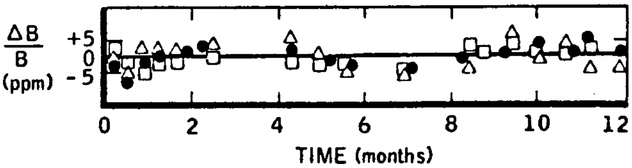


Fig. 4.6 Long-term stability of Alnico 6 magnets. [From W. L. Zingery *et al.*, Evaluation of Long-Term Magnet Stability, *J. Appl. Phys.*, *37*(3): 1101-1103 (1966).]

Materials in the vicinity of the air gap or across any other region of high magnetic potential should be nonmagnetic to avoid undesirable flux distortion and shunting. Structures joining the magnet assembly to the duct should have low thermal conductance, and thermal insulating material should be interposed between the duct and magnet assembly. A protective housing is recommended to prevent inadvertent demagnetizing contacts.

The orthogonal relation of the electrode axis, velocity vector, and magnetic-flux vector should be maintained to produce the maximum emf. Small deviations have little effect, however, since the emf is a function of the sine of the angles. Experiments [14] have shown that deviations as large as 5° in the angular relation between the electrode axis and the magnetic field are not detectable and deviations as large as 15° reduce the terminal voltage by less than 3%. The magnetic-flux density within a magnet air gap is not uniform. Consequently the emf generated is a function of the electrode-axis position relative to the pole faces. However, an appreciable fraction of the volume within the air gap, typically at the center, is sufficiently uniform that the placement of the electrode axis is not extremely critical. Longitudinal displacements as much as 6% of the pole face have been shown to have no effect on the terminal voltage in flowmeters having a high ratio (~ 4) of pole-face length to air-gap length [16]. Even with a ratio as low as ~ 1, a 6% displacement [24] results in a decrease of only 1.8%.

The magnetic field traversing the liquid metal is distorted by the metal flow as the result of induced currents, a phenomenon treated in detail in literature on magnetohydrodynamics. The distortion is a function of the magnetic Reynolds number, $R_m = \mu\sigma v d$, where μ is the liquid-metal magnetic permeability in henries per meter, σ is the liquid-metal conductivity in mhos per meter, v is the linear velocity in meters per second, and d is a "characteristic length" in meters generally taken to be the duct inside diameter. At $R_m < 1$ the distortion is negligible, but, at $R_m >> 1$, the magnetic lines are described as frozen in and are shifted in the direction of flow. In small liquid-metal flowmeters, the R_m is so low that the distortion is very small. Moreover, in small flowmeters the ratio of the pole-face length to the air gap can be made high enough to conveniently produce a uniform field of sufficient extent that a small shift does not result in a reduced flux density at the electrode axis. In large flowmeters considerations of magnet weight and bulk lead to the use of low ratios, with a correspondingly small region of uniform flux. A magnetic-field shift at high flow rates causes a flux-density reduction at the electrode axis resulting in a decreased response. Figure 4.7 shows terminal voltage vs. flow rate for several electrode locations on a 12-in. flowmeter [24]. Nonlinear response was also reported by Pfister and Dunham [25] and discussed by Shercliff [11]. Nonlinearity can be reduced by (1) extending the pole faces to make a longer region of uniform flux density, (2) placing the magnet so that the electrode axis is at an optimum location for the flow-rate range covered, or (3) using multiple electrodes and selecting for the best response. Method 1 is considered best.

One of the few disadvantages of a permanent-magnet flowmeter is the possible change in air-gap flux density that results in calibration changes. A flux-measuring instrument was built into some flowmeters to monitor the flux density to provide correction data. This practice is not common today.

If the external influences to which a magnet is subjected are fully known and if the magnet is prepared by accepted standards, it will not incur unexplained change. Permanent magnets used in all types of precision instruments have given excellent service for many years.

The following factors are pertinent to stability:

1. "Normal" changes with time, sometimes called viscosity and relaxation effects, are the result of the time lag

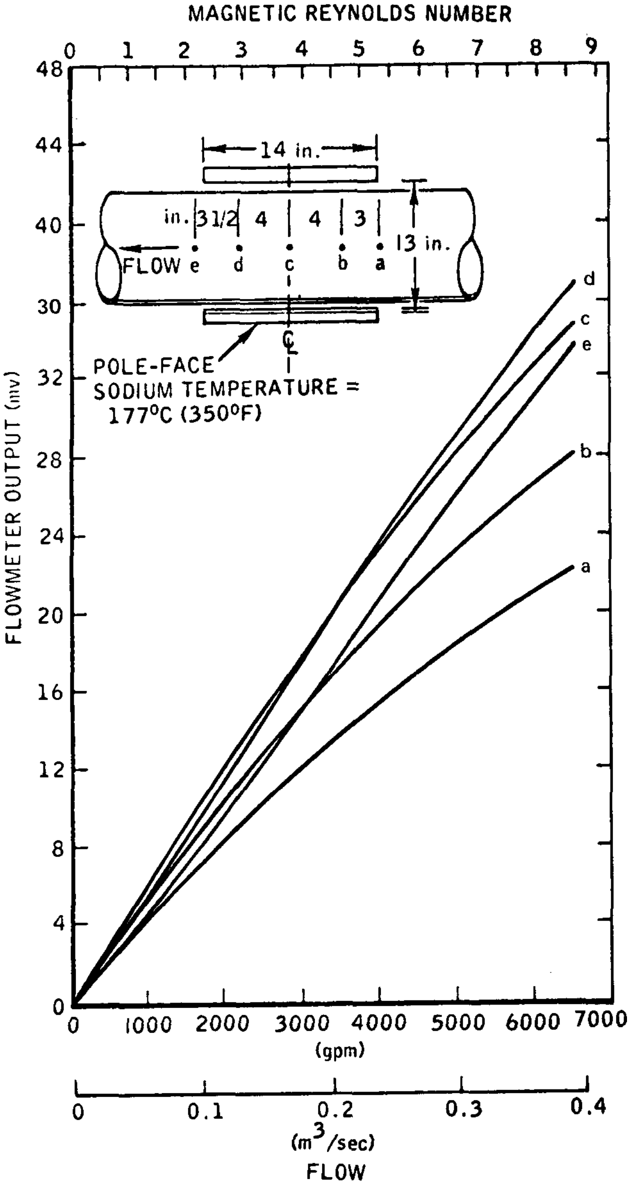


Fig. 4.7 Flowmeter output voltage as a function of flow rate.

in magnetization and the slow approach to equilibrium. Experimental work [17], in agreement with theoretical analysis, shows that the magnetization decreases linearly with the logarithm of time. The decrease is a function of the working point on the demagnetization curve, i.e., the permeance coefficient. The loss due to relaxation is very small, as illustrated [26] for three magnet materials in Fig. 4.8.

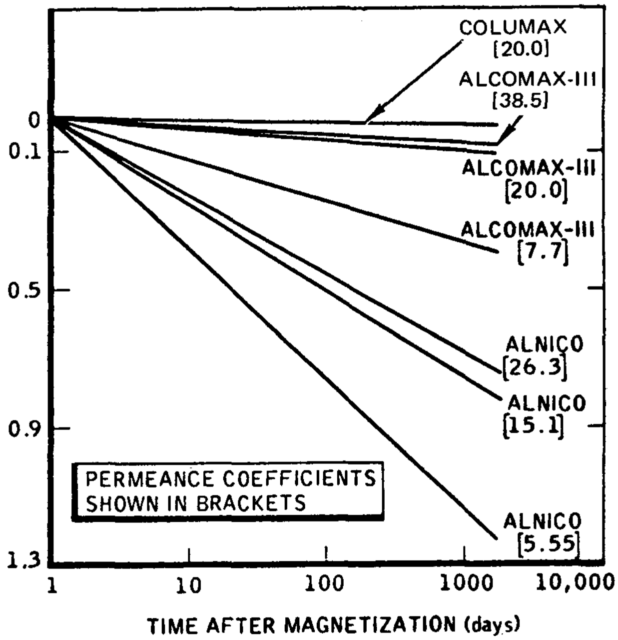


Fig. 4.8 Loss in magnetization as a function of time for three magnet materials (unstabilized). [From C. E. Webb, The Stability of Permanent Magnets, *Proc. Inst. Elec. Eng. (London), Part C, 108*: 317 (1961).]

2. Structural rearrangement or changes in the crystallographic structure result in a permanent change. This type of change does not occur [27] in the Alnico alloys 1 to 4 at temperatures below 450°C and alloys 5 to 8 at temperatures below 550°C. In most installations the magnet temperatures can be maintained well below these values.

3. Mechanical stress induced by shock and vibration affects some magnetic materials, particularly those of low coercive force, but has very little effect on the high-coercive-force alloys. Repeated stresses rapidly lead to a magnetization-loss limit, which for the Alnico alloys [17] is less than 1%.

4. Nuclear irradiation usually has little effect on the Alnico permanent-magnet materials [17,18,27]. Exposure to 3×10^{17} fast neutrons/cm^2 caused no effects within the error of measurement range [18]. Other investigations [28] indicated effects only above 10^{20}

neutrons/cm^2 (>0.5 ev). "Soft" magnetic materials (iron, etc.) used for pole faces and yokes are susceptible to radiation effects at levels generally lower than those which affect the "hard" permanent-magnet materials. The radiation effects on magnet materials are reviewed by Gordon and Sery [29].

5. Temperature effect is described in terms of reversible, irreversible, and structural-change losses. The first thermal cycle results in reversible and irreversible losses. Subsequent cycling over the same or a lower temperature range results in successively smaller irreversible losses so that after about three [30] to five [18] cycles the irreversible losses are negligible. Losses due to structural changes occur at relatively high temperatures, as discussed earlier. Thermal shocks as high as 38°F/sec are reported to have no deleterious effects [31].

6. An external field in the vicinity of a magnet results in a shift of the operating point down the demagnetization curve. Removal of the field does not result in a return to the initial operating point. Repeated exposure to demagnetizing fields of lower strength than the preceding has little or no further effect. The ability of a magnet to withstand the effect of demagnetizing fields is directly proportional to the magnet's intrinsic coercive force. External fields to consider in flowmeters are those caused by large currents in the magnet vicinity (such as those sometimes used in welding) [32], high currents in the liquid metal (eddy currents), and reluctance changes in the magnetic circuit (often caused by separation of joints).

Stabilizing a magnet against the effects described requires a treatment specific to the factor involved. The general principles of stabilization practice are implied in the discussion of the loss factors - the magnet is subjected to controlled cycles of field, temperature, and mechanical stress somewhat greater than the values expected in service. The rule-of-thumb for ordinary stability requirements is a knockdown of 5%. Stabilization methods are discussed by Zingery *et al.* [23] and in greater detail by Parker and Studders [18] and Hadfield [17], who treated high stability in addition to average stability. A factor often slighted is the need for symmetrical demagnetization during stabilization. The effect is illustrated [23] in Fig. 4.9.

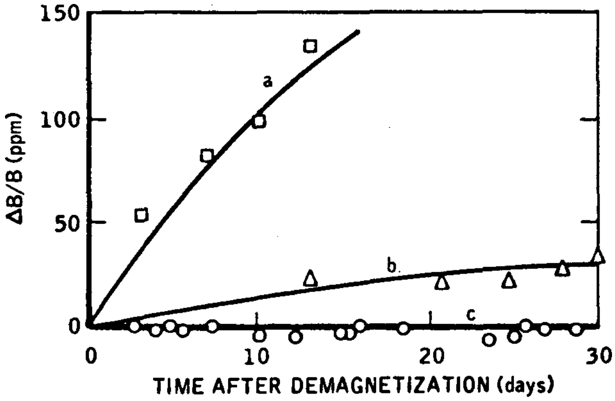


Fig. 4.9 Effects of asymmetric demagnetization; B is the flux density; a, extremely asymmetric demagnetizing a-c field; b, a-c field with small gradient; and c, demagnetization in uniform a-c field. [From W. L. Zingery *et al.*, Evaluation of Long-Term Magnet Stability, *J. Appl. Phys.*, *37*(3): 1101-1103 (1966).]

Commercial magnets are available from the manufacturer magnetized or unmagnetized. Unmagnetized magnets are preferred for ease of handling, inspection, assembly, and similar operations and because they eliminate concern over a decrease in magnetization during these operations. Although magnetization after completion of flowmeter assembly is recommended, the lack of magnetizing facilities often precludes this sequence.

Permanent-magnet flowmeters are less sensitive to upstream disturbances than most other flowmeters. They are insensitive to the velocity profile, provided the profile is axially symmetrical, but severe asymmetry can result in very large errors. Flowmeter response to upstream asymmetrical disturbances as far away as 19 pipe diameters was reported in profile sensitivity tests [33]. In typical operation the effect is much less, e.g., a 3% change caused by a partly opened gate valve four diameters upstream [24]. In other tests [14], a 90° bend seven pipe diameters upstream reduced the flowmeter signal by 2.5%. In one installation flow-indicator fluctuations were attributed to a fluctuating signal from a flowmeter placed eight diameters from a tee [34]. Swirl is reported to have no effect [11]. A rectangular-duct flowmeter can be designed to be insensitive to flow disturbances [11].

The calibration of a permanent-magnet flowmeter can change because of the accumulation of magnetic material (e.g., iron and nickel) between the magnet poles. In addition to the magnetic-field change, the accumulation within the duct results in a reduction in cross section, causing a velocity increase. Such accumulations have caused voltage increases as great as 12.5% [Ref. 14].

The pressure loss is the usual frictional hydraulic loss of the duct plus the magnetic-braking loss caused by currents circulating within the flowmeter. The currents are those flowing through the walls and those flowing in the end regions (for which voltage-output correction factors are provided). The magnitude of the pressure loss caused by end effects is a function of the magnetic-field profile. A rectangular profile causes the greatest pressure loss [11,35], and an exponentially decreasing field incurs the least loss [11,36]. Sutton, Hurwitz, and Poritsky [36] provided a detailed analysis.

For typical profiles the pressure loss, Δp, in neutrons per square meter (1 psi = 1.45×10^{-4} N/m^2) is given by the relation [11]

$$\Delta p = 0.14 \frac{B^2 Q\sigma}{d} \qquad (4.5)$$

This pressure loss is often regarded as negligible; this is generally true, especially in large flowmeters in which the value of B may be small. The magnetic-flux density, B, must be relatively high in small flowmeters to produce sufficient voltage to operate conventional indicators, as shown in Fig. 4.3. In small low-dynamic-pressure systems, the small-flowmeter pressure loss can be significant. The force involved results in a reaction against the magnet. The magnet weight and other factors ordinarily require mounting structures sufficiently rugged and stiff to make this force negligible. However, a very lightly suspended magnet will move in response to flow.

Flowmeter accuracy depends on the extent to which the degrading factors are controlled. Properly designed and operated flowmeters can be expected to have "calibrations that are linear and reproducible over a long period to ±0.25%, while achievement of more commonplace accuracies of the order of ±1% is very easy in most situations" [11]. Where design and operational factors are only average, the flowmeter accuracy may be reduced but generally can be taken to be within ±5%. When correction factors were used, calibration tests [16] of small flowmeters (2 and 3 1/2 in.) indicated an accuracy, a linearity, and a reproducibility each better than 1%. Calibration in place generally is unnecessary when an axially symmetrical velocity profile at the flowmeter entrance is ensured [11]. Calculated calibration is reported [16] to be no better than 8%. Substantial improvement is possible by designing specifically for calculated calibration [11].

The electrical-conductivity-limiting rate at which the magnetic field can penetrate the liquid metal limits the response time of the electromagnetic flowmeter. The phenomenon involved is essentially that described as skin effect in electrical engineering [11] (see Terman [37]). A more relevant treatment is presented in several texts on magnetohydrodynamics [38], where it is shown that in a length of time, *t*, a magnetic-field disturbance can travel only a distance of the order of $(t/\mu\sigma)^{\frac{1}{2}}$.

The relation between magnetic-field diffusion time and diffusion distance in sodium at 650°C (1200°F) is presented in Fig. 4.10. The diffusion time can be interpreted as response time and the diffusion distance as the flowmeter size [11]. However, much faster response time than is indicated has been observed in tests.

Flow measurement through fuel assemblies (in-core) imposes several intractable constraints, such as high operating temperature and radiation fields, size, and configuration. A special flowmeter design for use in a 650°C sodium-cooled reactor is described in Refs. 39 and 40.

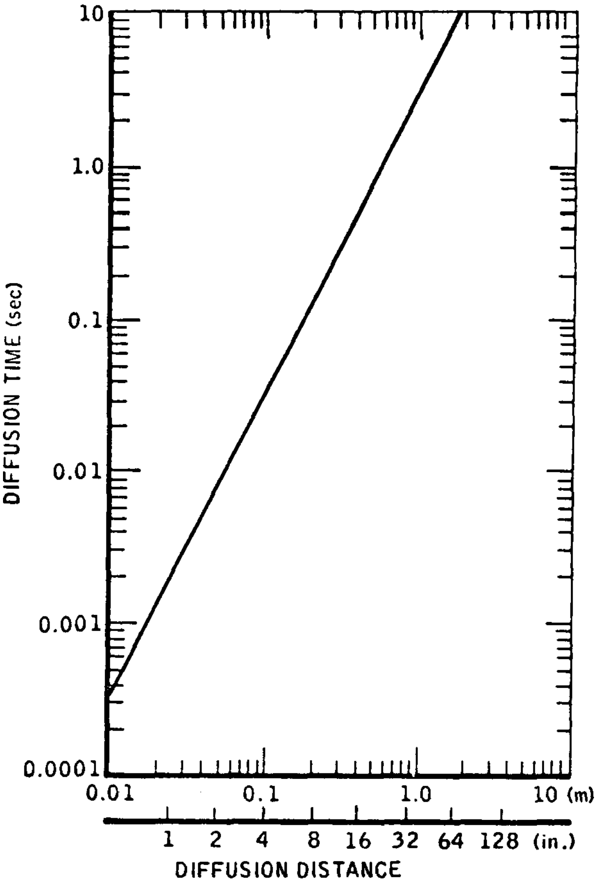


Fig. 4.10 Diffusion time of magnetic field in sodium as a function of distance; ρ is 35.6×10^{-8} ohmmeter at a sodium temperature of 650°C (1200°F).

When an electromagnetic flowmeter is used in space vehicles, the effect of the magnetic field on other instruments having a high sensitivity to magnetic fields and the torque on the vehicle due to interaction with the ambient magnetic field (the earth's field if in an earth orbit) are also considered.

In space applications the permanent-magnet flowmeter is preferred since it requires no external power for operation and satisfies all other performance requirements. The important requirements of weight, size, and configuration can be accommodated by the variety of magnet materials available. In systems using a d-c conduction pump to circulate the liquid metal, the flowmeter can be closely coupled to the pump to share its magnet and thus save weight and ease configuration problems [41]. Another method of measuring flow when a d-c conduction pump is used is to use the pump terminal voltage as the flow signal. Potential leads on the electrodes are placed as close to the duct wall as is practical to minimize electrode-voltage-drop corrections. This method is possible because a d-c conduction pump functions by generating a voltage proportional to the flow rate according to the same principles as the flowmeter. This flow-generated voltage, together with the voltage drop in the pump resistance, is the voltage at the terminals. Hence, in systems in which voltage caused by resistance is known, the terminal voltage can be used as the flow signal, thereby eliminating the need for a flowmeter as a separate component. This technique has been used in space applications [42].

(b) *Electromagnetic Flowmeter*

The magnetic field required for an electromagnetic flowmeter can be supplied by an electromagnet. Since the flux density of an electromagnet is a function of the current, the power supply must maintain a current sufficiently constant in magnitude to keep the flowmeter within the required accuracy range. For a d-c flowmeter the magnet power supply must be capable of providing a direct current. Since an electromagnet requires a well-controlled, continuous supply of power to duplicate the accomplishment of a permanent magnet, which expends no power, the electromagnet is seldom used as a field source.

In some applications, however, the advantages of using electromagnets outweigh the disadvantages. For example, the magnetic-flux density can be adjusted by controlling the current; in special cases, this is an advantage. In some cases an electromagnet meets configuration and weight requirements more easily. However, when the weight is taken to include the power supply, the electromagnet system always weighs more than the permanent magnet.

Two deleterious factors to consider are high coil temperature and radiation effects on the coils. Generally, an electromagnet can be designed so that the coil temperature is well within the limitations of high-temperature insulated wire, and radiation does not usually impair the wire, but some insulations are damaged in high radiation fields.

In large flowmeters with magnetic fields extending several diameters to reduce nonlinearity caused by flux shift, an electromagnet often is favored to reduce magnet bulkiness and weight. In some designs the coils in a rectangular spiral are curved into a saddle form and applied to sides of the duct (outside the thermal insulation) [43,44]. Field shaping for large flowmeters is theoretically treated by Karpov [45].

(c) *Field-Shift Flowmeter*

The operation of a field-shift flowmeter is based on measurement of the electromagnetic-field shift caused by liquid-motion-induced currents. This form of flowmeter is commonly called an eddy-current flowmeter or an induced-field flowmeter.

Figure 4.11 shows installation and schematic diagrams for a flowmeter [46] consisting of a thimble containing a central coil energized by an a-c power supply and a pair of matched coils at each end of the central coil. The end coils are connected differentially so that the net voltage output is zero. Metal surrounding the coils modifies the field distribution, but, in the absence of motion, the field is symmetrical and the net output remains at zero (or a small residual value). Flow of the liquid metal adds an induced component to the symmetrical eddy-current distribution, resulting in asymmetry of the current paths and therefore distor-

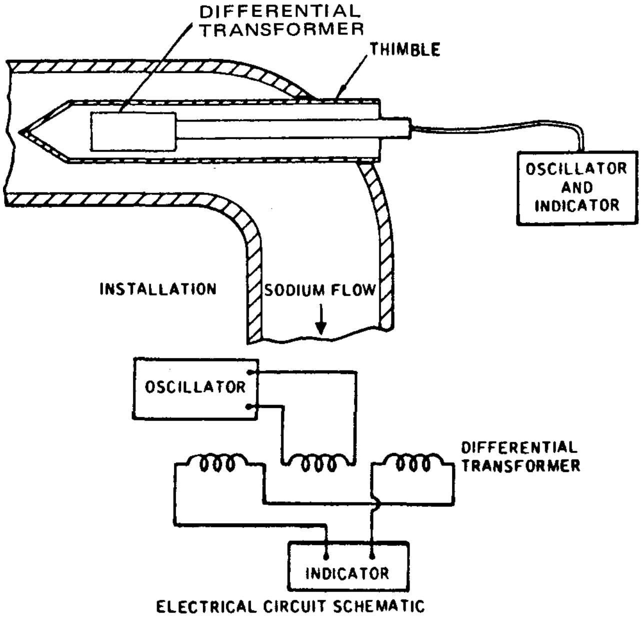


Fig. 4.11 Field-shift flowmeter. [From D. F. Davidson and E. Duncombe, Some Electromagnetic Transducer Techniques for Use at Elevated Temperatures, *Trans. Soc. Instrum. Technol.*, *18*(2): 51-61 (1966).]

tion of the field created by the center coil. The field is displaced downstream, and unequal inductive couplings to the two end coils result. This causes an imbalance, and, since the coils are connected differentially, a voltage appears at the terminals.

Because of skin-depth effects, the external field penetrates into the liquid metal only to a limited extent. The region of penetration, near the stationary surface, has a large velocity gradient, the velocity distribution being a function of Reynolds number and of the ratio of pipe-to-thimble diameter. Empirical calibrations [46] have shown that the voltage output is substantially linear with local mean fluid velocity. The coils are anodized aluminum wire wound on a three-section ceramic spool [46]. The voltage output depends on the liquid-metal conductivity, and hence the meter is temperature sensitive. Wiegand [47] and Cowley [48] analyzed this type of flowmeter.

The field-shift flowmeter has been constructed in other configurations, notably those in which the duct passes axially through the coils and those in which the windings are on an external E-core.

4-2.2 *Thermal-Transit-Time Flow Measurement*

The thermal-transit-time flowmeter is based on the measurement of the transport time of a thermal noise pattern over a known distance. Random temperature (noise) patterns are inherent in a turbulent fluid stream after a large exchange of heat [49]. The temperature patterns are detected by two thermocouples spaced along the direction of flow; the resulting fluctuating signals are amplified and analyzed to give the transit time and hence the liquid velocity.

A schematic diagram of the measuring equipment [49] is shown in Fig. 4.12. The thermocouples are placed only a few duct diameters apart. The thermocouple signals (at the microvolt level) are amplified and recorded on tape for subsequent analysis. If a computer is available, the measurement can be done directly using continuous real-time correlation [44]. The mean transport time of the thermal signals in the liquid is not substantially influenced by flow profile and therefore is substantially independent of upstream conditions. Measured temperature signals are typically 0.01 to 1.0°C peak to peak at frequencies below a few cycles per second [49].

Thermocouples are selected in pairs that have similar response characterstics to avoid errors introduced by differences in thermocouple response time [49]. The accuracy is estimated to be about ±2% under ideal conditions and between ±3 and ±5% in practical applications [43,49]. Less optimistic estimates [49] are ±10%. The estimated statistical error in sodium tests [49] was 4%. Statistical errors can be reduced only by increasing the averaging period, and in practical situations this must be at least 10 min or more if the transit time is long and the coherence is low.

Randall and Logan [50] reported other investigations of transit time using thermal-noise-analysis techniques.

4-2.3 *Differential-Pressure Flowmeter*

The differential-pressure flowmeters, commonly called variable-head flowmeters (orifice, nozzle, and venturi types), are well established in process flowmeter technology and are generally satisfactory in liquid-metal applications. Disadvantages (mainly in relation to the permanent-magnet flowmeter) include pipe penetration for pressure taps; dependence on other instruments, particularly pressure transducers; obstructions in the flow path and hence pressure loss; nonlinear response; and sensitivity to flow conditions. Since the differential pressure varies as the

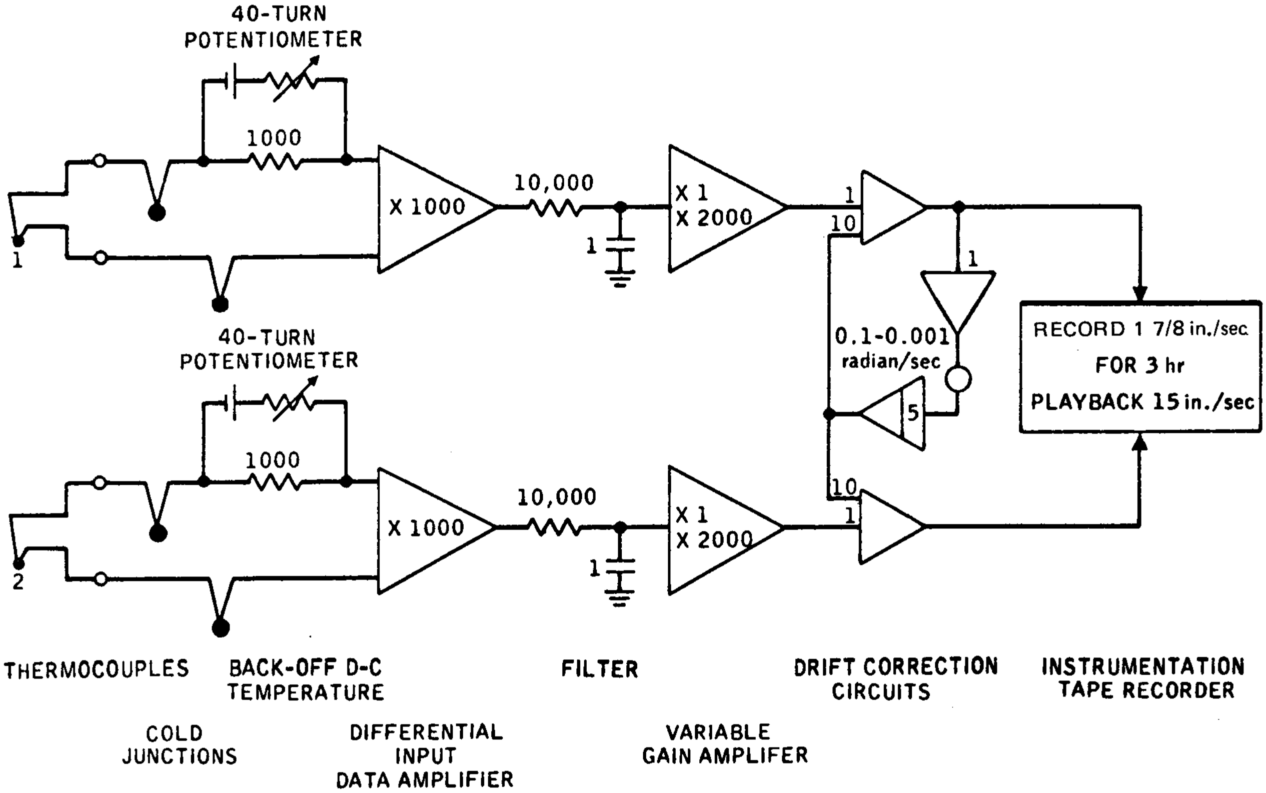


Fig. 4.12 Thermal-transit-time flowmeter circuit. [From P. G. Bentley and D. G. Dawson, Fluid Flow Measurement by Transit Time Analysis of Temperature Fluctuations, *Trans. Soc. Instrum. Technol.*, *18*(3): 184 (1966).]

square of the flow rate, the flow-rate range that can be accommodated by a single pressure transducer is limited. Generally, the flow-rate range is considered to be limited to about 3 to 1. Additional transducers of appropriate ranges are used to cover a much larger range. The well-developed technology, accuracy, and reproducibility are often cited as advantages, and, when these are dominant considerations, the differential-pressure flowmeters are often used. The principles of operation, design features, and performance factors are readily extended to liquid-metal service. These factors are not peculiar to liquid metal, and standard literature in this field is readily available (see, for example, Ref. 51).

Flowmeters of this type ordinarily are calibrated with water. The accuracy with which water calibration can be extrapolated and substituted for liquid-metal calibration is questionable. A study [52] of the applicability of water-model testing to liquid-metal problems concluded that calibration of a liquid-metal flowmeter in a water-model test is justified if only limited accuracy (not better than about 5%) is required. Calibration accuracy can generally be improved by improving the uniformity of flow, by using a high degree of geometrical similitude (preferably full scale), by avoiding any cavitation, and by improving pressure-measuring techniques. The accuracy can be improved to significantly better than 5% by very careful full-scale prototype calibration.

4-3 PRESSURE MEASUREMENT

Pressure measurement in sodium is

similar to that in other branches of process technology of comparable range and environmental factors. Nearly all pressure measurements in sodium are made by a pressure gauge using some form of elastic element - a diaphragm, Bourdon tube, or bellows. Pressure measurement based on the height of displacement of a column of sodium against the force of gravity is seldom used.

Most pressure measurements are made in liquid-metal systems to determine the static pressure. Static pressure is measured by placing the sensor in the liquid at the point at which the measurement is desired in such a way that the liquid is not disturbed. Generally it is not practical to locate the sensor to meet these objectives exactly. The sensor is commonly placed outside the containment wall and is connected through a short length of tube or standoff. This can have an effect on the pressure indication and hence can introduce error. One factor is the effect on response time. This is a complicated function of geometry, but generally the effect is negligible for short tubes. Another factor is the weight of the liquid metal in the tube contributing to the pressure at the sensor; this is an amount proportional to the elevation difference between the sensor and the measuring point. A third factor, when the measuring point is in a moving stream of sodium, is the probe- or pressure-tap-caused disturbance to the flow stream; this disturbance can contribute to the indicated pressure. These sources of error are treated in the literature on pressure measurement. In liquid-metal systems an additional factor to consider is the plugging of the tube or standoff.

Since a sensor performs better at temperatures considerably below the typical system temperature, the temperature is reduced along the length of the standoff. In regions where the temperatures are below the solubility limit of dissolved impurities, the impurities, mainly oxide, precipitate and the accumulation of the precipitate causes plugging. This behavior is essentially that of a cold trap as described in Vol. V, Chap. 1.

The possibility of plugging is minimized by having a large opening and a large-diameter, short standoff. However, structural and fabrication factors favor the use of small-size containment-wall penetrations. When flow is involved, the small-size opening is favored to minimize flow disturbances that cause pressure errors.

The choice of mounting orientation depends on several factors. Mounting the sensor above the pipe or vessel enables draining, but this orientation permits the formation of gas pockets during filling, and these impair the response-time characteristics. Mounting the standoffs downward eliminates the problem of gas pockets, but then the standoff and gauge are not easily drained. Unless drainage is a significant factor, the downward orientation is preferred. Horizontal mounting, as a compromise, does not necessarily solve the problems.

4-3.1 *Elastic-Deformation Pressure Gauges*

A number of materials commonly used as flexural elements in pressure gauges are not satisfactory for use in contact with liquid sodium. The basic criteria are compatibility with sodium and satisfactory flexural properties in the sodium environment over the required operating life. This limits the selection to the austenitic stainless steels and possibly a few other materials. The effects of sodium on materials is discussed in Vol. V, Chap. 2.

In the most conventional concept of a pressure gauge, a flexural element (1) serves to sum the fluid forces and (2) provides the elastic properties on which the force-displacement relation (spring rate) depends. The simple diaphragm gauge in which the diaphragm displacement is sensed directly by a transducer is an example of this type. The diaphragm functions as a calibrated spring. This calibration can be impaired by contact with hot sodium, which can cause thickness reduction by corrosion; diametral changes, including buckling by thermal expansion; and reduction in the modulus of elasticity with increasing temperature.

In a different design, generally better suited to sodium service, the two functions, force summing and force measurement, are performed by separate devices. The force summing is accomplished by a relatively compliant flexural element, for example, a bellows having a low spring rate. The element is coupled mechanically to the force-measuring device, which has a relatively high spring rate. With this arrangement the force-displacement relation is controlled by the characteristics of the force-measuring device with relatively little influence from the elastic characteristics of the force-summing flexural element. This separation of functions reduces the constraints on the force-measuring device and permits its operation in a more favorable environment, free from contact with sodium and the associated environmental problems. In this design the main problem in relation to the effect of sodium is the integrity of the flexural element in contact with sodium, and that effect is limited to corrosion. Thickness reduction has negligible effect on calibration. A flexural element used in this manner is called a chemical seal or simply a seal. Examples of this concept are gauges using a spring-restrained bellows and gauges using a NaK-filled transmission line connecting the back side of a seal to a pressure gauge.

True elastic behavior, that is, a simple linear reversible relation between stress and strain (Hooke's Law), is an idealized concept. When time is considered in the elastic processes, the deviations, or anelastic effects, appear. These include elastic hysteresis and creep. These material properties and other factors associated with mounting contribute to the effects described [53] as:

1. Hysteresis - difference between the displacement at a given load, for decreasing and for increasing loads.
2. Drift - increase of displacement with time under a constant load.
3. Aftereffect - displacement remaining immediately after removal of the load, i.e., hysteresis at no load.
4. Recovery - decrease of aftereffect with time under no load or also the time decrease of hysteresis at a constant load.
5. Zero shift - permanent deformation, i.e., the difference in no-load deflection before loading and sufficiently long after unloading for recovery to occur (the difference between aftereffect and recovery).

A low stress level, a common design objective, is particularly important in the design of the elastic elements used in pressure gauges. Some designs, based on a measurement of the force required to prevent elastic-element displacement, minimize the defects described previously.

(a) *Bourdon Tube Gauge*

Typically, a Bourdon tube gauge is connected to the system so that the system fluid enters the tube and actuates it. This arrangement is not entirely satisfactory in liquid-metal applications unless an adequate ambient temperature is maintained, since the Bourdon tube and any connecting line (a capillary tube) can freeze or function as a cold trap, with consequent plugging, impaired operation, and tube damage. The gas-trap method avoids the problem of liquid metal in the Bourdon tube (and connecting line) by measuring the gas pressure required to maintain a reference level in a reservoir connected to the system. However, this method generally is unsatisfactory because of condensation of liquid-metal vapors in the connecting line or Bourdon tube.

Despite these problems the Bourdon pressure gauge is used satisfactorily as a transducer in conjunction with a diaphragm pressure gauge, discussed in the following section. Bourdon tube design is treated in Refs. 54 to 57.

(b) *Diaphragm Pressure Gauge*

A simple diaphragm is a thin, flat, circular plate having a fixed edge supported in a rigid mounting ring. The diaphragm is joined to the ring by welding at the outer edge of the ring when the diaphragm is used in gauges for liquid-metal service. This method has been satisfactory in commercial gauges made for liquid-metal service. Friction between the diaphragm and the support ring can contribute to mechanical hysteresis. The possibility of hysteresis and the problems of making a satisfactory closure by welding can be avoided by making the diaphragm and ring of one piece. Generally this method of fabrication is preferred, but its use is limited by the practical difficulties of machining a diaphragm of large diameter-to-thickness ratio to achieve high sensitivity.

The deflection-pressure relation of a diaphragm is nearly linear over the range of deflection up to a deflection-to-diameter ratio of 0.02. Diaphragm design and characteristics are discussed in detail in Refs. 53, 58, and 59.

A diaphragm so thin that its stiffness to bending forces is negligible is called a membrane. The possibility of failure of a very thin element discourages the use of a membrane. The use of several membranes stacked together to form a multi-ply diaphragm is common practice in liquid-metal gauges.

Corrugation of the diaphragm permits larger deflections and better control of the shape of the pressure-deflection curve. Increasing the number of corrugations increases the initial flexibility in the low range and the average flexibility over the usable range, but diaphragms with more corrugations have nonlinear characteristics and become progressively stiffer for large deflections. Diaphragms with triangular and trapezoidal corrugations have a linear response for deflections up to 2% of the diameter. Diaphragms with shallower corrugations have higher initial flexibility but have a decreased linear range. A trapezoidal form is stiffer than the smooth-curve form, but the triangular form is slightly more flexible than the smooth-curve form.

A pressure sensor having an unrestrained diaphragm integral with its housing is illustrated [60] in Fig. 4.13. The diaphragm deflection is sensed by a variable impedance transducer in close proximity to the diaphragm. The complete gauge consists of the sensor unit and an oscillator and demodulator unit that delivers a d-c output signal of 0 to 5 volts. Manufacturer's data [60] give the following characteristics:

Pressure ranges, above ambient (gauge pressure):

0 to 1.48×10^6 N/m^2 (0 to 200 psi)
0 to 7.4×10^6 N/m^2 (0 to 1000 psi)

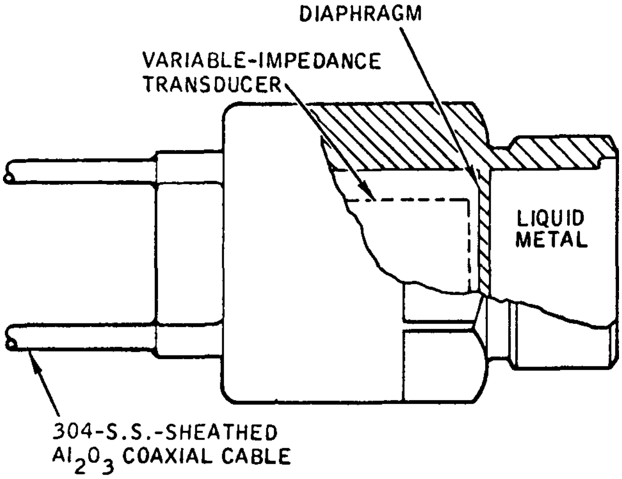


Fig. 4.13 Pressure sensor with integral unrestrained diaphragm. [From Kaman Nuclear, Data Sheet K-1900, Colorado Springs, Colo.]

0 to 1.48×10^7 N/m^2 (0 to 2000 psi)
Proof pressure:
300% of pressure range
Operating temperature range:
-18 to +538°C (0 to +1000°F)
Calibrated temperature range:
20 to 538°C (68 to 1000°F)
Diaphragm resonance: >15 kHz
Nonlinearity: <±1% of full range
Thermal zero shift: <10%
Thermal sensitivity shift: <3%
Transmission-line length: 3 m (10 ft)

Kirillov *et al.* [14] described an arrangement using an unrestrained diaphragm to operate a differential transformer through a pushrod. Lack of diaphragm-overload protection was cited as a shortcoming leading to frequent failure.

Clark [61] described a differential-pressure diaphragm sensor with a spring restraint which operated a differential transformer through a pushrod.

The pneumatic-balance diaphragm gauge, evaluated in a test program [62], was found to have excessively high zero shift due to temperature and a nonlinear response.

Figure 4.14 shows a very successful design in which the diaphragm deflection, resulting in a volume change in the NaK-filled chamber behind the diaphragm, is communicated via the NaK-filled transmission line to a transducer [62]. The diaphragm and housing, transmission line, and transmitter are joined as a unit, and the volume to be filled is cleaned, filled with purified NaK, and sealed at the time of manufacture to prevent the problems associated with impurities and voids. When this type of sensor was tested with several types of transmitters [62], the best performance was obtained with a model using a Bourdon-tube strain-gauge transmitter. Tests [62] over a temperature range of 20 to 760°C (68 to 1400°F) and a pressure range of 0 to 100 psi showed an accuracy of 0.4% of full scale and a zero shift of less than 3% of full scale when the temperature of the case containing the transmitter and compensating resistor did not exceed 93°C (200°F).

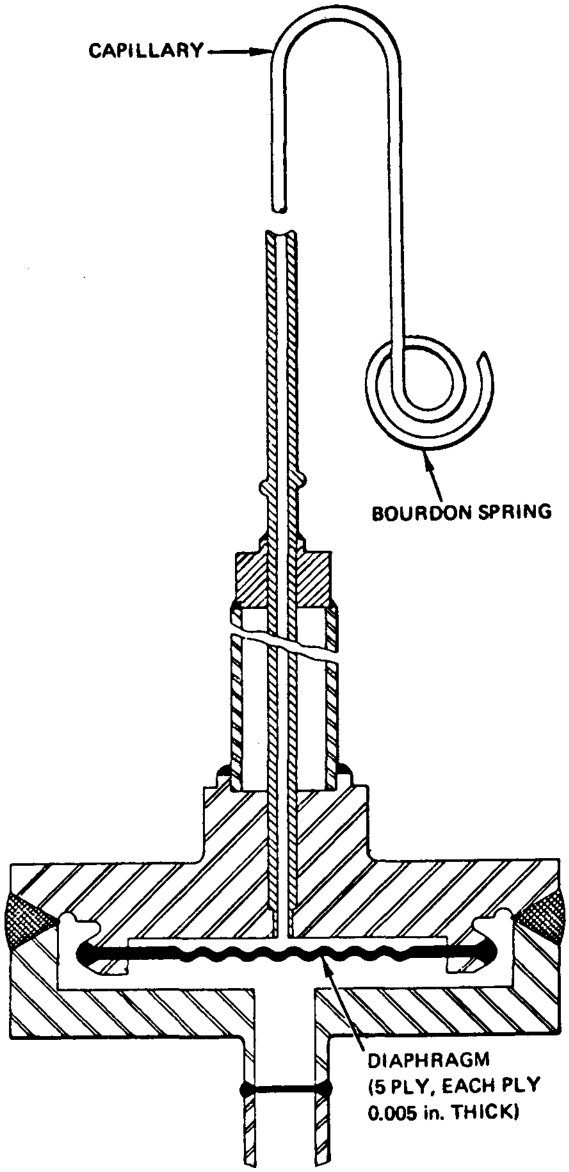


Fig. 4.14 NaK-filled diaphragm pressure sensor.

The accuracy capability of these pressure sensors can be increased significantly by operating them at a constant temperature. Resistance heating, separately controlled by a temperature sensor located on each pressure transducer, accomplished this. The most significant effect of the change in temperature on the calibration curve for this particular type of transducer is a shift in the zero reading of the instrument with an equivalent shift at all other points on the characteristic curve. A very slight change in the slope of the characteristic curve occurs with changes in temperature. It is impossible to predict the characteristic for any given pressure gauge, however, since the actual output curve is extremely sensitive to variations in NaK filling of the capillary. Therefore, the individual characteristics of each sensor must be determined by calibration [63].

The response time of this type of gauge is less than 1 sec [62]. In addition to high accuracy, significant advantages cited were:

1. The signal output is electrical (direct current).
2. The strain gauge can be zeroed and spanned remotely.
3. The unbonded strain gauge does not contain organic insulators that can be damaged by radiation.
4. The NaK transmission-line method permits adjustments on the transmitter to be performed away from the hot piping.
5. The use of a NaK transmission line provides, in effect, a double containment of the process fluid [62].

Other tests and operating experience with these pressure gauges reported good performance [64-67]. A variation for measuring differential pressure [64] is shown in Fig. 4.15. The sensor is larger and has a single-ply diaphragm

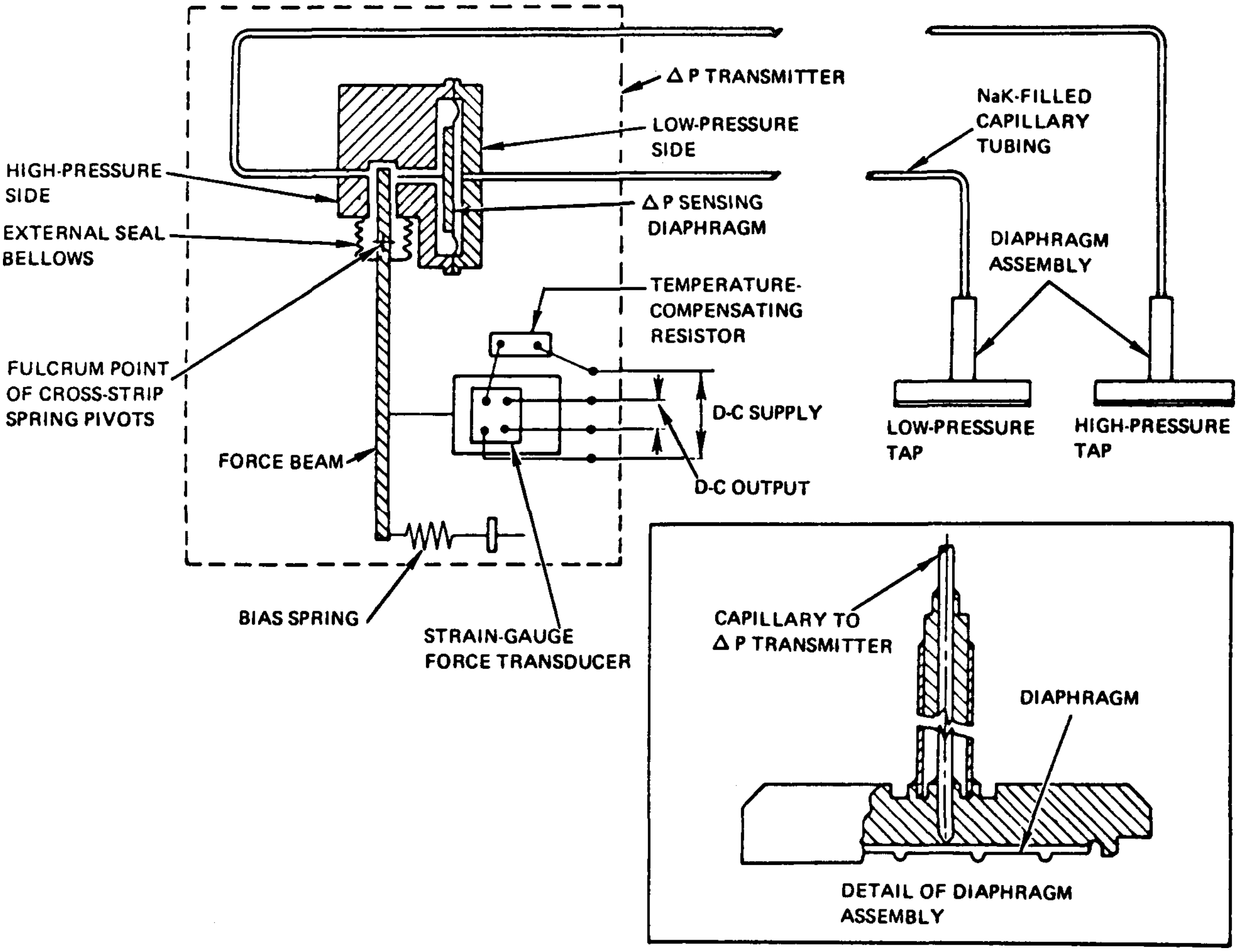


Fig. 4.15 NaK-filled differential pressure gauge.

0.127 mm (0.005 in.) thick for higher sensitivity. Compared with the thicker diaphragm, it is more susceptible to a permanent set if subjected to a vacuum or an overpressure. The use of two liquid-filled sensors, as illustrated in Fig. 4.15, requires a correction for any difference in elevation between the two sensors. The head difference multiplied by the specific gravity of the NaK gives the correction value or zero shift due to the elevation difference.

Other experience with differential pressure gauges of this type is discussed in a series of progress reports [68] beginning in 1963.

Hluchan [69] described a design for NaK-filled pressure gauges in which the differential form uses a single housing for the two diaphragms.

(c) *Bellows Pressure Gauge*

Bellows permit greater displacement than a diaphragm of the same diameter. This enables the use of displacement-to-signal transducers, which function well for relatively large displacements and consequently are out of the range of the characteristic interference factors.

A bellows pressure sensor using a pneumatic null-balance mechanism [70] is illustrated in Fig. 4.16. This type of sensor is used in conjunction with a pneumatic relay, the assembly being connected as illustrated in Fig. 4.17. Liquid-metal pressure surrounding the bellows causes a compression that results in restriction by the nozzle seat of gas flow through the orifice and a consequent increase in the gas back pressure. The relay responds to the back pressure.

The manufacturer's data [70] show the following:

Maximum operating pressure:
1.55×10^6 N/m^2 (225 psi)
Warranted operating temperature:
427°C (800°F)
Maximum operating temperature:
649°C (1200°F)

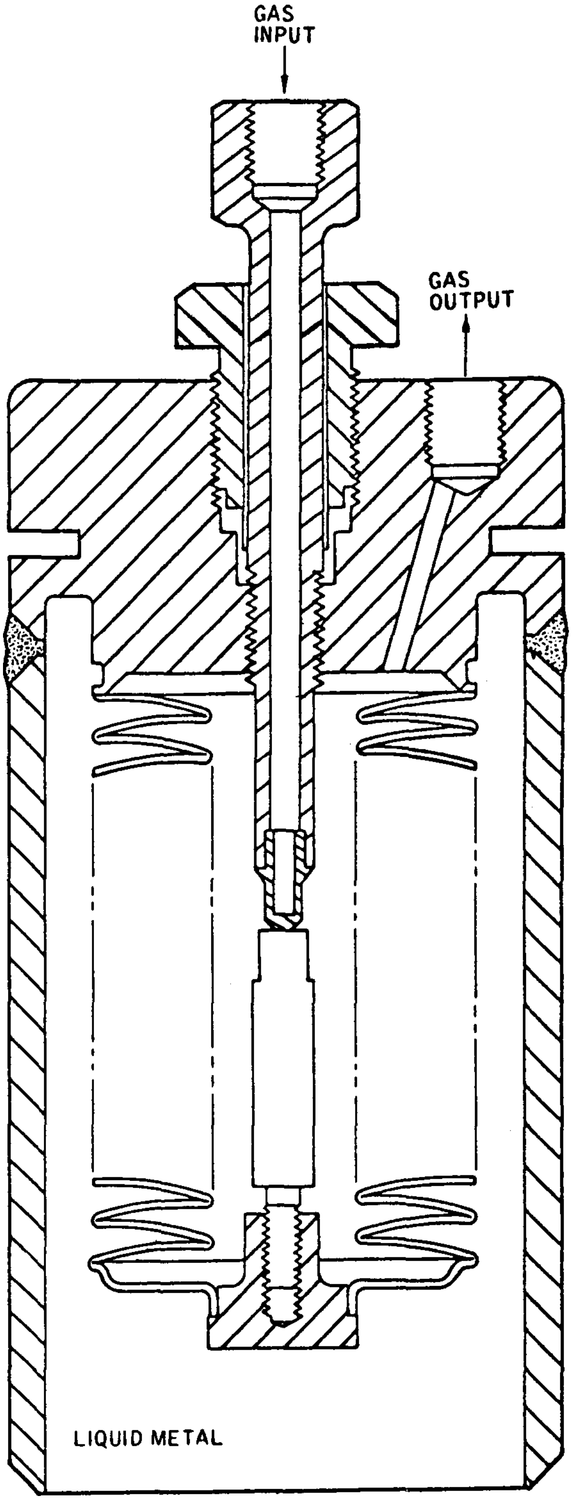


Fig. 4.16 Bellows pressure sensor using pneumatic null-balance mechanism. [From Moore Products Co., commercial literature, drawing No. 12528-2-M, 1967.]

Maximum overrange (differential across bellows):

1.38×10^6 N/m^2 (200 psi) at 316°C (600°F)

2.07×10^5 N/m^2 (30 psi) at 538°C (1000°F)

Repeatability at constant temperature: 4.98×10^2 N/m^2 (2 in. H_2O)

Linearity: $\leq$ 0.5% full scale

Input-to-output ratio of 1 to 1: $\leq$ 2%

Zero shift for 427°C (800°F) temperature change: 1.724×10^3 N/m^2 (0.25 psi) maximum

Long term drift: 1.724×10^3 N/m^2 (0.25 psi) maximum.

The performance, particularly temperature effects and drift, can be affected considerably by the method of installation. Errors can be minimized by setting the zero at the operating temperature. Zeroing at high temperature presents problems since the adjustment components are hot and rather difficult to operate. These sensors have been operated [70] at temperatures up to 760°C (1400°F); however, at such temperatures satisfactory operating lifetime is reduced. At temperatures above 427°C (800°F) an inert gas for operating the pneumatic system is recommended to minimize bellows corrosion [70]. Various earlier models of this type of pressure sensor were subjected to an evaluation program [62]. Subsequent experience in the use of later models at the Enrico Fermi Atomic Power Plant (EFAPP) was reported by Reicks [64] and Scott [67].

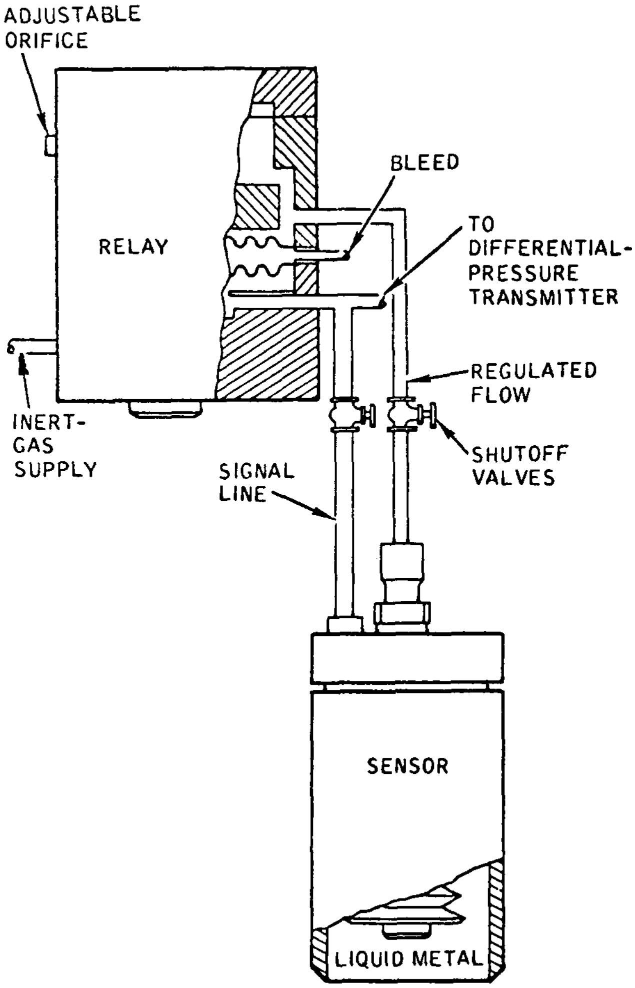


Fig. 4.17 Bellows pressure sensor and relay.

A compact pressure gauge designed particularly for high temperature, 871°C (1600°F), in high-radiation environments [71] is shown in Fig. 4.18. Liquid-metal pressure in the lower bellows causes an extension that moves the coupling disk to contact the thermocouple junction, which is part of an electric control circuit. A slightly greater gas pressure applied to the upper bellows forces the coupling disk from the thermocouple contact and breaks the circuit. The minimum gas required to prevent contact is equal to the liquid-metal pressure. This design performed well in radiation exposures of 2×10^{20} nvt fast and 10^{21} nvt thermal. Out-of-pile sodium tests [71] at 260 to 593°C (500 to 1100°F) demonstrated accurate pressure measurements at 4.48×10^5 N/m^2 (65 psi). The bellows were made of 0.076-mm (3-mil) 347 stainless steel. The housing is 8.89 mm (0.35 in.) in outside diameter and 10.2 mm (0.4 in.) long. Overall length [71], including pressure connectors, is 16.5 mm (0.65 in.).

A spring-balanced bellows-type pressure sensor [72] using a differential transformer to sense bellows compression caused by liquid-metal pressure is shown in Fig. 4.19. The full-range deflection

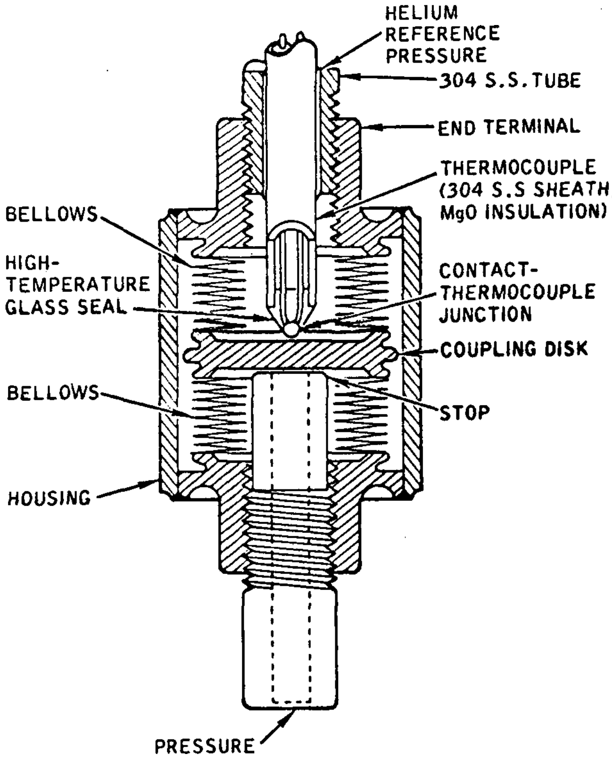


Fig. 4.18 Miniature null-balance bellows pressure sensor.

is of the order of 1.27 mm (0.05 in.). The spring rate of the balancing springs is 50 times that of the bellows spring rate to minimize the effect of the changing of the bellows spring rate with liquid-metal temperature. The balance springs operate in a relatively cool region due to the poor thermal conduction path between the bellows region and the springs.

The manufacturer's data [73] indicate the following:

Output current: 0 to ±1 ma
Ranges above ambient (gauge pressure):
  0 to 6.89×10^4 N/m^2 (10 psi)
  0 to 1.73×10^5 N/m^2 (25 psi)
  0 to 3.45×10^5 N/m^2 (50 psi)
  0 to 6.89×10^5 N/m^2 (100 psi)
  0 to 1.38×10^6 N/m^2 (200 psi)
  0 to 2.76×10^6 N/m^2 (400 psi)
  0 to 4.14×10^6 N/m^2 (600 psi)
Liquid-metal temperature:
  <871°C (1600°F)
Ambient temperature:
  -17.8 to 93.4°C (0 to 200°F)

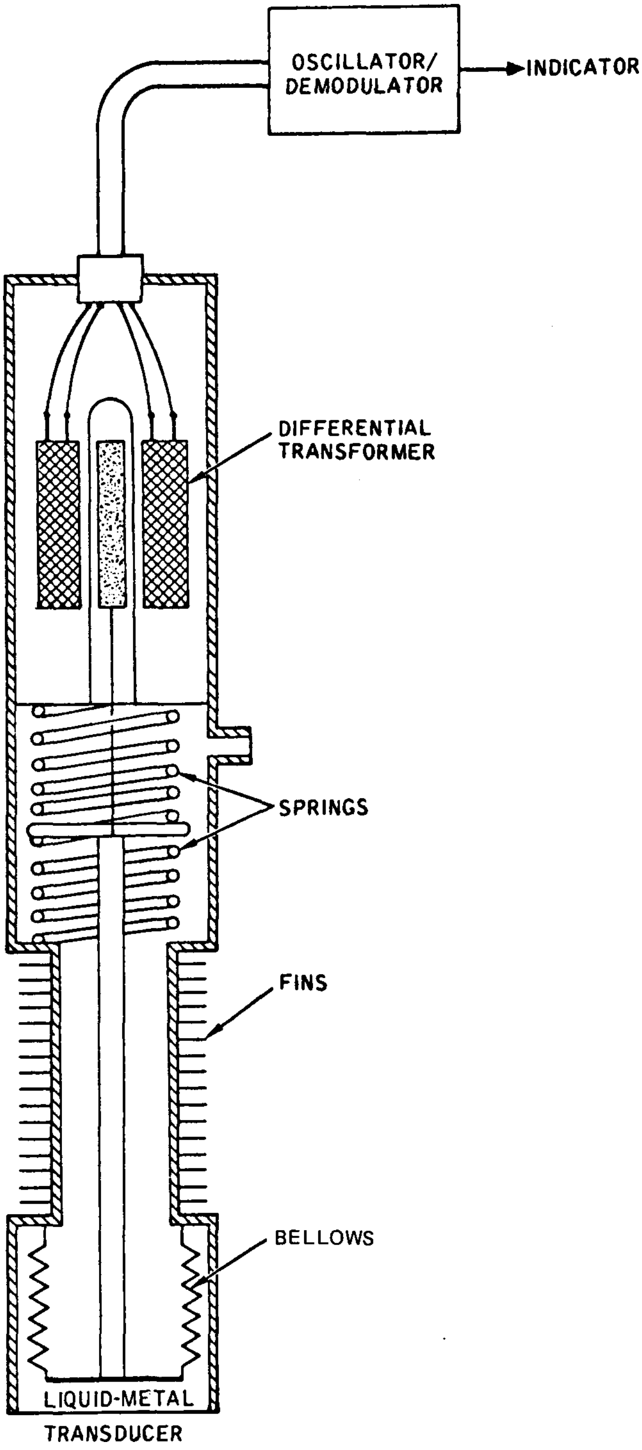


Fig. 4.19 Spring-balanced bellows pressure sensor with differential-transformer displacement transducer.

Sensitivity: 0.5% full scale
Accuracy: ±2% full scale over the

range 93.4 to 538°C (200 to 1000°F)

Linearity: within 1% full scale.

Calibration in place at the operating temperature gives greater accuracy. The zero is a function of the bellows ambient pressure. Evacuation or pressurization is accomplished through the tube at the side of the housing. Evacuation shifts the zero to provide measurement of liquid-metal absolute pressure. High bellows ambient pressure permits shifting the zero to a relatively high value. This shift enables a relatively high resolution over a selected narrow span, a small fraction of the system pressure [72]. Miller [62] reported the performance evaluation of an early model of this gauge.

A pressure gauge similar in operating principle [74] is shown in Fig. 4.20. The use of the ring as the flexural device provides easy calibration and linear characteristics over the relatively small range of deflections required. The accuracy of this gauge is ±1% at transducer head temperatures up to 400°C [61]. Thacker [74] presented design details including working drawings. A similar gauge using a ring is described in Ref. 75.

A bellows-type differential-pressure gauge [76] is illustrated in Fig. 4.21. Pressure on the sensor bellows results in a compression displacing the NaK filling into the transmission line. The NaK displacement communicated to the differential unit compresses the bellows contained. A differential pressure between the two sensors, thus communicated to the differential-pressure unit, results in a corresponding mechanical shift in the pair of mechanically connected bellows. These pressure gauges are made in a wide range of differential-pressure values from 6.89×10^3 to 3.45×10^6 N/m^2 (1 to 500 psi) [76]. Transmitters can provide additional span reduction and zero suppression. Thermal sensitivity is minimized by minimizing the amount of NaK in the regions subjected to high temperature. This is aided by the use of

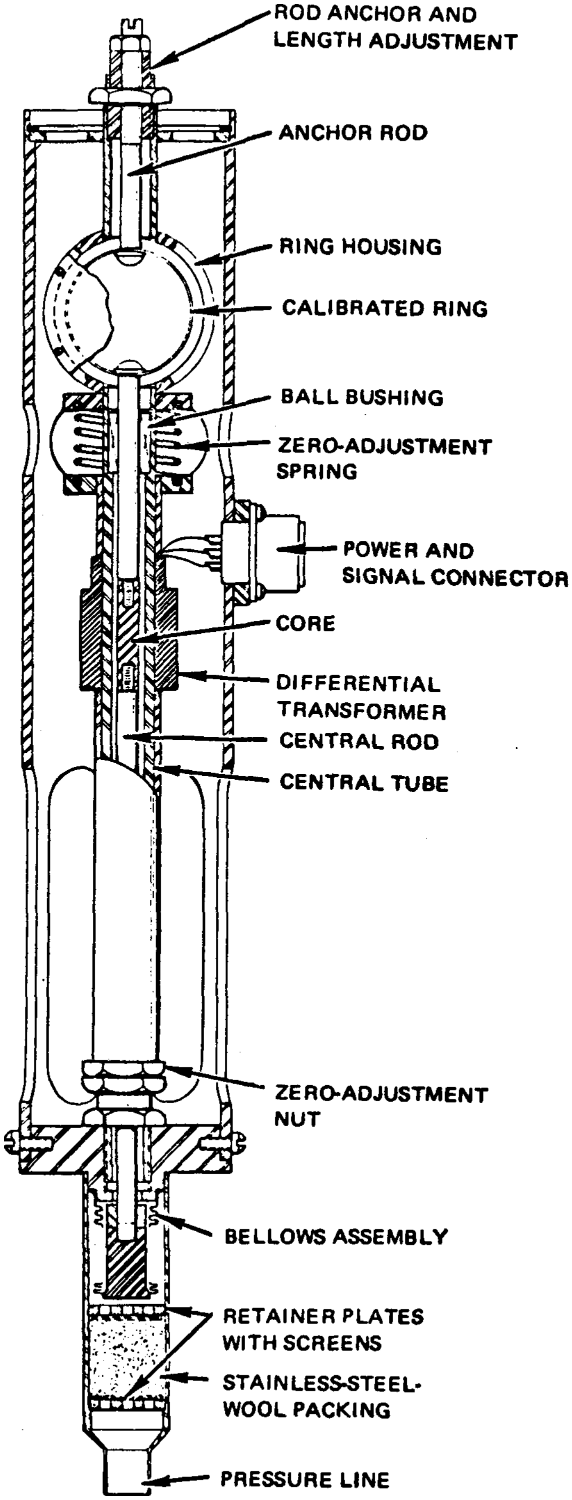


Fig. 4.20 Section view of a bellows-type pressure gauge using a differential transformer displacement transducer.

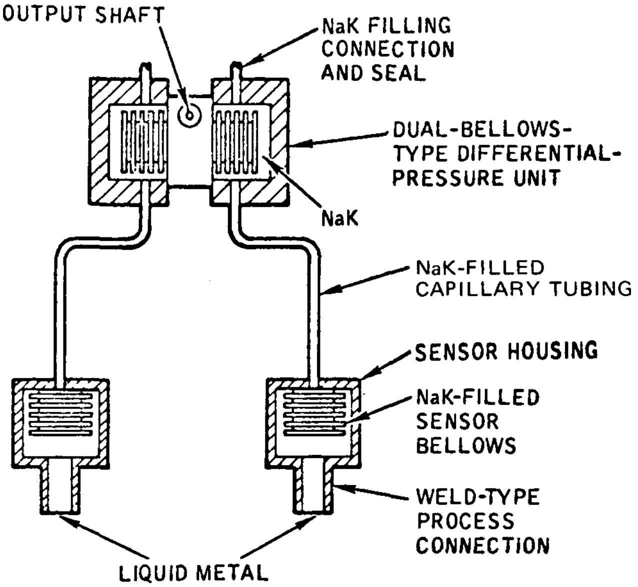


Fig. 4.21 Bellows-type differential-pressure gauge.

small-bore capillary tubing for transmission and by displacers inserted within the bellows cavity [76]. The response time is approximately 1 sec for a 10-ft capillary and 5 sec for a 100-ft capillary. Lawford [76] presented design and fabrication data.

A bellows-type differential-pressure gauge, using a pair of bellows that jointly operate a differential-transformer armature, is described in Ref. 77.

In another design [14] using a pair of bellows, one bellows is the liquid-metal sensor contacting the liquid metal and is connected by a pushrod to the other bellows, which serves to produce pressure in a hydraulic (oil) line connected to a conventional pressure gauge.

4-3.2 *Manometer Pressure Gauge*

The manometer method of measuring liquid-metal pressure circumvents many of the problems associated with elastic-deflection devices. The manometer can be made as rugged as required with little sacrifice of sensitivity. Despite the numerous advantages of the manometer, its disadvantages of slow response, need for a level gauge, and bulkiness (except for low differential pressures) deter widespread usage.

4-4 LEVEL MEASUREMENT

Most of the level-measurement techniques commonly used in the process industry and in scientific work have been evaluated for use with liquid metals, and some have been successfully applied to liquid-metal level measurement. The high electrical conductivity of liquid metals provides the basis for several techniques that are not practical with many other liquids. Most liquid-metal level measurements are made by the electrical conductivity techniques. Methods based on liquid-metal density and temperature are less widely used.

Level gauges are categorized as discrete-point or continuous types, and as contacting or noncontacting types. Often a discrete-point gauge is made variable so that it can function as a continuous gauge by providing movement or a series of point sensors spaced at suitable levels for the desired degree of continuity. Generally, a point sensor gives better resolution and confidence than a continuous sensor. Direct-contact sensors in liquid metal are subject to the conditions of compatibility and structural integrity, and, in addition, sensors depending on electrical conductivity are subject to the condition of wetting. Noncontacting sensors are not subject to these conditions since they are mounted outside the containment vessel or, more commonly, in a closed-end tube (thimble) immersed in the vessel. The noncontacting sensor is relatively easy to replace and service.

4-4.1 *Direct-Contact Sensors*

(a) *Resistance-Tube Level Gauge*

The operation of a resistance-tube level gauge depends on the electrical shorting of the tube along the length covered by liquid metal. For good performance the contact resistance between the liquid metal and the resistance tube must be very low and constant. The contact resistance is a function of the wetting of the tube by the liquid metal. The quality of wetting is a function of time, temperature, tube surface condition, and the nature of the materials involved. Satisfactory wetting usually is obtained after contact with the liquid metal at temperatures above 316°C (600°F). Wetting takes place at lower temperatures and in a shorter time in a tube with a rough surface obtained, for example, by sandblasting and washing to remove the grit [78]. A polished surface should be avoided [78]. Jordan and Lane [79] discussed the theory of wetting by liquid metals, and Fanciullo [78] and Wahl [80] reported experimental investigations of wetting and ways of improving it, as related to resistance-tube level gauges. Wetting is an important factor to consider in the use of these gauges during the initial operation of a system when the temperature is low. The wetting problem vanishes after operation for a time at high temperature.

The tube should have a high resistance per unit length to satisfy the electrical-circuit parameters. Most materials suitable for use, typically the stainless steels, have a resistivity well above that of sodium or NaK. The resistance is an inverse function of wall thickness; thus the wall should be as thin as possible, considering such factors as mechanics, corrosion, and reliability.

(1) *I-Tube*. An I-tube gauge [81], such as that shown in Fig. 4.22, provides a continuous measure of level. The element is made of stainless-steel tubing swaged over two MgO-insulated stainless-steel wires. One end of the tube is welded closed, forming a welded junction with the two wires. The assembly is inserted into the vessel from the bottom. One internal wire is for current and the other is for potential measurement; the two wires are connected to the end of the tube outside the vessel [81].

Accuracies of ±1% of full scale can be achieved on I-tubes by calibration. Calculated values of level can be obtained to within ±5% [81].

The material used for the wires and sheath is 304 stainless steel with sheath outside diameters of 4.76 mm (0.187 in.), 6.35 mm (0.25 in.), or 9.52 mm (0.375 in.), all with walls approximately 0.762 mm (0.03 in.) thick. The wires are 0.406 mm (0.016 in.) in diameter in each size [82]. I-tubes of this design, having the 3/8-in.-OD tubing, have been as long as 48 in. [83]. The accuracy was ±2% of the active length at 204 to 760°C (400 to 1400°F) with a-c excitation. The same accuracy was obtained with d-c excitation when correction was made for the thermoelectrical emf [83].

With these materials operation is satisfactory up to 816°C (1500°F). For higher temperature [to 1204°C (2200°F)], refractory metals (Nb-1% Zr) were used for the tube and wires, and hard-fired alumina (Al_2O_3) was used for the insulation [83].

Since the wire resistance, R_w, is approximately 100 times the resistance of the tube wall, $R_{ta} + R_{ti}$, where R_{ta} designates the active portion and R_{ti} designates the inactive portion of the sheath-wall resistance and the resistance of the shunting liquid metal is negligible, the output of the I-tube is given by

$$E_{out} \doteq E_{in} \frac{R_{ti} + R_{ta}}{R_w} \tag{4.6}$$

With E_{in} held constant or any variations accounted for in the readout instrument, the output voltage E_{out} is a linear function of the liquid-metal level; it decreases as the liquid-metal level increases, the minimum signal depending on the inactive length of the I-tube

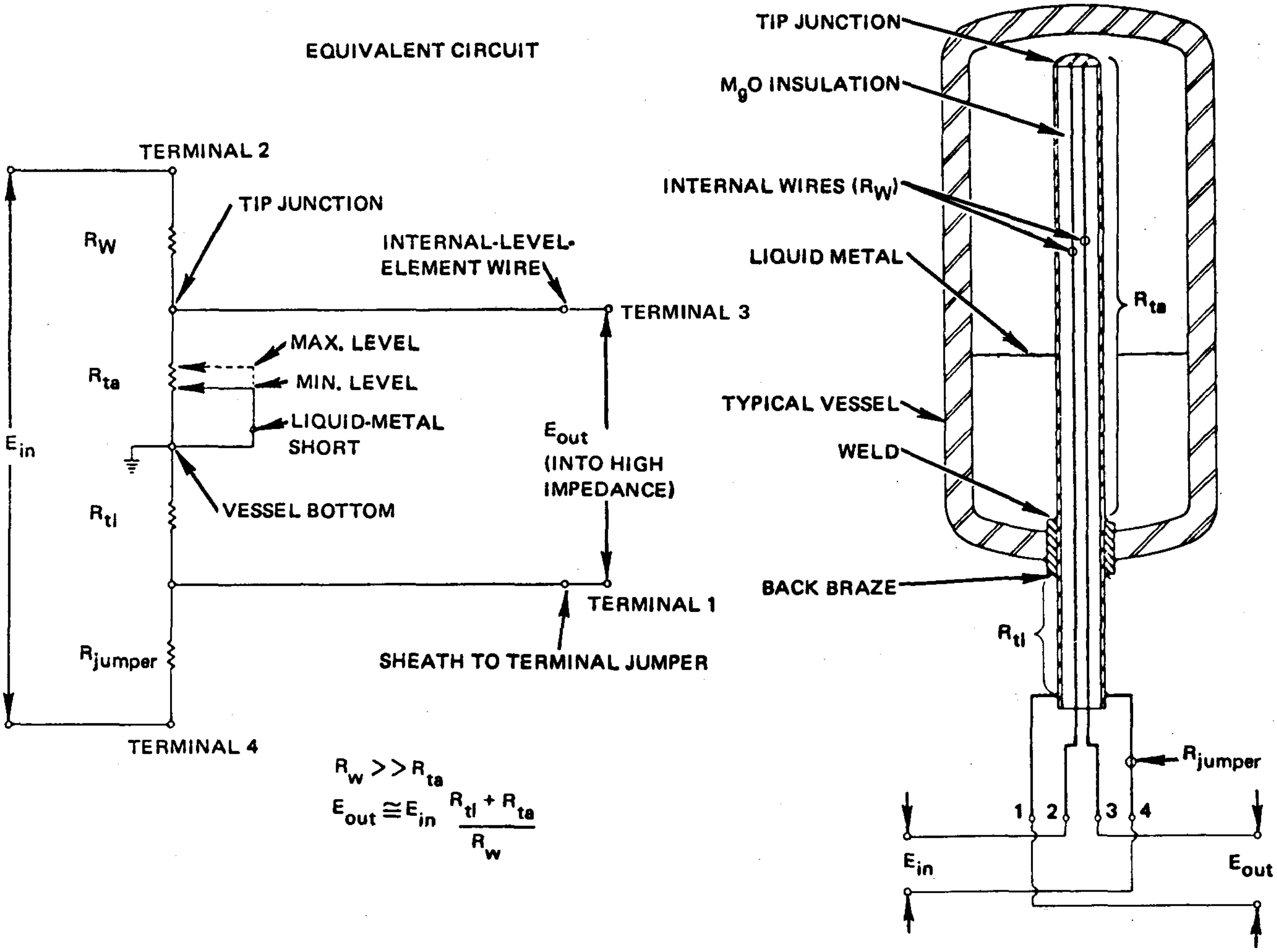


Fig. 4.22 I-tube liquid-metal level element.

below the process vessel.

Because the sheath and the internal wires are made of the same material, the ratio of resistances, $(R_{ti} + R_{ta})/R_w$, should remain unchanged with temperature; thus temperature compensation is inherently achieved. This is an advantage over the J-tube. Other advantages are that the I-tube is easier to fabricate and requires much less space in the process vessel.

The level elements can be excited by either a-c or d-c power supplies. With d-c excitation the output voltage may contain an error because of the thermoelectric emf generated between the sheath and the liquid metal owing to temperature gradients existing along the I-tube and the liquid metal [82]. A comparison of calibration as a function of temperature with a-c and d-c excitation [83] is shown in Figs. 4.23 and 4.24.

The thermoelectric emf was found to be as much as ±15% of the output signal [84]. The problem of thermoelectric emf's is not so severe where the I-tube has a short active length and is installed in a large vessel where fairly isothermal conditions exist.

When the resistance tube is installed in the top of the vessel, the probe is shunted by the resistance of the vessel wall, which is electrically in parallel with the resistance tube. This shunt resistance causes the sensitivity to vary with the level so that the calibration curve is nonlinear.

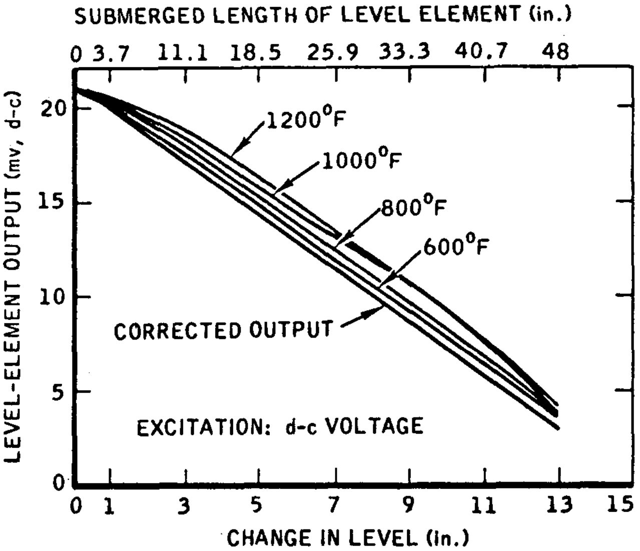


Fig. 4.23 Level-element output with d-c excitation.

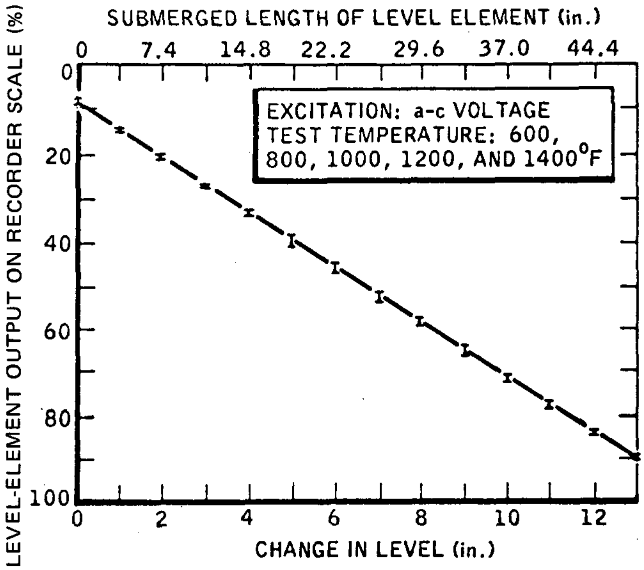


Fig. 4.24 Level-element output with a-c excitation.

Popov [85] described a design variation in which the voltage taps are placed at intervals along the length of the tube (inside). Affel, Burger, and Pidgeon [86] discussed early work on the I-tube.

(2) *Twin I-Tube*. The twin I-tube consists of two I-tubes connected as illustrated [84] in Fig. 4.25. The advantages over the simple I-tube are (1) complete cancellation of the thermal emf generated (it can therefore be used with d-c excitation without the need for thermoelectric emf correction), (2) doubling of the level signal generated in each sheath, and (3) output signal at zero for full level, thus eliminating the need for a suppressed-range readout instrument. Figure 4.26 shows the curve obtained with a twin I-tube level gauge [84].

(3) *J-Tube*. The J-tube is an I-tube bent into a J configuration [78] as shown in Fig. 4.27. The purpose of the modified shape is to permit vessel top mounting but to avoid the nonlinearity caused by the electrically shunting vessel wall, as occurs in a top-mounted I-tube. The J dimensions are chosen so that the minimum level to be measured is at the bottom of the J and the maximum level is at the end of the J. A design providing internal temperature compensation [78] is shown in Fig. 4.28. Fanciullo [78] presented a treatment of J-tube theory, temperature effects, construction, and experimental test data. The use of swaged construction has eliminated some of the fabrication and reliability problems associated with earlier J-tube designs, which had several straight pieces welded to form the J [86].

Delisle and Lions [75] described a variation of the J-tube design.

(b) *Single and Multipoint Electrode Level Gauge*

A very simple type of level gauge is an electrical circuit in which the liquid metal constitutes one electrode of a switch and a rod projecting into the vessel through an insulating sleeve constitutes the other electrode. Closing the switch in the electrical circuit causes electrical contact between the rod and the liquid; this contact actuates an indicator. This method is generally unsatisfactory because of shorts caused by deposits on the insulator.

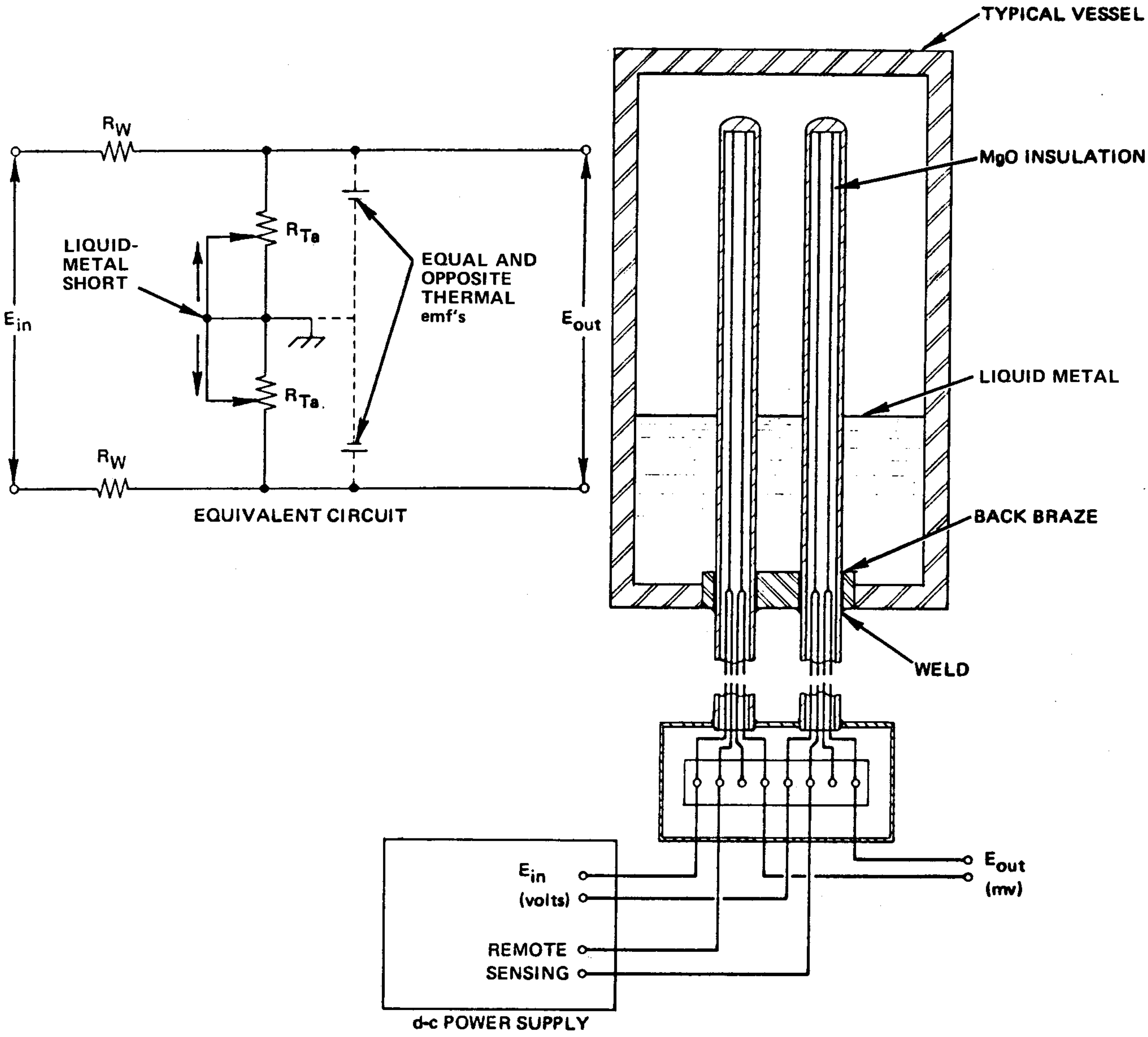


Fig. 4.25 Twin I-probe and its equivalent circuit.

A probe in the form of a spark plug was used in the early models, but deterioration of the ceramic insulation was a significant problem [86]. However, ceramics and ceramic-to-metal seals have been used successfully recently [87].

A discrete-point level gauge of the type in Fig. 4.29 has been used to avoid the problems encountered with an insulator. The circuit is designed so that the probe-tube resistance is high enough to make sufficient current available in the relay coil to attract the armature when the probe tube and the liquid metal do not contact; at a higher level, however, the contact results in an electrical shunt that reduces the coil current to a value too low to hold the armature. The circuit can be operated by direct current but alternating current is preferred [86]. Although a frequency of 60 Hz has been used [86], a different frequency is preferred

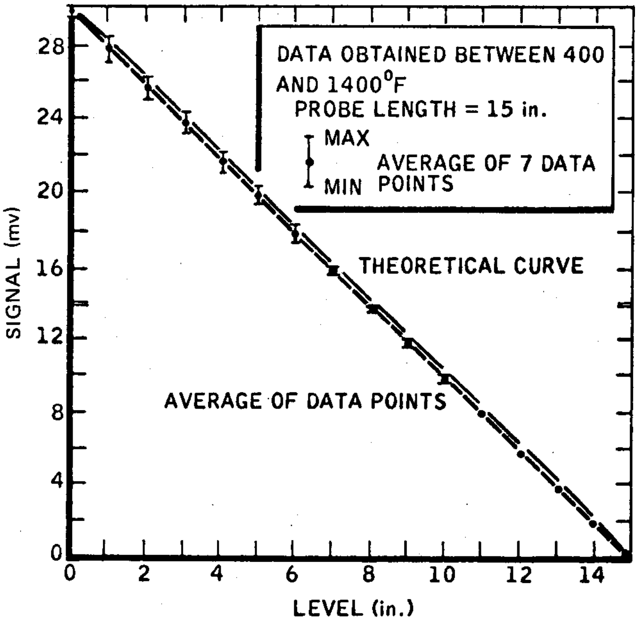


Fig. 4.26 Twin I-probe level-element output with d-c excitation.

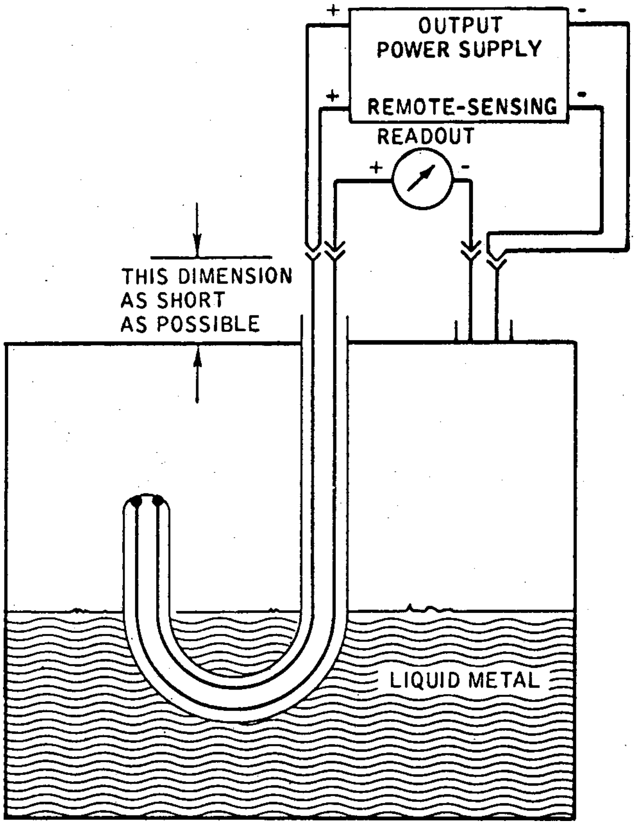


Fig. 4.27 Two-wire J-probe with externally connected temperature-compensation circuit.

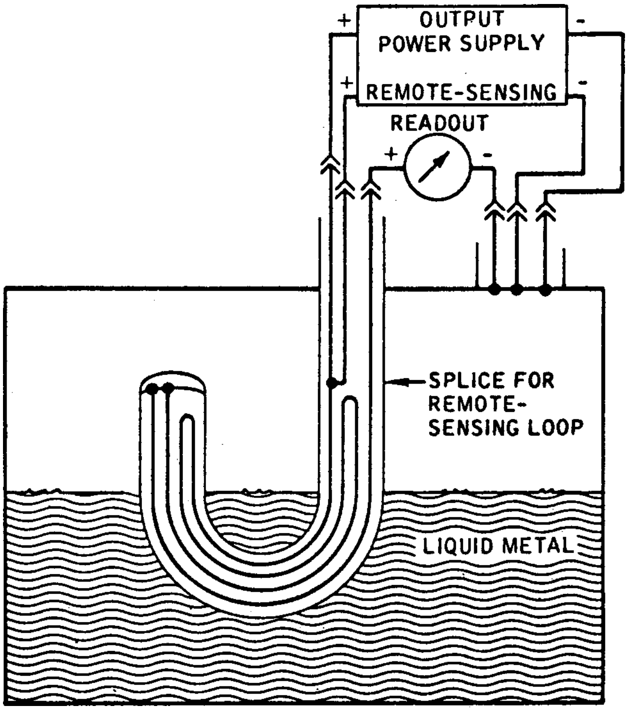


Fig. 4.28 J-probe design with internally connected temperature-compensation circuit and increased-resistance remote-sensing loop.

to avoid any interference by stray pickup from power lines. In some designs a frequency of 1000 Hz is used as a compromise between probe performance and losses in signal cables [88].

A variation in design makes use of a probe having two leads within the tube, as in the I-tube. One lead serves as the current lead and the other as the potential lead [78,86,89]. As a convenience in obtaining a readily available form of tube having two conductors connected to the closed end, a grounded junction thermocouple is commonly used as a probe. One of the thermocouple wires serves as the current lead, the other as the potential lead [90,91].

In the designs described the relay must respond to a relatively small voltage change in a relatively large voltage. This requires critical adjustments. The design [88] shown in Fig. 4.30 provides a circuit in which the voltage applied to the indicator is zero when the liquid metal does not

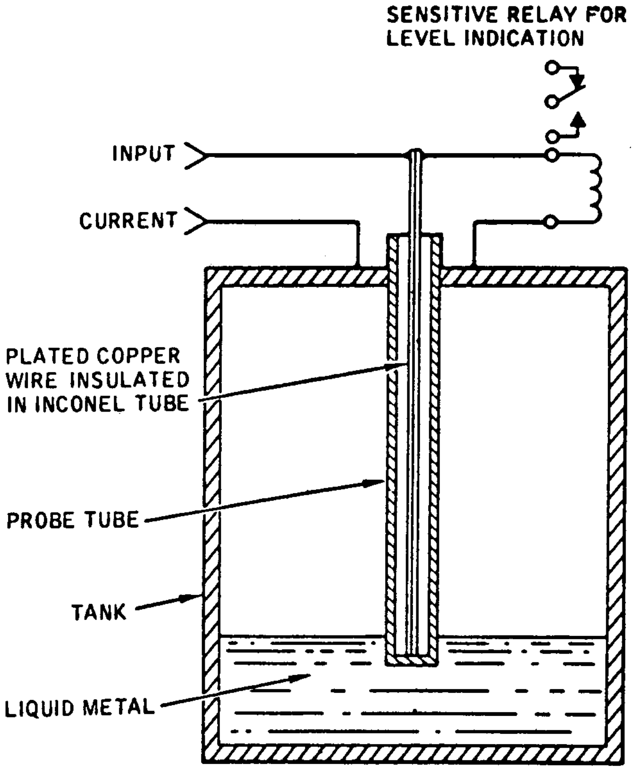


Fig. 4.29 Resistance probe, on-off type.

contact the probe. This results in an on-off signal from the probe, which obviates the need for a relay to convert a two-level signal to an on-off signal.

These methods have been extended to designs for multipoint level gauges. The use of several individual gauges set at the required levels is common practice. A configuration for a two-level discrete-point level gauge [68] is illustrated in Fig. 4.31; its performance has been described as satisfactory.

(c) *Ultrasonic Level Gauge*

The ultrasonic level gauge shown in Fig. 4.32 was developed as a single-point gauge for use in the Molten Salt Reactor Experiment (MSRE) program [81]. This is an acoustical impedance device in which the amplitude of the standing wave on the excitation rod is a function of the terminating impedance. Contact of the sensor bar with the liquid metal greatly increases the terminating impedance above the value in gas. The ultrasonic energy is transmitted through the containment-vessel walls by the special force-insensitive mount, which provides satisfactory sealing while minimizing the absorption of energy. This force-insensitive mount allows the transducers to be located in a satisfactory environment outside the containment vessel. A critical factor in operation is to maintain the excitation oscillator frequency at the excitation-rod resonant frequency. A relatively small deviation of 300 Hz from the nominal operating frequency of 50 kHz was sufficient to cause malfunction of the test model [84]. The resonant frequency of the excitation rod deviated as a function of temperature as the result of its thermal expansion, but the deviation was relatively small

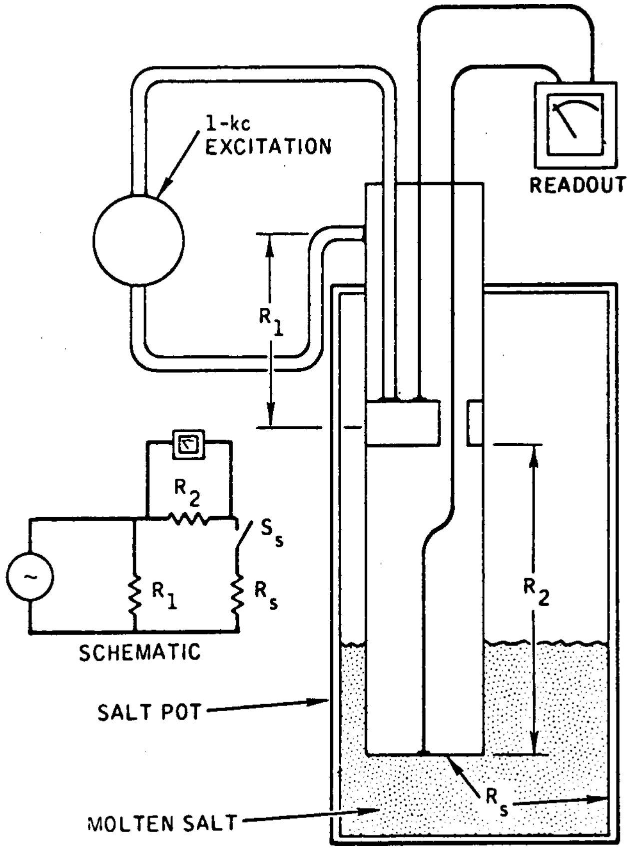


Fig. 4.30 Single-level discrete-point level indicator.

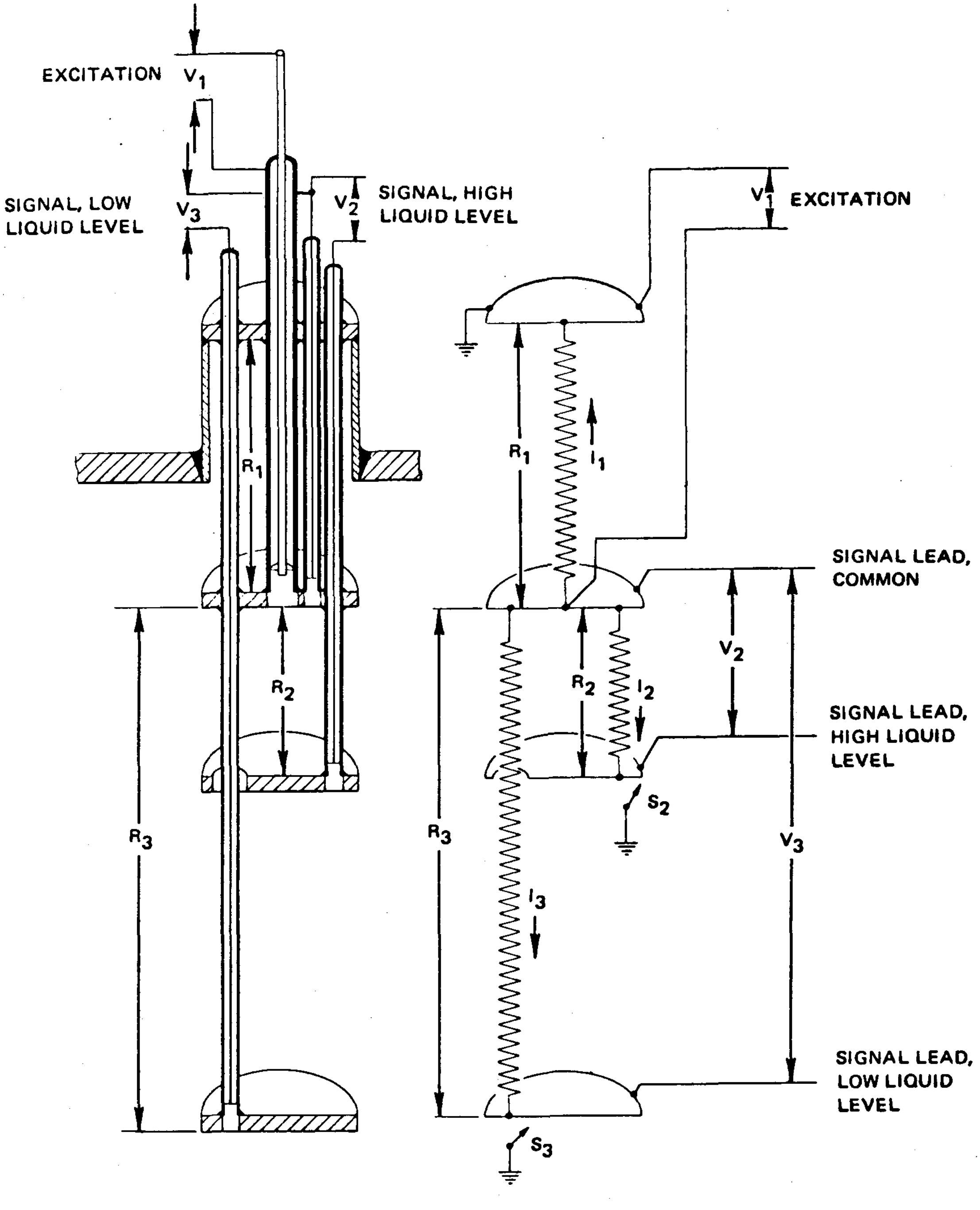


Fig. 4.31 Multiple-level discrete-point indicator; S_2 and S_3 are used to indicate that the molten salt grounds the contact plates to produce the desired signal.

and was well within the tolerance. The excitation oscillator required special component selection to obtain sufficiently stable operation to maintain its frequency within the tolerance. When used with a sufficiently stable excitation oscillator, this type of level gauge is dependable [81]. Sensor materials (typically stainless steels) need not impose any temperature or compatibility problems.

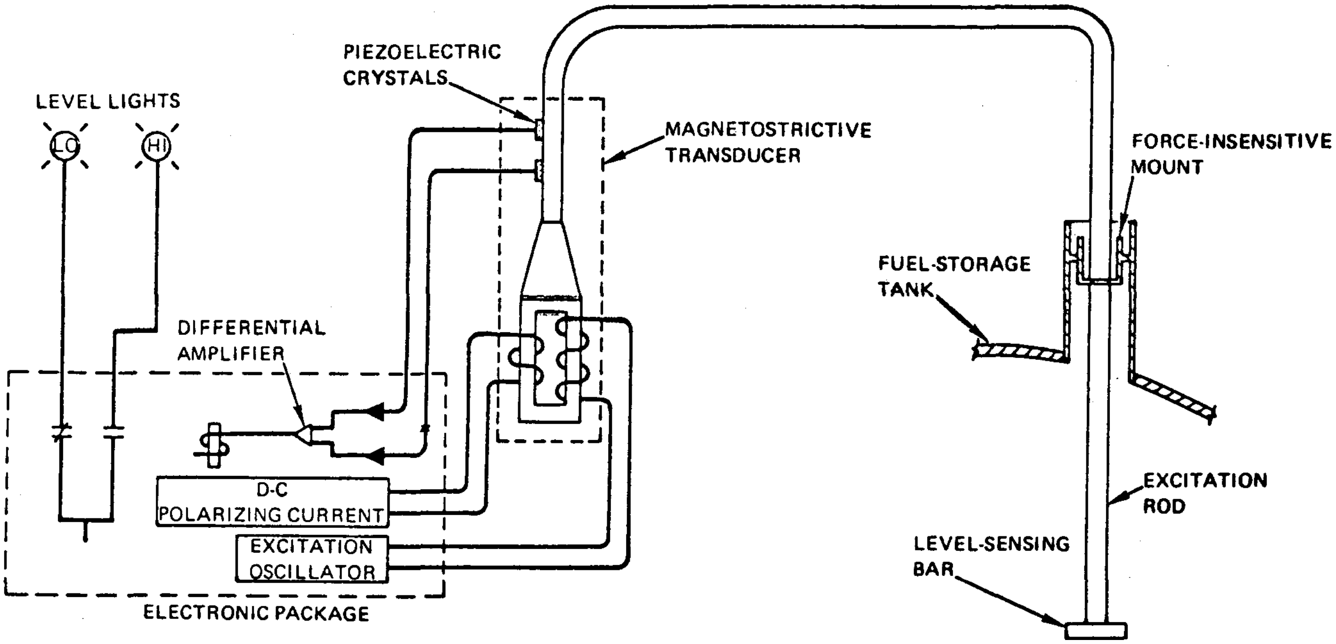


Fig. 4.32 Ultrasonic-level-indicator system.

(d) *Thermal-Contact Level Gauge*

In the thermal-contact method of level measurement, a thermocouple is ordinarily used as the sensor, hence the common designation, thermocouple level gauge. For reliable operation a significant temperature difference between the liquid metal and the thermocouple in the absence of contact is required so that contact causes a discernible temperature rise. At low liquid-metal temperatures, the temperature difference may not be sufficient to enable satisfactory operation. At high temperatures a difference of at least 50°C can be expected [92], which is a sufficient difference.

Although the thermal-contact gauge is inherently a discrete-point gauge, it is common practice to use an array of thermocouples at different levels to provide a range of values; and, if a sufficient number are used, a nearly continuous-level indication can be obtained.

In one design [93] eight thermocouples were welded to the inside of a 1-in.-diameter closed-end tube at a 1-in. spacing along the length. The inside of the tube was ventilated to ensure sufficient temperature difference. Operation was described as satisfactory.

An array of 24 thermocouples with their junctions in a vertical line in the vessel was used in another installation [92]. A commutator was used to sample each thermocouple reading sequentially for comparison with the reference junction. Commutation starts with the lowest thermocouple and is arranged so that the reference junction is always covered by the liquid metal. Electronic circuits provide signal conversion for indicators.

(e) *Buoyant-Element Level Gauge*

The buoyant force exerted upon a body suspended in a liquid measures liquid level by measuring position of a float or the force on a displacer. This method provides a continuous measurement of level. The indicated level is a function of the liquid density, a factor that introduces a temperature dependency. Generally, this temperature effect is smaller in the float design than in the displacer design. In some cases, particularly in deep tanks, at long range, or when there is turbulence, some form of restraint or guides must be provided. In many buoyant level gauges, sliding surfaces, linkages, pivots, and similar mechanisms are involved. Since these mechanisms are a potential source of difficulty in liquid-metal systems, they are used sparingly and with caution.

A float-type level gauge (Fig. 4.33) developed in the MSRE program is an example of a successful design [94]. The float actuates the armature of the differential transformer, which produces the level signal. The electromagnetic coupling of the armature to the transformer coils is through the containment walls. Since the length of the differential transformer must be somewhat greater than the range to be measured, this gauge often has relatively narrow range of use [95]. The armature is constructed of Armco iron canned in a protective sheath. The differential transformer consists of three machined Lava A sleeves with the primary and secondary windings in the grooves on the inner sleeves. The coils are pure nickel wire.

No zero shift nor sensitivity change was apparent in a three-month test, and the temperature effects [88] were less than 2% at 454 to 760°C (850 to 1400°F). In a two-year test period [96] the calibration shift was 0.2 in. (4%), and a temperature change, 538 to 704°C (1000 to 1300°F), caused a shift in indication of 7.62 mm (0.3 in.) or 6%. No forma-

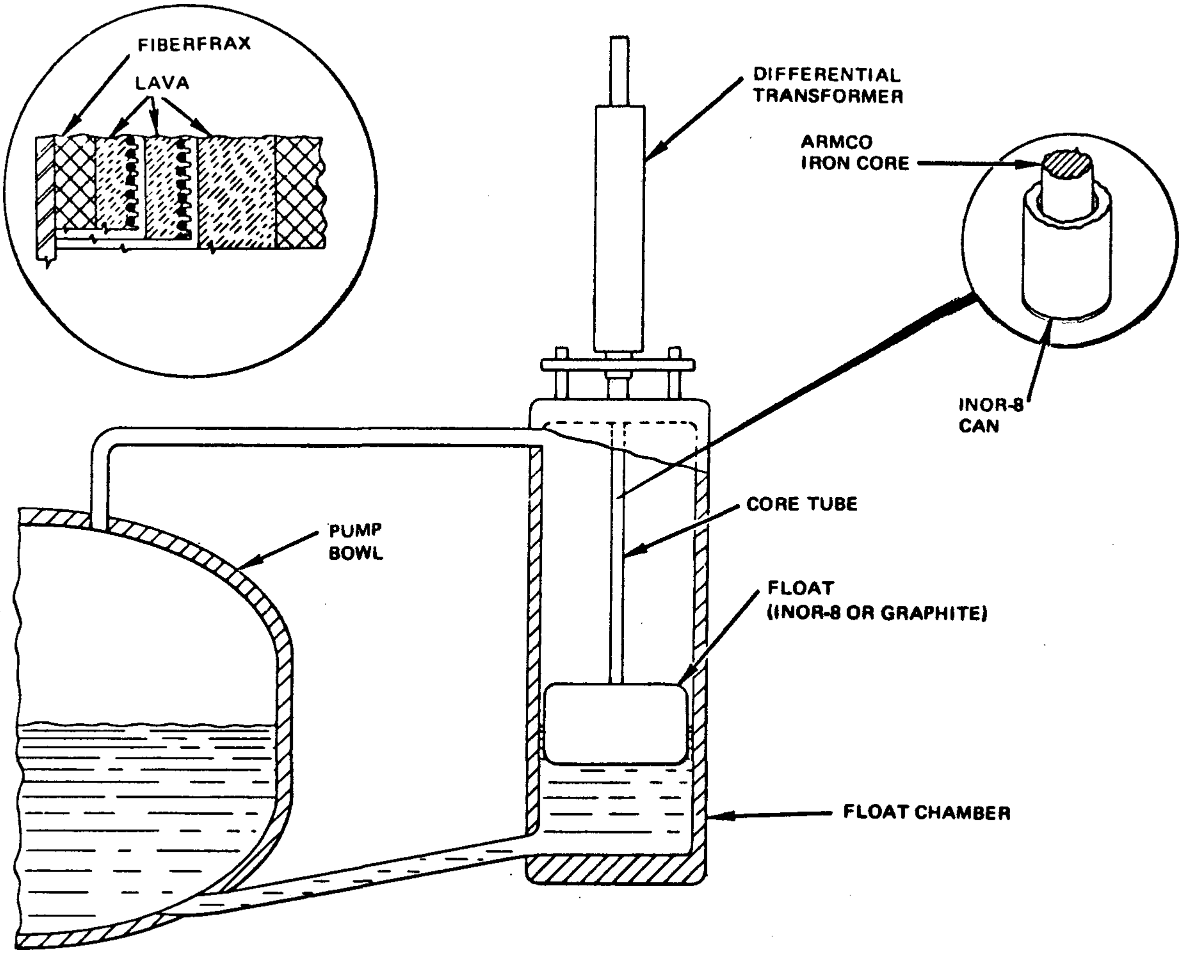


Fig. 4.33 MSRE float-type level instrument.

tion of deposits sufficient to restrict the tube movement or otherwise affect the instrument performance was found [68]. This type of level gauge has performed satisfactorily over a period of more than 4.5 years [84].

A float gauge using a different type of inductance transducer and a closed-loop control circuit is described by Southern [97]. This gauge provided an accuracy of ±1% when operated at a controlled temperature of 1100 ± 50°F. Operation over a wider range was possible with a sacrifice in accuracy.

Other experience with float-type gauges in large sodium tanks indicated that they were not completely reliable [90].

Commercial displacer-type level gauges, slightly modified for liquid-metal service, have performed satisfactorily. The displacer is connected to a transducer through an elastic member, such as a torque tube, bellows, or diaphragm, which provides the restoring force and serves as the containment seal. Since the elastic properties are a function of temperature, the elastic member contributes to the instrument temperature effects. A commercial model using a torque tube gave excellent service in 538°C (1000°F) sodium in the Sodium Components Test Installation (SCTI).

(f) *Differential-Pressure Level Gauge*

The differential-pressure method of level measurement provides a continuous indication of level. Two forms of this technique have been used: (1) a pair of pressure gauges, one submerged and one in the cover-gas region above the liquid metal, and (2) a bubbler.

(1) *Elastic Deformation Sensor.* Differential-pressure instruments are seldom used for level measurement. Metz and Yarosh [81] cited the following reasons: Temperature compensation is not easy; a differential-pressure gauge is temperature limited, depending on the system pressures; and it is radiation resistant only when seals are used to isolate the gauge from the system.

Two types of differential-pressure gauges were used [64] in the EFAPP to measure levels in sodium at a nominal temperature of 288 to 482°C (550 to 900°F), pneumatic null-balance bellows and a NaK-filled diaphragm. The bellows-type provided an accuracy of ±3 in., but periodic calibration and correction factors for changing temperatures and pressures were required [64]. Some operating difficulties, mostly those characteristic of this type of pressure gauge, have been experienced. The NaK-filled diaphragm gauges provided one of the best available level-measuring methods. Accuracy, small temperature shift, linearity, reproducibility, and small maintenance requirements were cited as the noteworthy advantages [64]. The differential-pressure-gauge system used is illustrated in Fig. 4.15 [64].

(2) *Gas-Pressure (Bubbler) Sensor.* The bubbler, or dip-tube, method is comparatively simple but is generally considered unsatisfactory for level measurement in liquid metals, the main problem being the tube's susceptibility to plugging. This can be caused by rapid pressure changes forcing the liquid metal into a cooler region of the tube or, more commonly, by plugging by precipitated material due to the gas impurities. The bubbler method was evaluated over a period of several years in the MSRE program, and the performance was described as generally satisfactory [98]. Problems of instability in gas flow rate and zero offset were attributed to characteristics of the specific installation [98].

(g) *Frequency-Domain-Reflectometry Level Gauge*

Although frequency-domain reflectometry requires contact with the liquid metal, this technique is discussed more conveniently in the category of noncontacting methods [Sec. 4-4.2 (b)].

4-4.2 *Noncontact Sensors*

(a) *Inductance-Coil Level Gauge*
A coil energized by an alternating current induces a current in any closed conducting path around the coil. The induced current results in a power loss so that the effective inductance of the coil is reduced. This effect is utilized as the basis of operation of several types of level gauges. In the simplest form a coil is inserted into a thimble or well and the extent of coverage by the surrounding liquid metal is indicated by a corresponding reduction in the effective inductance of the coil. The inductance or inductance change is measured by one of several well-known methods.

The conductance of the thimble contributes to the effective inductance reduction. To minimize this effect, the thimble should have a high resistivity-to-wall-thickness ratio. The induced current density in the thimble and any surrounding liquid metal decreases exponentially with radial distance from the coil. The skin depth must be greater than the wall thickness to induce a current in the liquid metal sufficient to contribute significantly to the inductance reduction. The penetration distance as a function of frequency and resistivity is presented in Fig. 4.34. The higher values of resistivity shown are characteristic of the range of values for stainless steels at temperatures to about 760°C (1400°F). The lower values are characteristic of the resistivities for sodium and NaK. The curve shows that for adequate penetration the frequency should be low. However, at lower frequencies the mean radii of the eddy-current paths are larger, resulting in a decreased coupling with the coil. The optimum value usually is determined experimentally.

The decrease in inductance caused by induced currents in a surrounding conductor is a function of geometry. The sensitivity of the inductance coil to the presence of surrounding liquid metal increases with the ratio of coil diameter to thimble outside diameter, becoming greater as the ratio approaches one. The sensitivity also increases with the coil length-to-diameter ratio; however, little gain is achieved at ratios greater than three. The effect of conductors in the vicinity of inductance coils is treated in numerous references on coil design or radio engineering (see, for example, Terman [37]).

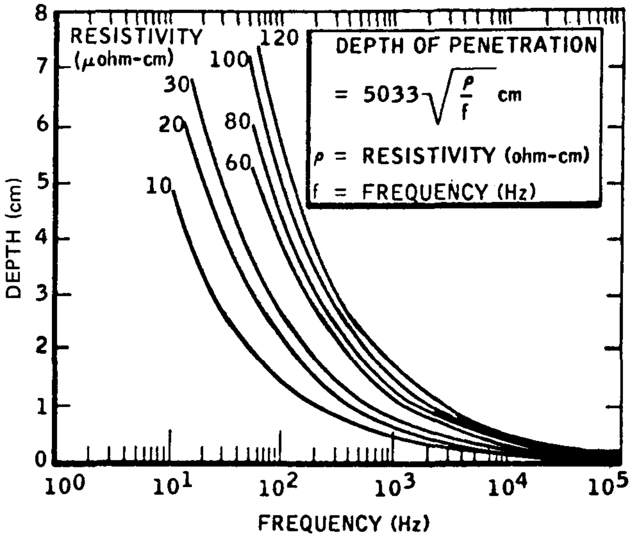


Fig. 4.34 Depth of penetration of an a-c field as a function of resistivity and frequency.

Since the inductance-coil-type level gauge need not contact the liquid metal, the coil can be placed within a thimble, a significant advantage. The requirement for electrical insulation imposes temperature limitation. Designs amenable to the use of sheathed mineral-insulated wire can operate at temperatures much higher than those limited to conventional high-temperature wire.

(1) *Self-Inductance Coil.* A simple self-inductance level gauge consists of a single coil of a length to span the desired range connected to an impedance measuring instrument. A bridge circuit (Fig. 4.35) is used to provide

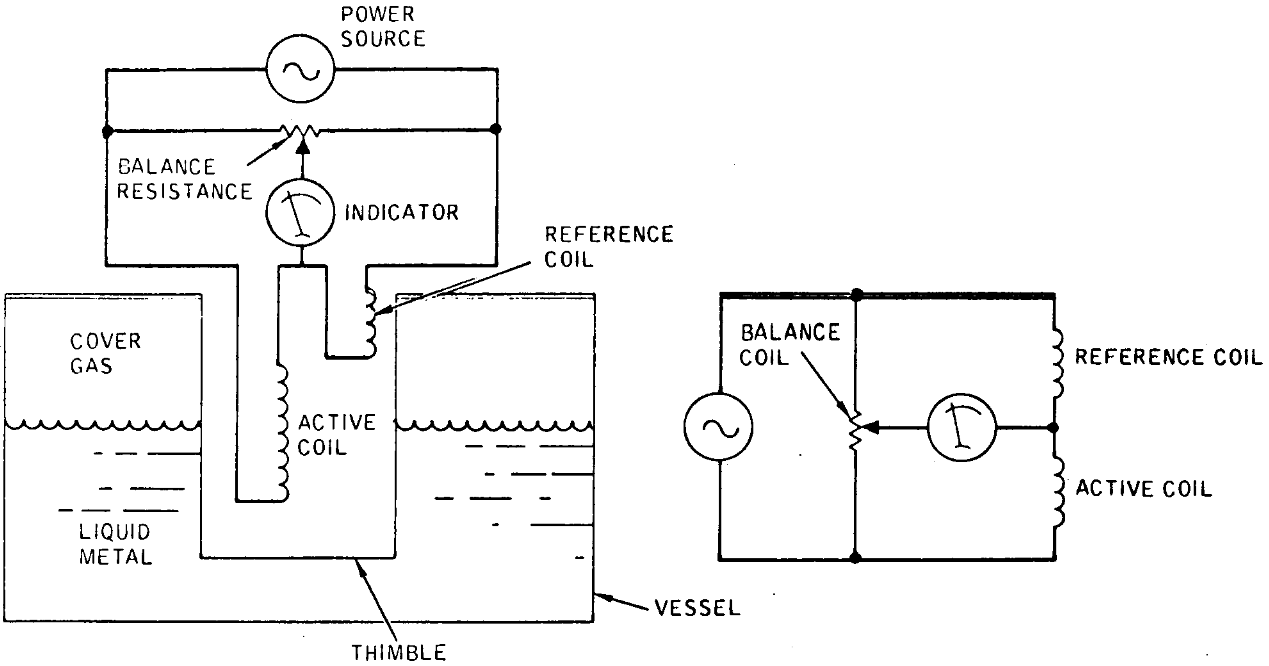


Fig. 4.35 Self-inductance level gauge in temperature-compensating bridge circuit.

increased sensitivity, facilitate temperature compensation, and give a zero reading at zero level. The active coil is placed within the desired level range span so that the inductance of the coil varies as a function of level. The reference coil in the other leg of the bridge circuit is placed at the top of the thimble out of the range of the liquid metal. Since the reference coil is within the region of the active coil, its temperature is nearly the same; hence it functions as a temperature compensator.

Since the resolution is proportional to the full-scale reading (or coil length), the uncertainty in level determination can be excessive for applications involving a large range. The segmenting technique is customarily used to avoid this problem; this results in a step-level gauge [65]. In this method the coil length providing the resolution required is determined, and then a sufficient number of coils of this length are stacked in the thimble to cover the required range. The coils are electrically connected to the bridge circuit through a selector switch. The level is determined by sequentially connecting the coils until the indicator shows the coil that senses the interface of the liquid metal and the cover gas. The position of this coil in the stack provides the reference-level value, and the reading on the indicator provides the distance of the interface beyond the reference level. The sum of these two values is the liquid level.

This type of level gauge has been used at temperatures as high as 537°C (1000°F). The resolution for a coil 305 mm (12 in.) long was ±8.3% of the length. A frequency of 3000 Hz was found to be the optimum value for this design [99].

King [89] and Hosler and Smith [100] described a variation using a single active coil to traverse the range by means of a servomechanism. Test data [87] show that such a level detector is accurate to within ±3.16 mm (0.125 in.).

(2) *Mutual-Inductance Coil.* The mutual inductance between two coils and the degree of coupling are affected by surrounding conductors, e.g., liquid metal rising around thimbles enclosing the coils. The several uses of the variation in coupling differ in operating principle according to the manner in which the liquid metal affects the coupling. The circuit for a method using a bifilar winding of Nichrome wire on an alumina core inserted into the thimble [101] is shown in Fig. 4.36. In this method the coils are closely coupled initially, and the liquid metal surrounding them decreases the coupling. As the liquid metal rises around the thimble, the mutual inductance is progressively decreased, with consequent decrease in secondary voltage. The secondary voltage indicator is calibrated in terms of level. For operation at 200 to 700°C (392 to 1292°F), the average deviation in measured liquid level was 2 to 3% of the probe length [the probes were 127 mm (5 in.) and 356 mm (14 in.) long].

A pair of bifilar coils connected in a differential circuit has been used to provide improved temperature compensation [102]. One bifilar coil is used for measuring and the other for temperature compensation. The use of a pair of bifilar coils connected in a differential circuit and mounted to traverse the level range is described by Stillwell [103].

Figure 4.37 illustrates a level gauge using stainless-steel-sheathed mineral-insulated cable in coaxial form as a coil [46]. The windings are brazed to a central support tube to give good electrical and mechanical stability. This method of construction permits operation at temperatures up to 600°C, either by direct immersion of the coil or in a thimble as illustrated [46]. The power sensitivity of this type of level gauge is low, but this disadvantage is offset by the use of wires with excellent high-temperature characteristics (Nichrome, for example) so that high energizing powers can be used [43]. The sensors have a mutual inductance,

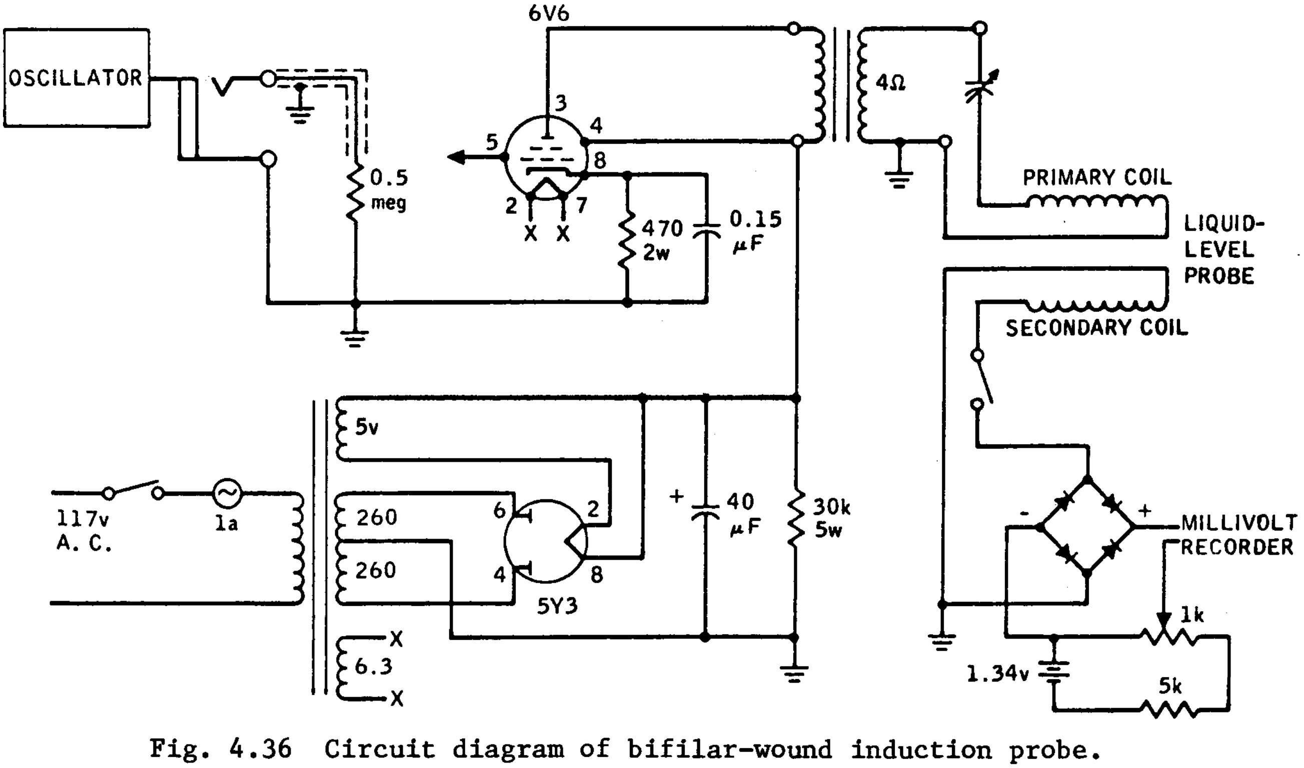


Fig. 4.36 Circuit diagram of bifilar-wound induction probe.

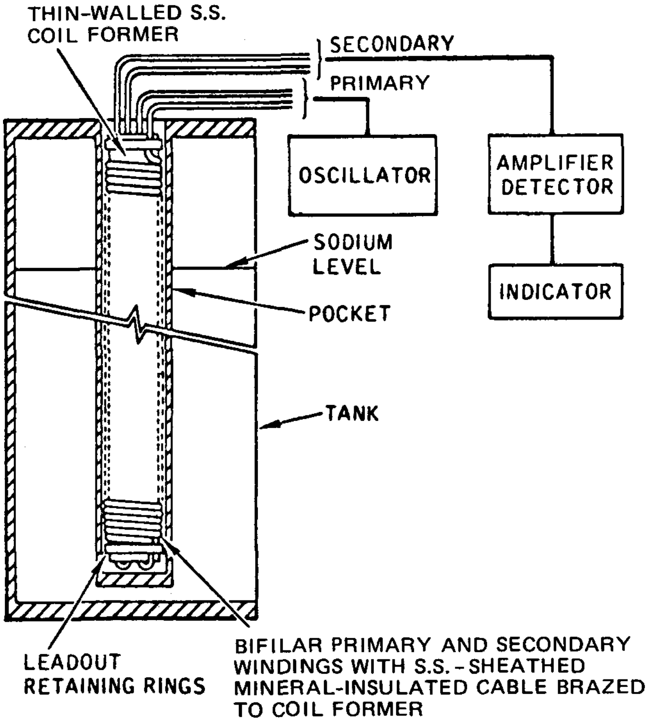


Fig. 4.37 High-temperature mutual-inductance-type level gauge. [From D. F. Davidson and E. Duncombe, Some Electromagnetic Transducer Techniques for Use at Elevated Temperatures, *Trans. Soc. Instrum. Technol.*, *18*(2): 51-61 (1966).]

typically of a few microhenries, changing by approximately 25% from the "dry" to the fully immersed state of the thimble at an energizing frequency of 2000 Hz. Direct immersion of the coil in sodium gives a change in mutual inductance approximately three times as great as when the coil is inserted in the thimble. Measurements indicate that linearities within 0.5% can be achieved over the central 90% of the active coil length. A similar construction was used for mechanically traversed short-search coils for detecting small changes in sodium levels [43].

In other forms of level gauges based on mutual induction, the coils are placed in separate thimbles. The coils are flat (i.e., they have a large equivalent-diameter-to-length ratio) and are placed in the thimbles so that the coil axes are colinear and normal to the thimble axis. As the liquid metal rises around the thimbles, the coupling between the coils is reduced proportionately, and the voltage delivered by the secondary coil is reduced. A number of factors contribute to the reduced coupling, but the most evident is that contributed by the liquid metal functioning as a shield between the two thimbles.

An alternate design, which uses the mutual-inductance effect differently, involves the coupling between two parallel adjacent coils mounted as a pair in a thimble. Two such coils wound on nonmagnetic cores have nearly zero electrical coupling when no conductor encircles the pair. When the coils are surrounded by a closed-circuit conductor, they are coupled. Such a pair immersed in a thimble in a liquid-metal system shows increased coupling, as indicated by the output-voltage rise as the liquid metal rises around the thimble.

One advantage to be gained in the use of mutual-inductance methods often is overlooked; this is the reduction of temperature sensitivity by arranging the circuit so that coil resistance is not a factor. This is accomplished by operating the primary coil from a high-impedance power supply so that the magnitude of the current is substantially independent of the primary-coil-resistance variations; hence the induction field is independent of coil-resistance variation. Furthermore, if the voltage induced in the secondary coil is measured with a high-impedance voltmeter, the effect of a variation in the resistance of the secondary winding is negligible.

(3) *Differential Coupling.* The operation of the differential-transformer level gauge is based on the imbalance occurring as the transformer passes through the interface between the liquid metal and the cover gas as the result of a difference in electrical conductivity

in the two regions. Since the response is limited to an interface, the gauge is basically a discrete-point indicator.

Figure 4.38 is a schematic diagram of one model. The three coils comprising the primary and a split secondary are contained in a detecting head, and the leads are passed out through the dipstick handle to the oscillator and indicator assembly. The principle of detecting the liquid-metal level is based on the inductive shorting effect as the coils are immersed. The primary is energized by an alternating current from an oscillator. A frequency of 1000 cps was found to be the optimum frequency in one design.

A voltage is induced in each of the secondary coils. The secondary circuit is balanced; i.e., when the coils are connected in opposition, the resultant voltage delivered to the indicator is zero. As the assembly is immersed, the inductive shorting affects the lower coil so that the balance is impaired, and the voltage is delivered to the indicator. The imbalance increases with further immersion until the upper coil is affected and the imbalance is diminished. When both coils are completely submerged and are affected alike, the balance is restored, and the voltage at the indicator is zero. The maximum imbalance voltage occurs when the plane of the liquid-metal surface or interface is midway between the pair of secondary coils. Several variations of this design have been used.

This type of level gauge is commonly used as a dipstick, as described, and is inserted into a thimble or well. The depth or level is read on the graduated

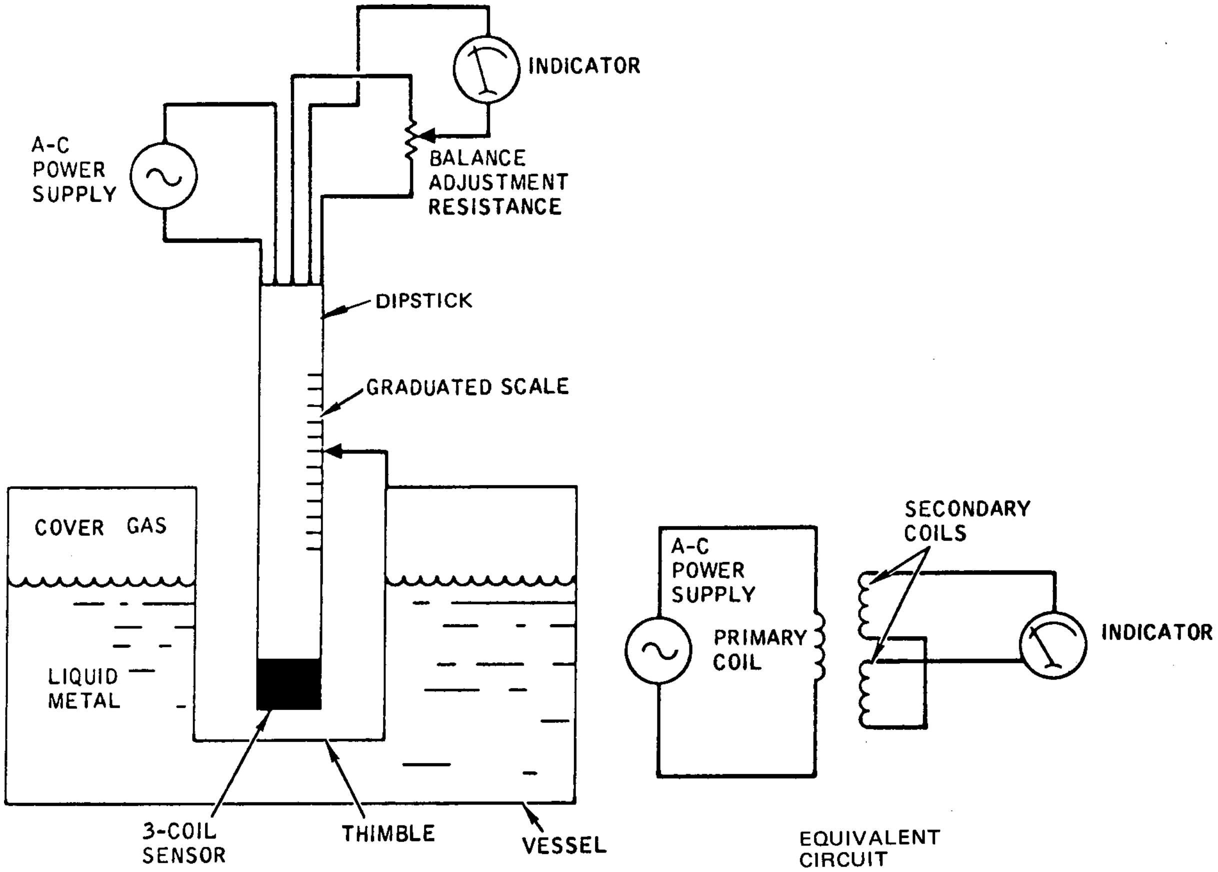


Fig. 4.38 Differential-transformer dipstick level gauge.

scale along the length of the dipstick. When used in this manner, the interface can be determined to within ±1.59 mm (0.0625 in.). The method is inherently free of many error factors (e.g., temperature effects) that are prevalent in other types of level gauges. The design factors to consider include (1) the oscillator frequency upper limit imposed by the wall thickness and resistivity and the lower limit imposed by sensitivity considerations and (2) the ability of the wire and insulation to withstand the high temperature. Ceramic-insulated nickel-coated copper wire used in one model permitted continuous operation at about 500°C (932°F). When this gauge is used manually as a dipstick, this temperature problem is not severe since the measurement can be made rapidly and the dipstick can be withdrawn before the coils become very hot.

Subject to satisfying the temperature limitations of the coil material, the dipstick can be mounted in a fixed position to provide single-point indication or can be operated by an automatic mechanism to provide a continuous indication over a wide range of levels.

Another differential-transformer level gauge is described by Davidson [102].

(b) *Radio-Wave-Reflectometry Level Gauge*

Radio-wave-reflectometry methods are based on the use of a high-frequency transmission line as the sensor; the level is determined by radio-wave reflection at the liquid-metal and cover-gas interface. The product of the wave velocity and one-way transit time is the measure of distance from a reference point on the transmission line to the reflecting point. One form, called echo ranging, or time-domain reflectometry, is based on the measure of the transit time of a pulse to the interface and back. The other form, called frequency-domain reflectometry, is based on a measure of the frequency at which a standing wave can be established on the transmission line.

Reflection of a wave on a transmission line occurs at the point of impedance change, the interface being the primary point of change.

(1) *Time-Domain Reflectometry.* Figure 4.39 is a schematic diagram of a coil-type delay-line level gauge with excitation at the lower end.

Pulse excitation of the level sensor at the upper, or unimmersed, end is less desirable than at the lower end because of possible interference reflections that can occur from surface films and deposits as well as from impedance variations caused by large thermal gradients along the unimmersed portion of the sensor. However, satisfactory performance should be obtainable with upper-end excitation if (1) the maximum temperature differential along the sensor does not exceed 10% of the lowest gradient temperature, (2) the sensor surface condition is such that no encircling films of the liquid metal remain above the sodium level, and (3) the liquid metal is so clean that no

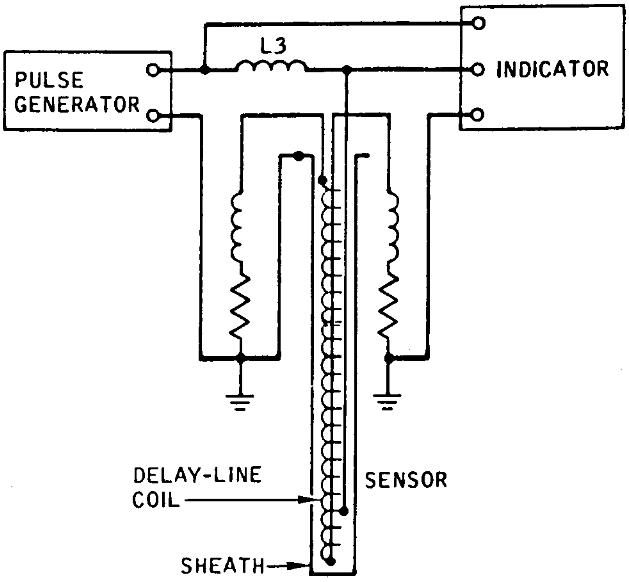


Fig. 4.39 Schematic of a delay-line level gauge.

impurity deposits collect on the sensor surface. Upper-end excitation, though less desirable than lower-end excitation for the reasons given, has the electrical advantage of providing a reflected signal that is opposite in polarity from that of the excitation signal. Ordinarily pulses of opposite polarity can be more easily separated than those of like polarity.

The transit time of the measured signal as a function of level is shown in Fig. 4.40. The nonlinearity is attributed to impedance variations along the delay line due to winding nonuniformities.

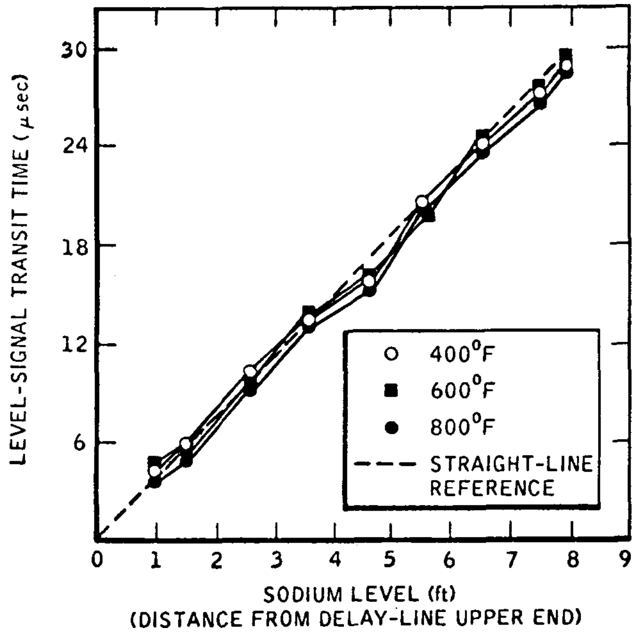


Fig. 4.40 Transit-time characteristic of 8½-ft sensor in sodium tests to 800°F.

The working length of the delay-line sensor is somewhat less than the total physical length of the line, because a portion of the length is needed for time separation of the return signal pulse and the outgoing pulse. The coil length required is roughly the active length plus a 12% allowance (but not exceeding 1 ft) at the driven end for offset of the transmitted pulse.

Change of propagation velocity of the unimmersed sensor in going from room temperature to 427°C (800°F) measured only about 5%, with roughly the same change occurring in the characteristic impedance. Long-term change in these values was negligible. Time-delay nonlinearity encountered was of the order of 6% of the total line two-way delay. This figure, considered excessive, is attributed to nonuniformities in winding tension and in insulating-layer thickness.

In typical designs, the two-way transit time is of the order of 1.31 $\times 10^{-5}$ sec per meter of coil length.

In one design tested, a ½-in. Schedule-40 Inconel pipe with a narrow, lengthwise slot served as the coil core. The coil was closely wound with high-temperature ceramic-insulated wire and was encapsulated in a 0.254-mm- (0.01-in.)-thick Inconel sheath [104]. The tap on the coil provided a means of in-position calibration.

Operating theory, some construction details, and operating data are presented by Ziniuk [105].

(2) *Frequency-Domain Reflectometry.* An instrument based on the measurement of standing-wave frequency as a function of the electrical length of the transmission line is illustrated [106] in Fig. 4.41. The effective electrical length of the line is a function of the liquid-metal level. The calibration curve is linear and has good repeatability [106]. The need for electrical insulation and seals imposes operating-temperature limitations. The instrument has been operated at sodium temperatures up to 500°C (932°F) when the seal temperature was not allowed to rise above 350°C (662°F). The disturbance of seals during the replacement of a unit was cited as a disadvantage of this design [106]. Kirillov *et al.* [14], Petrenko [106], and Davidson and Pilling [107] discussed this method of level measurement.

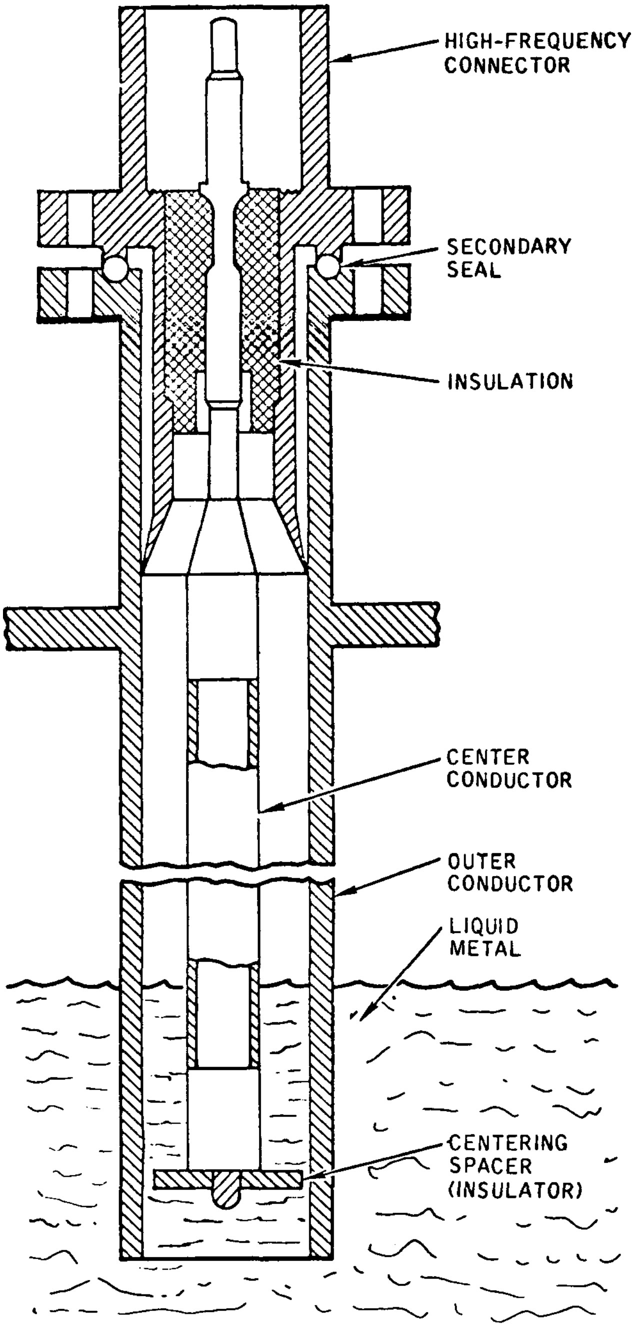


Fig. 4.41 Radio-wave-transmission-line level gauge.

4-5 IMPURITY-CONCENTRATION MEASUREMENT

Various aspects of impurities in liquid metals are treated in appropriate sections of other volumes, particularly Vol. I, Chap. 2, and Vol. V, Chaps. 1 and 2. Measurement of impurity concentration by laboratory analytical methods is treated in Vol. I, Chap. 2.

A number of techniques having possible application to in-line measurement have been evaluated, but only a few were found feasible. (See Refs. 108, 109, 110.)

Instruments developed for in-line service to detect oxygen, hydrogen, and carbon impurities and to measure their concentrations are classed according to their response selectivity as specific or nonspecific. Those which have a nonspecific response are sometimes called gross-impurity meters to indicate that they respond to several impurities.

The development, operating principles, and performance characteristics of in-line impurity instruments are reviewed by Davis [111].

4-5.1 *Specific-Impurity Instruments*

(a) *Oxygen*

Oxygen concentration in sodium is measured by an electrochemical (galvanic) cell using a ThO_2-Y_2O_3 solid electrolyte and a reversible O-Cu, Cu_2O reference electrode. The cell develops a voltage dependent on the thermodynamic activity (effective concentration) of the oxygen in sodium. A schematic diagram of the cell is shown in Fig. 4.42. The final report [112] on the development of this instrument reviews the theory of operation, design and construction details, and test results. Minushkin [113] treated installation and operation.

The operating temperature range is relatively narrow; the recommended operating temperature [113] is 315°C (600°F). At temperatures significantly above this value, the solid electrolyte is chemically reduced by sodium [114]. The instrument has been operated [114] at temperatures as high as 1000°F; however, lower temperatures give a longer operating life. At temperatures much below 260°C (500°F), the electrical

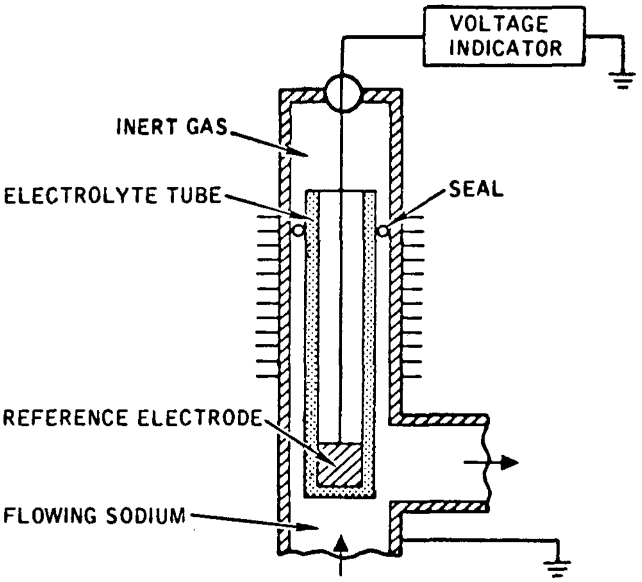


Fig. 4.42 Schematic of electrochemical oxygen meter.

resistance of the reference electrode is too high for satisfactory operation [113].

The solid-electrolyte tubes are sensitive to thermal shock; this is a general characteristic of ceramics.

Since typical systems do not necessarily operate within the recommended temperature range, a means of accommodating the system to temperature differences and changes must be provided. A regenerative heat exchanger (economizer) between the system and the cell is recommended. The economizer may function as a 315°C cold trap, but, since this temperature corresponds to oxygen concentration at the upper limit of the cell response, meter operation will not be impaired.

The accuracy of calibrated instruments was given [115] as ±10% at 1 to 30 ppm oxygen. Indications based on the theoretical predictions may be in error [115] by as much as 30%. Factors to consider relative to accuracy are:

1. *Stabilization.* The cell voltage drifts gradually during the first 24 hr of operation at the recommended operating temperature [113], 315°C (600°F). During the initial period of stabilization, an equilibrium is attained between the cell and the sodium. This limits practical use of the instrument to the period after stabilization.

2. *Temperature Sensitivity.* The cell is sensitive to temperature changes of the liquid metal in which it is immersed and to changes in the temperature of the meter housing. Sensitivity tests [115] show that a sodium temperature variation of 10°C (18°F) can cause an emf change corresponding to an oxygen-concentration change of approximately 36%. Errors are not appreciable if the temperature is controlled [112] to within 5.6°C (10°F). The effect of the ambient temperature of the cell housing is also significant. Ambient-air temperature fluctuations of ±17°C (36°F) cause emf fluctuations corresponding to fluctuations of ±30% in indicated oxygen concentration [115].

3. *Calibration.* The theoretical values of emf can be used for monitoring changes in oxygen concentration, but, for absolute values of oxygen concentration, the method results in significant error, a value of concentration too high. Calibration is necessary for high accuracy of absolute values. Calibration is accomplished after stabilizing by cold-trapping at a temperature below about 150°C (300°F) until the voltage is constant to within ±5 mv and the plugging meter or other indicators show a constant impurity content over a period of several hours. The process is repeated at a series of cold-trap temperatures to obtain additional calibration points. Selected data for four meters are presented in Fig. 4.43, and the theoretical relation is indicated. The band representing the theoretical performance is the result of estimated uncertainty in the solubility of oxygen at the recommended operating temperature, 315°C.

The initial accuracy can be maintained for a period of at least 2 months. The operating life of the cell may not be much longer, though opera-

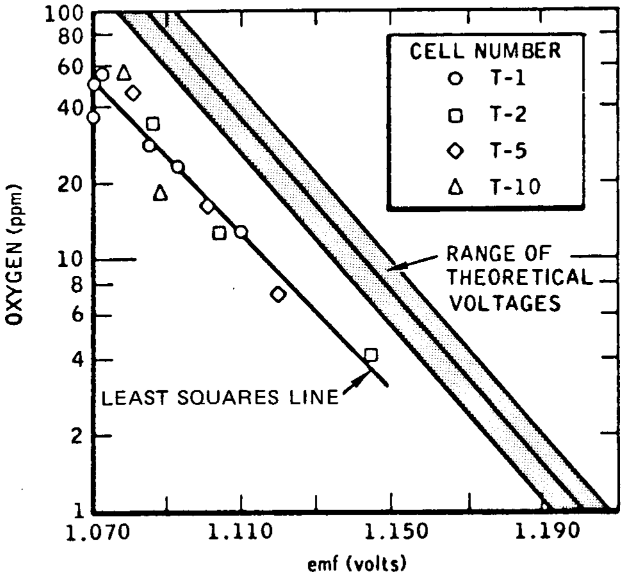


Fig. 4.43 Typical calibration of emf vs. oxygen (ppm) in sodium || ThO_2-15 wt.% Y_2O_3 || Cu, Cu_2O cells at 600°F.

tion for 1 year has been reported [116], and the manufacturer reports that the useful cell life at the recommended operating temperature exceeds 6 months [112]. The short-term stability is unsatisfactory. Indications are generally unreliable on a day-to-day basis because of the short-term, temporary changes in calibration [116].

Performance as a function of liquid flow rate has been evaluated for flow rates of 15.8 to 63.3 cm^3/sec (0.25 to 1 gpm) with no effect on calibration or response to changes in oxygen concentration [112].

4. *Selectivity*. The emf of the electrochemical cell provides a measure of the thermodynamic potential of oxygen dissolved in sodium. Under equilibrium conditions the measure is independent of the form of the oxygen, provided it is in solution. The electrochemical cell is considered to measure concentration by virtue of Henry's Law, which relates concentration to activity, a function of thermodynamic potential. Henry's Law is obeyed approximately. Since the activity of dissolved oxygen can be affected by other impurities, under some circumstances the indicated value of concentration may not bear the expected or intended relation to the thermodynamic potential. An error in expressing the oxide impurity concentration for general measurement purposes results, but the indication is correct as a measure of thermodynamic activity, which is the quantity of interest in assessing chemical and metallurgical effects in containment materials. Hence the effective oxygen content indicated is the equivalent concentration of dissolved sodium oxide that would exhibit the same activity or chemical potential.

For example, impurities that alter the relation between total oxygen content and activity are OH, CO_3, and $(Na_2O)_2 \cdot FeO$ [113]. It has been found that adding carbon to sodium does not affect the cell [117]. Hydrogen in the gas above the sodium can be troublesome if it diffuses to the cathode and interacts with the metal oxide [117].

5. *Response Time*. The response time is of the order of seconds [112]. The temperature as an aspect of environment has been discussed. The electrolyte is a ceramic tube and, compared with other components of liquid-metal systems, is fragile. No quantitative data have been reported on susceptibility to damage by mechanical forces. Preliminary tests indicated that cell response is affected by exposure to radiation [118]; however, some cells are negligibly affected.

A schematic diagram for the recommended installation [112] is shown in Fig. 4.44. The cell housing is constructed on a ½-in. Schedule-10 tee.

(b) *Hydrogen*

Extraction of hydrogen from liquid metal by means of a hydrogen-permeable diaphragm permits the sensing of hydrogen by one of several conventional methods. Nickel is the material generally used for the diaphragm since it is compatible with liquid metals, is a common engineering material, and has a

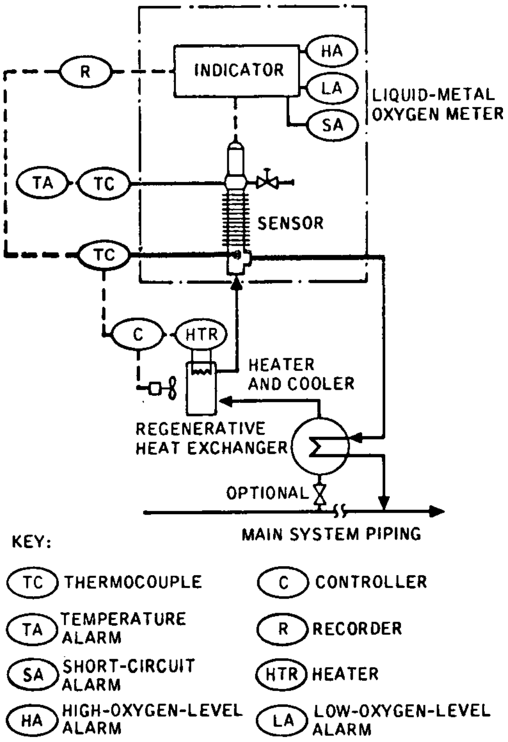


Fig. 4.44 Schematic of recommended liquid-metal-oxygen-meter installation.

high hydrogen permeability.

Figure 4.45 shows a hydrogen monitor [119,120] in which vacuum is established in the region outside the nickel tube and any hydrogen diffusing through the tube as indicated by the Pirani gauge. The valve is open initially to provide a low pressure, of the order of a few microns. When a sufficiently low pressure is attained, the valve is closed as far as possible, maintaining a steady pressure at the Pirani gauge. The near closing of the valve prevents pumping the hydrogen out as fast as it diffuses through the diaphragm and, thereby, permits its detection by the Pirani gauge. Hydrogen concentrations as low as 3 ppm can be detected by this method [120]. The diffusion rate through a permeable diaphragm is a function of temperature. Figures 4.46 and 4.47 show the response time as a function of temperature and hydrogen concentration in a test model [120] operating in sodium. In these tests water was injected into the sodium to produce hydrogen. It was found that when the tube axis was horizontal the sensitivity was higher than when the axis was vertical. This fact, in addition to the effect of velocity (Fig. 4.48), was taken to indicate that an arrangement permitting hydrogen to accumulate on the diaphragm surface is beneficial [120]. In other experimental work the velocity was shown to have no effect [121].

Figure 4.49 shows a method using a relatively long, coiled, palladium-plated nickel tube as the permeable diaphragm [122]. The hydrogen diffusing through the tube reacts with oxygen in the presence of the palladium, which functions as a catalyst, to produce water. The water is measured by a moisture analyzer with a sensitivity of 0.01 ppm hydrogen in sodium and a response time of 15 sec [123].

(c) *Carbon*

Carbon in liquid metal is extracted through a carbon-permeable diaphragm. The carbon is removed from the diaphragm by a decarburizing gas passing across its surface. A schematic diagram of a carbon diffusion cell with an iron diaphragm [124] is shown in Fig. 4.50. Diffusion rate is a function of temperature, and an adequate rate is achieved by operating the diaphragm at 760°C (1400°F). The decarburizing gas is chosen for compatibility with the diaphragm, stability, formation of a reaction product amenable to detection by conventional gas analyzers, and freedom from objectionable diffusion into the diaphragm. The reaction of water vapor, the preferred decarburizer, with carbon produces hydrogen and carbon monoxide.

4-5.2 *Nonspecific-Impurity Instruments*

(a) *Plugging Meter*

A plugging meter induces precipitation by temperature reduction, thus enabling detection of soluble impurities. The temperature at which precipitation

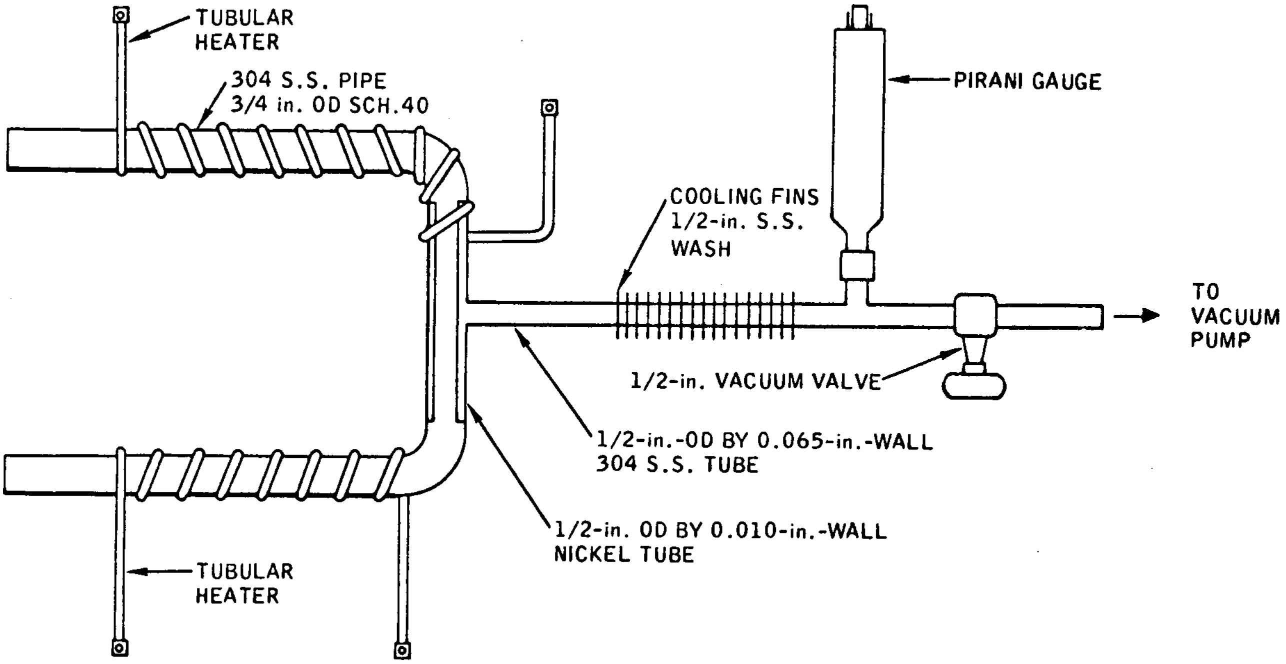


Fig. 4.45 Nickel-diffusion-tube hydrogen monitor.

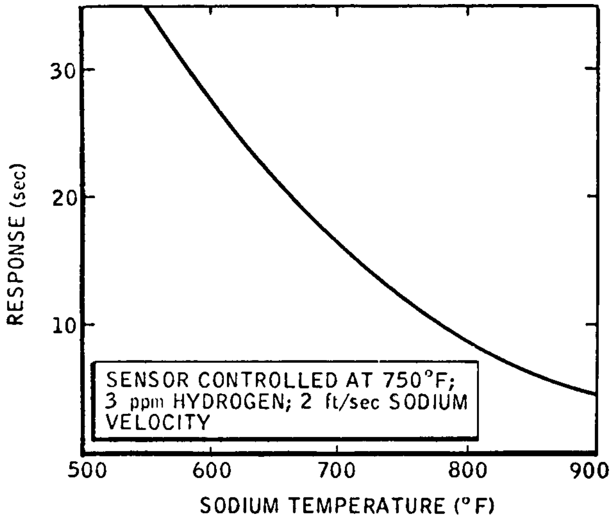


Fig. 4.46 Response time of diffusion-tube hydrogen monitor vs. temperature.

(plugging) occurs in the plugging meter indicates the temperature at which objectionable precipitation or plugging may occur elsewhere in the liquid-metal system. As such an indicator the plugging meter gives excellent performance. Plugging-meter sensitivity and resolution are expressed in terms of plugging temperature.

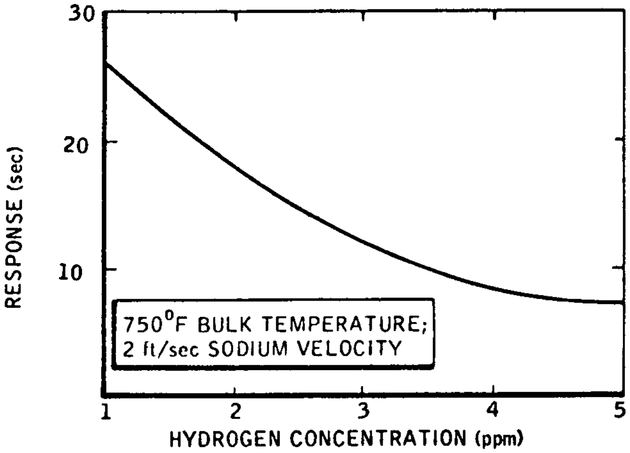


Fig. 4.47 Response time of diffusion-tube hydrogen monitor vs. hydrogen concentration.

The plugging meter functions as an impurity-measuring device because of the definite relation between precipitation temperature and impurity concentration. Since oxide is the usual precipitant, the plugging meter often has misleadingly been called an oxide meter. It

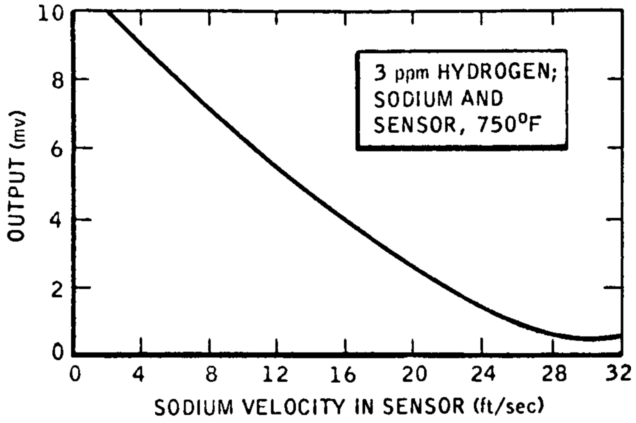


Fig. 4.48 Output of diffusion-tube hydrogen monitor vs. sodium velocity.

is an oxide meter when oxides are precipitated and the precipitation is not affected by other soluble impurities; similarly, it is a hydride meter when hydrides are precipitated and the precipitation is not affected by other soluble impurities. The solubility curves for oxygen and hydrogen are given in Fig. 4.51, based on data from Refs. 125 and 126. More-detailed data are presented in Vol. I, Chap. 2. The combinations of oxide and hydride, or other soluble impurities, may register simultaneously on a plugging meter under certain conditions. This can result in accelerated plugging and is revealed as a second break in the plugging curve. A break caused by accelerated plugging occurs less frequently than a break caused by retarded plugging. Breaks indicating retarded and accelerated plugging are reproduced [127] in Fig. 4.52. Experience with multiple breaks is detailed by Savage *et al.* [128], and some factors involved are discussed by Davis [111].

A plugging meter performs poorly at low plugging temperatures where the slope of the solubility curve is low [111]. The lower limit of plugging-temperature measurement depends on design, operational factors, and the impurity involved. Sodium plugging temperatures as low as 110°C (230°F) have been reported [129]. Typical values of minimum plugging-temperature capability are somewhat higher. Plugging temperatures have been determined [130] to an accuracy of ±1°C. Values such as ±5°C [130] and ±10°C [131] also are reported.

In terms of oxide concentration, 10

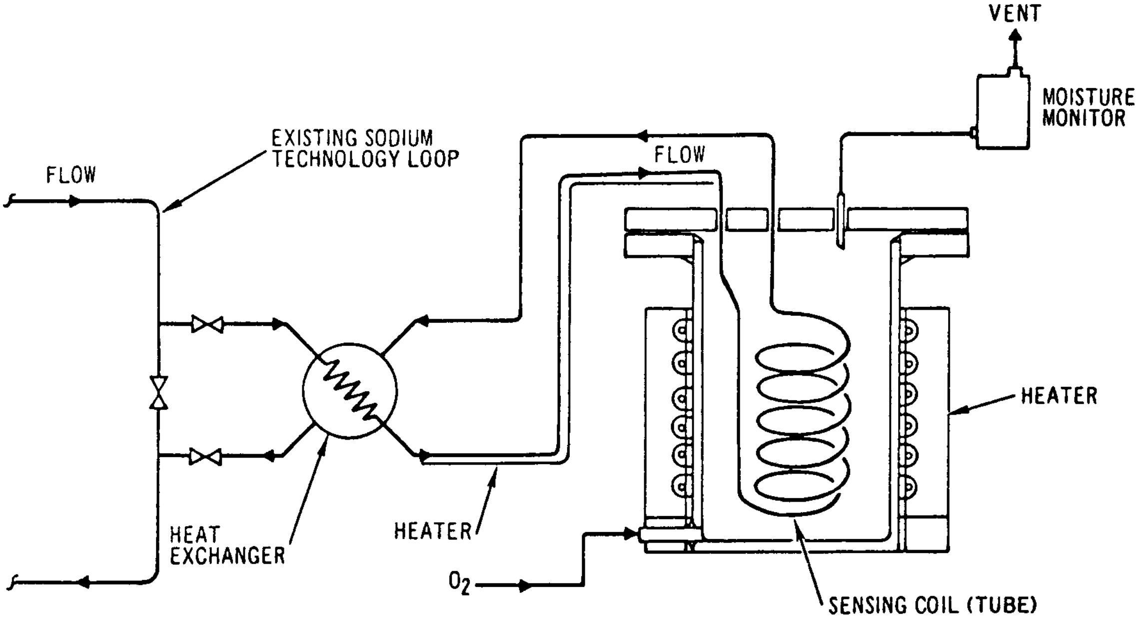


Fig. 4.49 Palladium-nickel-tube hydrogen monitor.

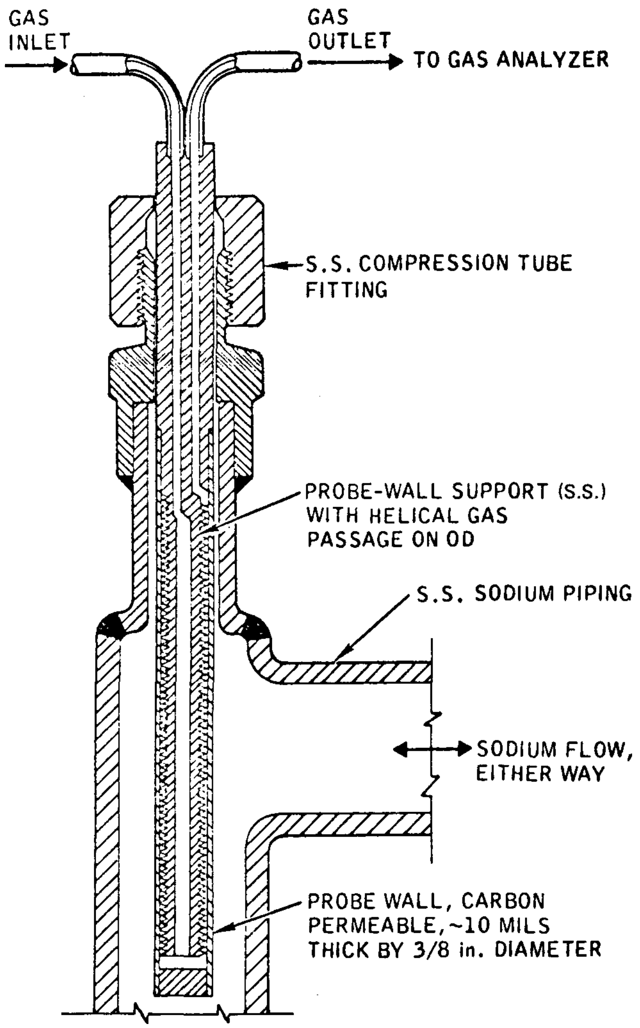


Fig. 4.50 Schematic diagram of carbon meter probe.

ppm often is taken as a typical value for the limit of satisfactory performance.

Values of reproducibility to within 2.7°C (5°F) [132] and within a band of 8.3°C (15°F) [127] have been reported.

Three operating methods are used with plugging meters:

1. *Manual Operation.* In manual operation the plugging run consists in actuating the cooler and observing the resultant flow-vs.-temperature relation. Cooling is continued until the flow is reduced sufficiently to enable the operator to determine the breakpoint in the flow-vs.-temperature curve. When this step is completed, the operator

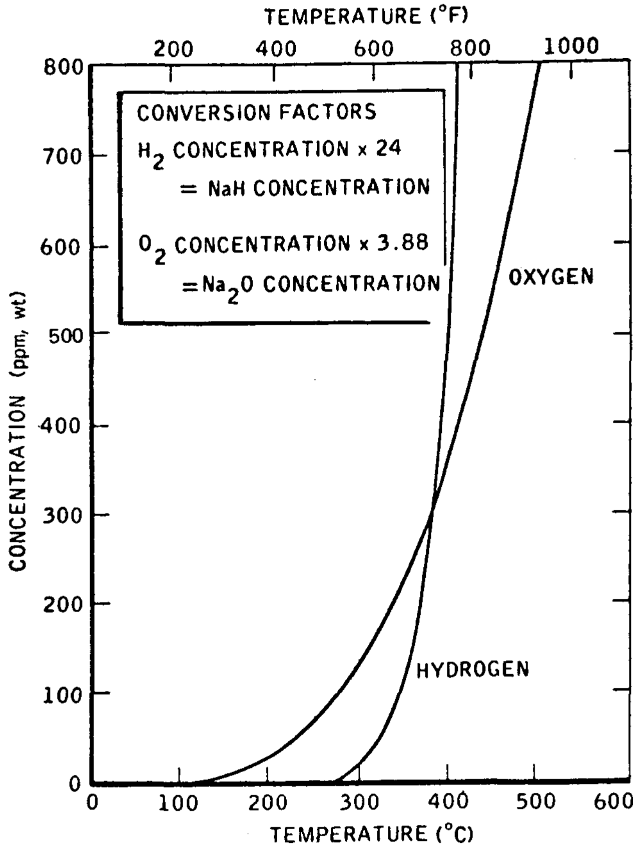


Fig. 4.51 Solubility of oxygen and hydrogen as a function of temperature.

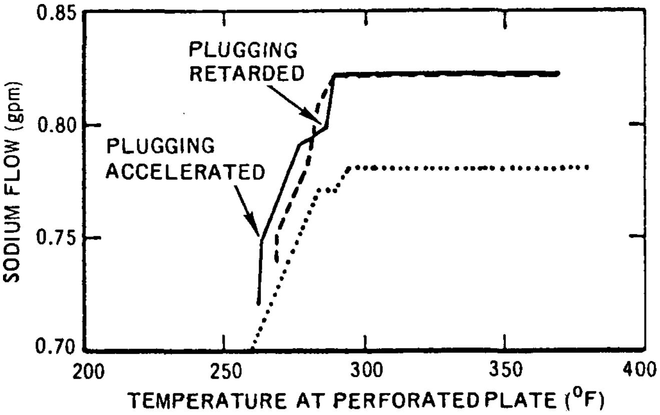


Fig. 4.52 Three plugging curves illustrating changes in plugging rate, or "breaks." (I. L. Gray, R. L. Neal, and B. G. Voorhees, Control of Oxygen in Sodium Heat Transfer Systems, *Liquid Metals Technology. Part I*, Chemical Engineering Progress Symposium Series, No. 20, p. 14, American Institute of Chemical Engineers, 1957.)

restores the temperature and flow through the orifice.

2. *Programmed Operation.* In programmed operation the sequence of events, the rates, and the limits are controlled automatically in accordance with a fixed program. The program provides continued cooling until the flow rate decreases to some designated fraction of the initial flow rate; then the temperature and flow rate through the orifice are restored by operation of the control devices.

3. *Automatic Operation.* Automatic operation is similar to the programmed method to the extent that the operation is accomplished by automatic controllers. In automatic operation, however, the cycle is determined by operating conditions rather than by a fixed program. The operation is similar to a closed-loop servo system and can be set to determine the point of incipient plugging and provide an essentially continuous indication of plugging temperature.

A sample listing of the great variety of plugging meters reported in the literature, together with some design features of each, is presented in Table 4.1.

The plugging meter illustrated in Fig. 4.53 is a manually operated type using a fixed orifice [133] consisting of a plate 1.59 mm (0.0625 in.) thick with 15 holes in the periphery 1.27 mm (0.05 in.) in diameter. The meter was sensitive and provided excellent reproducibility [133]. Some care was required to avoid complete plugging [133].

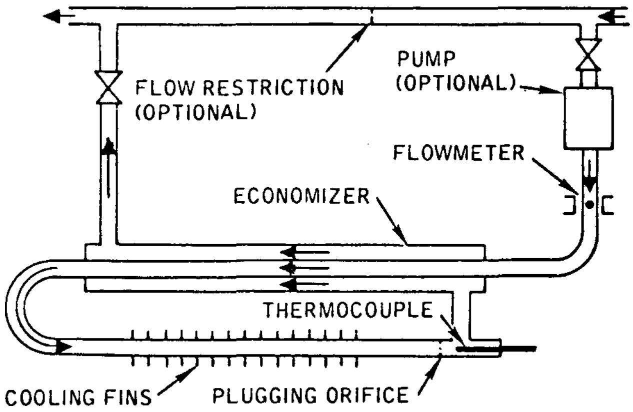


Fig. 4.53 A manually operated plugging meter using a fixed-plate orifice.

The problems associated with inadvertent complete plugging are circumvented by the use of a variable orifice rather than a fixed plate. A convenient form of variable orifice is a modified valve with the slots cut in the valve plug (or seat). When the valve is in the closed position, liquid metal flows through the grooves. When the grooves become plugged, the valve is opened and the resulting mechanical disturbance and the flow of hot liquid metal flushes away the precipitate. A plugging valve [134] is shown in Fig. 4.54.

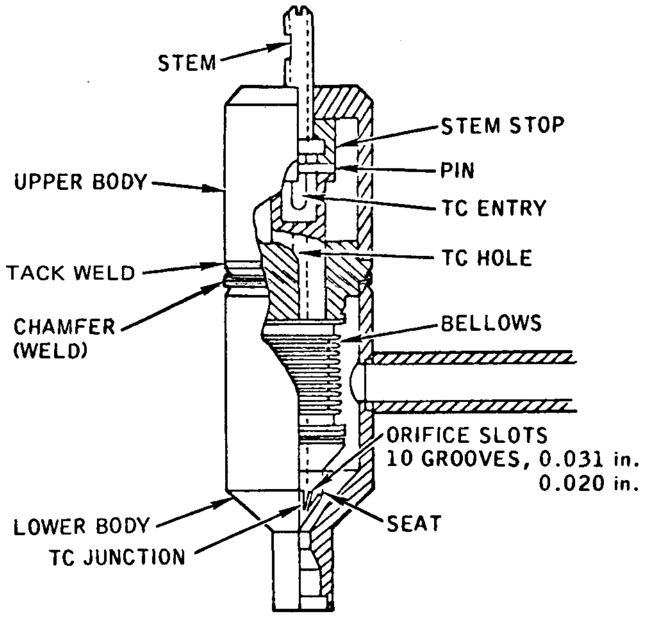


Fig. 4.54 Details of a plugging valve.

A plugging meter using a solenoid-operated variable-orifice valve to facilitate programmed operation [135] is illustrated in Fig. 4.55. The plugging valve is of special design; the valve body is made from 2-in. pipe and fittings. The plug and seat are of a 1-in.

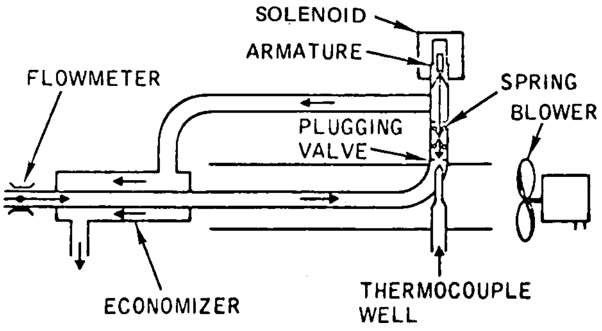


Fig. 4.55 A valve-orifice plugging meter designed for programmed operation.

design with the plug slotted to provide an orificed flow through the valve to conform to a proven plug and seat design. A movable core of a solenoid enclosed within the valve body is connected to the plug by a rod to provide remote electrical control of the valve. A positive spring return is provided to close the valve when the solenoid is deenergized. A variable-speed blower is used to force nitrogen over the finned surface of the cooler. In operation a bypass flow is taken from the main sodium stream; passed through a flowmeter, the economizer section, the nitrogen cooler, and the plugging valve; and then sent back through the economizer to the main sodium stream. With the plugging valve closed, the flow is 63.3 cm^3/sec (1 gpm) and the blower control is adjusted to provide a cooling rate of 0.046°C/sec (5°F/min). When plugging begins, the flow decreases to 0.6 of the initial value, the cooler is turned off, the heaters are turned on, and the solenoid is activated to remove the plug and prepare for another plugging cycle. The sequence is programmed as illustrated in Fig. 4.56. Curves traced during a laboratory test are presented in Fig. 4.57.

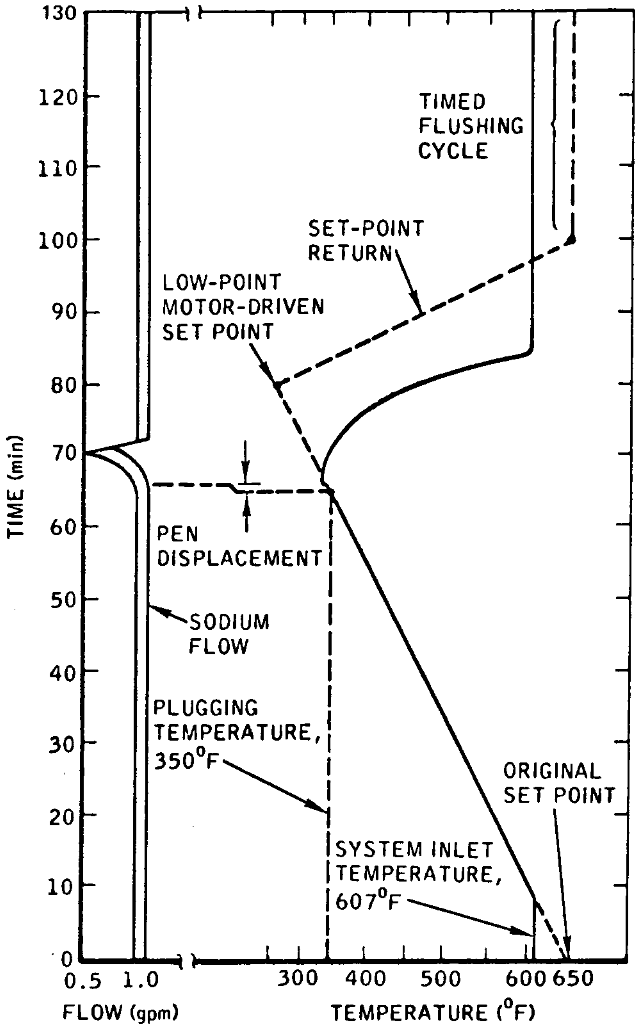


Fig. 4.56 Program for plugging meter illustrated in Fig. 4.53.

The schematic diagram of an automatic plugging meter [130] is shown in Fig. 4.58. The orifice consists of a cap having 12 notches 0.1 by 0.1 cm (0.0394 by 0.0394 in.) at the base of the economizer. The economizer is finned and air cooled at the plugging orifice end. The flow rate is of the order of 42 cm^3/sec (0.66 gpm) and the cooling rate is 0.0833°C/sec (90°F/min). The cooling rate is servo controlled by the sodium flow rate so that the flow is maintained at a constant value corresponding to a partial plugging of the orifice. Thus solution equilibrium exists between the precipitation and the impurity-saturated sodium. The temperature is measured at the orifice. The regulation is accomplished by first establishing the flow rate at some definite value below the unplugged value; then the regulator controls the cooler to

TABLE 4.1 – Plugging Meters

Place of use	Description				
	Flow rate, cm^3/sec	Cooling rate, °C/sec	No. of holes	Hole shape*	Hole size, cm
Rapsodie (France)	27.8	0.083	12	R	0.1
Rapsodie (France)	55.6	0.083	50	R	0.1
Rapsodie (France)	41.7	0.083	12	S	0.1 × 0.1
Rapsodie (France)	18.9	0.083	12	R	0.1
Rapsodie (France)	41.7	∿0.083	12	S	0.1 × 0.1
MSA (U.S.A.)	63.3		16	R	0.127
MSA (U.S.A.)			15	R	0.127
ORNL (U.S.A.)	6.33		4	½R	0.094
ORNL (U.S.A.)	5.67	0.371	4	½R	0.094
Hallam (U.S.A.)	63.3	0.046			
PFR (U.K.)					
ANL (U.S.A.)	7.1 to 16.2	0.055 to 0.358	10	S	0.081 × 0.040
AI (U.S.A.)	6.33	0.464	4	½R	0.127
USSR		0.005 to 0.618	16	S	
USSR		0.005 to 0.618	16	S	0.10 × 0.10
USSR		0.005 to 0.618	34	S	0.05 × 0.05
JAERI (Japan)	26.9	0.005	17	R	0.12
SRE (U.S.A.)	63.3	0.046 to 0.371			
KAPL (U.S.A.)	31.6	0.00093 to 0.046	8	R	0.127
KAPL (U.S.A.)	50.6 to 95.0	0.0093 to 0.185	16	R	0.127
MSA (U.S.A.)		0.00093 to 0.093	1	R	0.127
KAPL (U.S.A.)	19	0.046 to 0.092	17	R	0.117
KAPL (U.S.A.)	63.3		21	R	0.127

*R, round, S, square; ½R, half-round.

Described in the Literature

Description			Remarks
Orifice type†	Effective orifice area, cm^2	Ref.	
P	0.94	130	Type 1, manual, plug and unplug easy, operation satisfactory
	0.493	130	Type 2, manual, plug easy, unplug difficult, onset of plugging unclear, operation unsatisfactory
P	0.120	130	Type 3, manual, plug and unplug easy, operation very satisfactory (see Fig. 4.58)
	0.0943	130	Type 1A, discontinuous automatic, not entirely satisfactory
	0.120	130	Type 3A, very satisfactory
P	0.203	141	
P	0.190	133	Manual, satisfactory operation (see Fig. 4.53)
V	0.028	128	Manual, fluid NaK, satisfactory
V	0.028	128	Manual, fluid NaK, satisfactory
P		135	Programmed, plug and unplug easy, very satisfactory (see Fig. 4.55)
A		136	Automatic, used special pressure regulator, operation satisfactory (see Fig. 4.59)
	0.0328	137	Satisfactory, range of flow and cooling rate had no effect
V	0.048	139	Manual, satisfactory, range of flow and cooling rate had no effect
	0.160	140	
	0.160	140	
	0.085	140	
VP	0.127	129	Manual, plug and unplug easy, very satisfactory operation
		132	Manual, operation satisfactory
P	0.102	127	Manual, plug and unplug easy, operation satisfactory
P	0.203	127	Manual, plug and unplug easy, operation satisfactory
P	0.013	133	Manual, used to study effect of cooling rate
P	0.137	128	Manual, prototype of model used in USS *Seawolf*
P	0.268	137	Manual, used in early cold trap studies

†P, plate; V, valve; A, annular.

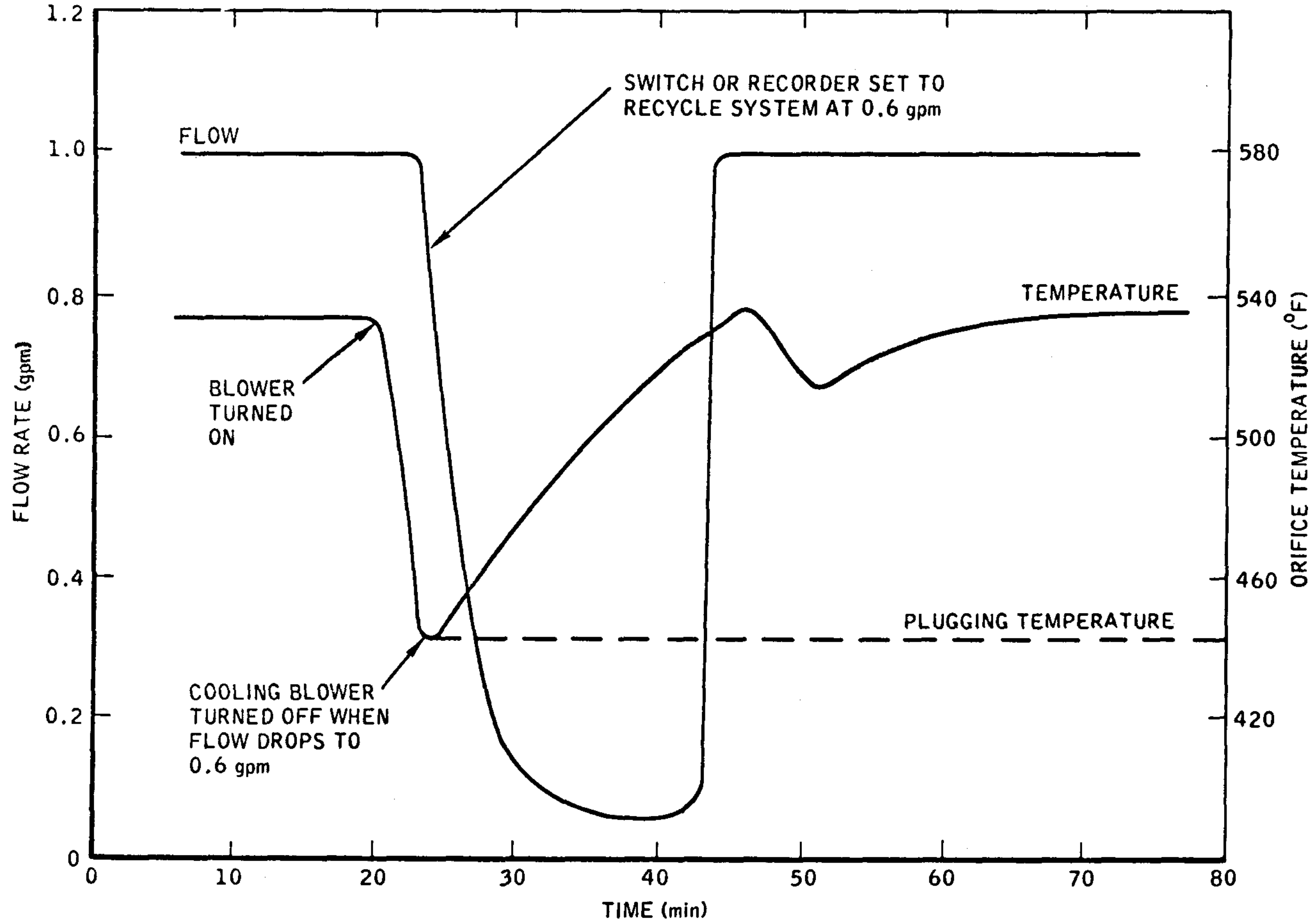


Fig. 4.57 Flow and orifice temperatures in programmed plugging meter (laboratory test data).

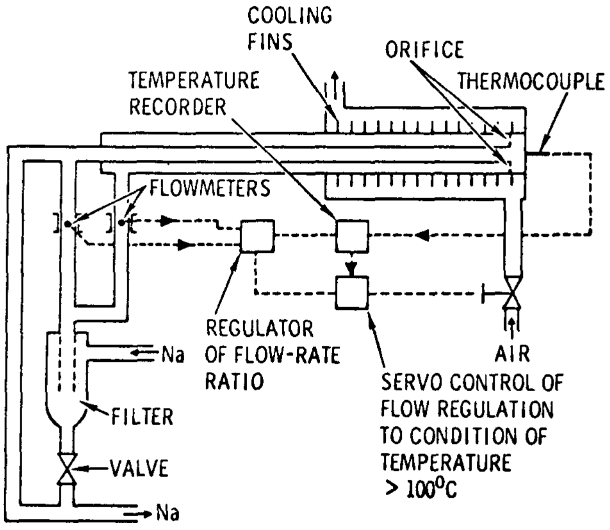


Fig. 4.58 Differential automatic plugging meter.

maintain this assigned flow rate. During operation, if the impurity content of the sodium decreases, the temperature at the orifice is higher than the saturation temperature, and the impurity precipitated in the orifice begins to dissolve. This dissolution enlarges the flow passage, permitting an increased sodium flow rate. The regulator, sensing the increased flow rate, operates the cooler to decrease the sodium temperature. The temperature decrease causes precipitation of impurities, thereby decreasing the flow-path area through the orifice and resulting in a decreased flow rate. This process of hunting continues about the set value of flow, and a steady-operation condition is attained. Automatic operation was very satisfactory, and plugging temperature was determined to an accuracy of ±1°C. Experimental work on this instrument showed that an excessive pressure caused flow-rate instabilities, which were attributed to the mechanical instability of the oxide deposit when the upstream pressure was greater than about 4.9×10^4 N/m^2 (7.1 psi).

An automatic plugging meter with an orifice in the form of an annulus [136] is illustrated in Fig. 4.59. The sample flow is divided between the fixed flow restrictor and the plugging annulus. When cooled below the impurity-saturation temperature, the annulus begins to plug and the flow rate decreases. The control system is designed to maintain the annulus flow at a small value equivalent to a partially plugged condition by adjusting the flow of cooling air. At the controlled equilibrium (i.e., with the establishment of the partially plugged condition),the annulus temperature coincides with the saturation temperature, which is measured and indicated in the output signal. The constant-pressure auxiliary pump avoids the need to measure flow ratio and also allows the meter to be independent of flow changes in the sampled circuit. The flow-sharing principle is used not only to give good sensitivity for a given mass of precipitated impurity but also to provide an adjacent continuous flow into which an accidental total plug of the annulus can redissolve with reasonable ease. The meter has operated satisfactorily with indicated plugging temperatures from 250 to 125°C.

The various forms of plugging orifices in use are illustrated in Fig. 4.60. Fixed and valve orifices have been used widely. Annular [136] and variable-volume orifices [129] are relatively new.

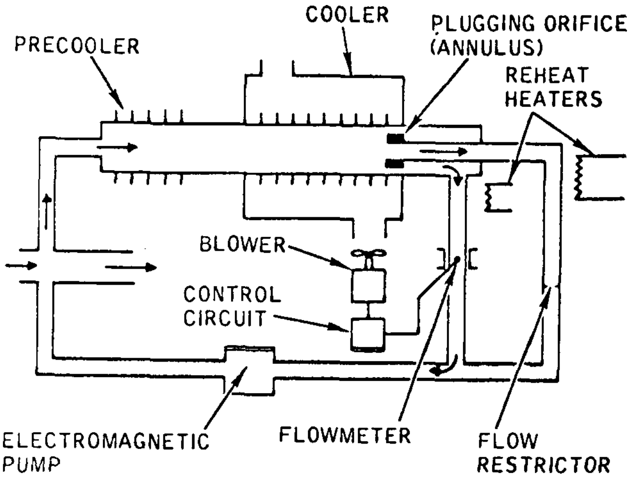
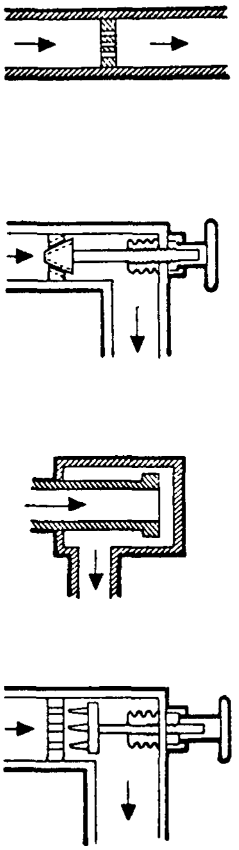


Fig. 4.59 Experimental design of a continuous automatic plugging meter.



(A) FIXED ORIFICE:

A PERFORATED PLATE PLACED IN A PIPE. IT WAS THE FIRST TYPE USED, BUT PROBLEMS WITH UNPLUGGING HAVE LIMITED ITS USEFULNESS.

(B) VALVE ORIFICE:

CONSISTS OF SLOTS IN THE VALVE SEAT OR IN THE VALVE PLUG. IT IS BECOMING WIDELY USED TO FACILITATE UNPLUGGING.

(C) ANNULAR ORIFICE:

THE ORIFICE IS THE ANNULAR CLEARANCE BETWEEN TWO CONCENTRIC TUBES.

(D) VARIABLE ORIFICE:

A PERFORATED PLATE AND A PLUG, CONSISTING OF TAPERED PINS MOUNTED TO PARTIALLY CLOSE THE HOLES IN THE PERFORATED PLATE. THE OBJECT IS TO PROVIDE A VARIABLE-AREA ORIFICE TO MATCH THE IMPURITY CONCENTRATION LEVEL.

Fig. 4.60 Various forms of orifices.

Tests to determine the effect of flow rate and cooling rate on plugging-meter performance produced conflicting views. One report [137] stated that the performance was unaffected by cooling rate; however, another report [138] indicated that plugging temperature can be depressed by increasing the cooling rate. Similarly, conflicting observations regarding the effect of flow rate have been reported [129,131, 137,139,140]. A study [111] showed that about 60% of the installations reporting satisfactory performance operated at flow rates designated in some reports as unsatisfactory. The seeming conflict is the result of different design features and operational methods and conditions, which determine the performance sensitivity to flow and cooling rates. An insensitivity to these rates over a limited range can be achieved. Rates reported for various plugging meters are presented in Table 4.1.

Plugging-meter sensitivity is affected by the pressure-vs.-flow characteristic of the flow source. A constant-pressure pump is commonly recommended, although a pump as such is not necessary; bypass lines can be used to achieve a suitable value of hydraulic impedance. The use of a constant-pressure pump (Fig. 4.59) improves sensitivity. The optional arrangements are shown in Fig. 4.53. Davis [111] treated this matter in some detail.

The nature of manual or programmed plugging-meter operation precludes a simple statement of response time. The time required to induce plugging, which is a function of the cooling rate, concentration, and extent of plugging required to meet the criteria of plugging, can be construed to be a response time. The plugging time generally is of the order of several minutes, typically 5 to 60 min depending on the conditions. However, in most applications where repeated measurements are to be made, consecutive measurements cannot be made at the intervals indicated by the plugging time since time for restoring the temperature and flow conditions must be added. The time required for the complete cycle can be called the response time.

Since the automatic plugging meter operates at the incipient plugging temperature or hunts about this value continuously, the response time is of the order of a few seconds.

(b) *Resistance Meter*

A schematic diagram of the resistance meter [142], commonly called a resistivity or rhometer, is shown in Fig. 4.61. The toroidal pipe and the liquid metal contained in the loop are arranged to constitute a closed secondary circuit on the transformer. The inductive coupling obviates the use of electrodes to contact the liquid metal. The transformer primary is part of an a-c bridge circuit; thus resistance changes in the inductively coupled liquid-metal circuit result in a bridge imbalance. The resistance of the liquid-metal-conducting loop is a function of geometry and liquid-metal resistivity. Entrained gas, voids, or nonconducting particulate matter can alter the effective length-to-area ratio of the liquid-metal-conducting circuit; hence their passage through the loop is registered by the indicator. Since the resistivity of the liquid metal is a function of soluble impurity content and temperature, a change in these within the toroid is registered by the indicator. The temperature coefficient of resistivity of liquid metals is large enough that a small temperature change produces an indication of the same order of magnitude as the impurity in solution. A temperature compensation circuit consisting of a resistance in thermal contact with the pipe inlet to the toroid and connected electrically to the bridge circuit is included to cancel out the temperature effects.

The instrument performs well in monitoring impurities or voids that alter the resistance of the liquid-metal circuit in the toroid.

The upper temperature limit is 315°C (600°F), a value established by the compensator [143]. The coil windings

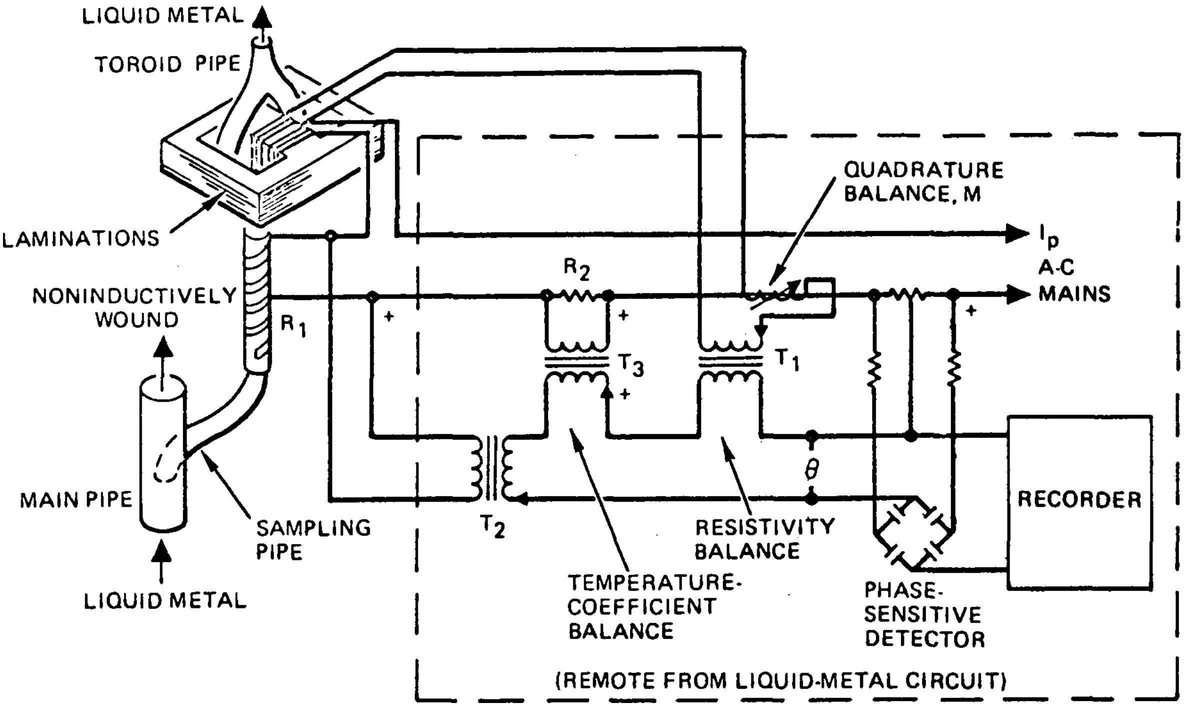


Fig. 4.61 Rhometer circuit diagram.

deteriorate as the liquid-metal temperature is raised [143] to 400°C (750°F). The transformer core, made of Super-Mumetal 50, must be operated below its Curie temperature, 432°C (800°F). The upper limit can be extended by compensator modification and by providing better thermal insulation between the toroid and the core and coils.

Accuracy in indicating resistance changes [144] is about 2%. Factors to consider in relation to accuracy are:

1. *Sensitivity*. Sensitivity to resistance changes of the order of one part in 10^4 is reported [144].

2. *Stability*. The stability was originally stated [142] to be one part in 10^4. In a subsequent performance evaluation [143], the drift was considered to be "not of significant magnitude;" however, in a later evaluation changes in sensitivity were found [116]. According to another evaluation [115] drift was significant and the "rhometer is of limited value in applications as an oxygen monitoring device in typical sodium systems." Dehn and Eames [144] gave a value of one part in 10^4.

3. *Temperature Sensitivity*. An uncompensated rhometer is impractical because of the very high temperature sensitivity. In the absence of temperature compensation, the liquid-metal temperature would need to be held constant to ±0.05%/°C to enable observation of low-level-impurity changes [144]. Compensation reduces the inherent temperature sensitivity to an acceptable value. The error is negligible over a ±5.5°C (±10°F) range about the set point, and a range of ±27.8°C (50°F) results in a change in indication corresponding to a 10-ppm change in oxygen content.

4. *Calibration*. Readings are expressed as percent of resistivity. Calibration is affected by a change in flow rate. At very low flow rates [e.g., below 63.3 cm^3/sec (1 gpm)], the heat generated by the current in the toroid is not readily dissipated and raises the temperature, causing an in-

creased resistance. At high flow rates [e.g., above 1266 cm^3/sec (20 gpm)], some cavitation occurs in the toroid, and this results in an erratic signal [143]. A flow rate of 475 cm^3/sec (7.5 gpm) is recommended since at about this value the relation of resistance change to flow change is linear.

5. *Selectivity.* The rhometer is a very sensitive device for measuring changes in resistance. Resistance is composed of two factors: (1) resistivity, a material property, and (2) geometry. Impurities affecting the geometry (entrained gas or suspended matter) are clearly indicated. Tests were conducted for response to a number of impurities, but the results are in question [118,119,145,146].

6. *Response Time.* The inherent characteristics of the rhometer indicate that the response time is established by the frequency used and the time constant of the circuits. For commercial power frequencies the response time can be taken to be about 1 sec. Time required for adjustment or zeroing must be added to this figure.

Preliminary tests in an X-radiation field indicated that the response is not affected by the radiation [118], but this does not imply that the materials of construction are radiation resistant.

Since the instrument is very responsive to entrained gas, the toroid should be vertically mounted to prevent the formation of gas pockets, and the connection to the system loop should be on a vertical section.

The theory of operation is treated in detail by Blake [142]. Dehn and Eames [144] presented a performance review and a discussion of design features and improvements.

4-6 LEAK DETECTION

The applicable methods of leak detection depend on the direction of the leak (i.e., from the liquid metal to the outside or from the outside into the liquid metal) and the observable effects created. Consequently a system may require a number of different leak-detection methods. The selection and location of leak-detection efforts depend on an evaluation of the potential sources of leaks. A leak-detection method must provide adequate sensitivity, fast response, and continuous operation.

4-6.1 *Visual Detector*

In some cases, particularly in development or test laboratories, visual observation is an excellent means of leak detection. This is hindered in regions covered by thermal insulation or other materials. In the case of a large leak from the vessel to the outside room environment, the issuance of the liquid metal is readily apparent. A small leak is also noticeable since reaction with moisture in the air produces a deposit on the vessel walls, and, depending on the circumstances, the reaction may result in smoke or fire. A leaking component in an enclosure such as a vacuum vessel produces a liquid-metal vapor or smoke deposit on view ports. If components are located in an area that precludes close personal observation, television can be used, depending on the nature of the liquid-metal system. The visual observation method has the disadvantage of requiring the presence and attention of human operators, but most operations involving liquid-metal technology must be unattended, at least part time.

4-6.2 *Electrical-Contact Detector*

Since liquid metals have a high electrical conductivity, their presence can be detected when they close an energized electrical circuit connected to an indicator. In one form of leak detector, a pair of corrosion-resistant high-temperature wires in close proximity but electrically separated is placed on the vessel so that a leak will short them. One such detector is a fabric tape with bare wires woven into it. It is applied over the surface to be monitored, and the leaking liquid metal is absorbed by the tape and short-circuits the bare wires in the fabric. The liquid metal penetrates the wires very slowly, especially at low temperatures. This slow response, among other factors, limits the acceptance of this method.

The problem of slow absorption is circumvented by the use of ceramic spacer beads, typically the two-hole type rather than fabric, as a means of positioning the pair of wires. Like the fabric tape, the ceramic-spaced wires are placed on the vessel to best advantage for leak detection. The spacing between beads permits penetration of liquid metal. This method often is unsatisfactory because inadvertent mechanical disturbances can cause shorting of the wires and give a false indication of a leak. The spark-plug method is used to detect leaks in bellows-sealed valves. The spark plug, consisting essentially of sheathed thermocouple wire, is inserted into the valve venthole so that the pair of wires exposed to the enclosed region around the bellows are shorted by any leaking liquid metal. This method of monitoring bellows-sealed valves has been very satisfactory.

In some instances, when the area to be monitored is sufficiently localized, the leaking metal is collected in a basin, and its presence is detected by a pair of electrodes mounted so that they are short circuited by the pool of liquid metal.

4-6.3 *Volume-Change Detector*

Liquid metal leaking to the outside certainly results in a decreased quantity within the vessel. The usual methods of measuring the quantity of liquid metal in the vessel are too coarse to indicate small leaks in large systems within a reasonable period of time. However, in the relatively small systems, the usual methods of measuring quantity are excellent. This is done in space systems by monitoring the magnitude of the expansion in the expansion compensator. In very large systems, or when the resolution of the level gauges or other instruments responsive to change in quantity is relatively coarse, other indications of leak probably would provide an earlier alarm.

4-6.4 *Third-Fluid-Change Detector*

The third-fluid method is based on monitoring the composition of a third fluid intermediate between the liquid-metal system and the water system in liquid-metal-to-water heat exchangers. Leak detection is accomplished by monitoring the fluid composition by any means appropriate to the specific intermediate fluid. The third-fluid method has several disadvantages. The selection of a suitable fluid is a problem; for heat exchangers, for example, no fluid available possesses all the required characteristics, and hence a compromise is necessary. Another disadvantage is the greater complexity of fabrication. This method is seldom used.

4-6.5 *Impurity Detector*

A leak from the outside to the liquid metal within the vessel can be detected by reaction of the entering material with the liquid metal. This situation can occur in sodium-to-water heat exchangers when the water, which is normally at a higher pressure, enters the sodium system. The reaction products include H_2, Na_2O, and NaH. Some of the impurity detectors discussed in Sec. 4-5 respond to one or more of these reaction products; hence an otherwise unexplained increase in the impurity level may be an indication of a leak into the liquid metal. Detectors sensitive to H_2 usually are used for this function. Hydrogen detectors for water-to-sodium leaks are discussed in Refs. 120, 121, and 147.

4-6.6 *Cover-Gas-Change Detector*

The generation of hydrogen caused by water entering the vessel results in an increase in cover-gas pressure, which can be the basis of leak detection. When this method is used, values of cover-gas pressure characteristic of normal operation must be established. A pressure rise creating an excess of 5 psi has been used as the criterion of a leak [148]. A hydrogen detector (e.g., a thermal-conductivity cell) placed in the cover-gas region can be used [149].

4-6.7 *Optical Detector*

The vapor or smoke that ordinarily accompanies a liquid-metal leak to the surrounding atmosphere can be detected by its absorption or scattering of light. This method is used in a system [43] where a light beam from a low-pressure sodium lamp traverses the region under surveillance to an optical detector cell (CdS). The cell responds to such interference with the light beam as occurs when vapor or smoke density in the path is high enough.

The limiting bulk sensitivities to sodium vapor and smoke are nominally 75×10^{-6} and 1.5×10^{-3} g/m^3, respectively. A reference beam path and a white-light source are used as a self-checking system to differentiate between the presence of vapor and smoke and instrument faults when the alarm circuit is activated.

This equipment functions reliably and well. Its main defect is that it is of good sensitivity and response speed only for leaks in the immediate vicinity of the detecting beam. With a large or complex sodium circuit, many instruments must be used to give satisfactory coverage [43].

4-6.8 *Room Air Sampler*

When the sodium system is enclosed, standard gas analyzers set for sodium can be used by circulating the atmosphere through the analyzer. The analyzer may be mounted within the enclosure or in a ventilating exhaust duct. When the sodium is radioactive, a gamma detector generally is used as a leak detector.

4-6.9 *Reaction Product*

The reaction of leaking sodium with the ambient atmosphere provides a leak indication by the production of smoke or fire as mentioned previously. However, this requires an atmosphere containing suitable reactants; oxygen and a small amount of moisture are sufficient and often are present. In a system enclosed in an inert atmosphere (N_2, for example, as is common), no reaction occurs. One technique is based on adding a specific reagent to the atmosphere to provide a readily detected reaction product. A small amount of methyl alcohol has been used in this manner to produce H_2. This method is more effective at lower temperatures than most other methods.

4-7 TEMPERATURE MEASUREMENT

4-7.1 *Techniques of Measurement*

Ordinarily it is not practical to measure liquid-metal temperature directly; the temperature-sensitive element is separated from direct contact with liquid metal.

The factors involved in liquid-metal temperature measurement are containment material and fabrication and correction for the liquid-metal-to-containment-material (point of measurement) temperature difference.* Beyond this, liquid-

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*These subjects are treated in the appropriate sections elsewhere in this book.

metal temperature measurement technology is essentially the same as that in any other application subject to the same temperature, environment, and configuration factors.

Table 4.2 provides a guide to the various temperature-measurement techniques. Instrumentation for temperature measurement in liquid-metal systems is based almost entirely on thermocouples, mainly type K (Chromel-Alumel) thermocouples. Resistance thermometers are used infrequently, and a few other techniques are used, generally, only as auxiliary methods or for special operations or circumstances.

Since coverage of temperature measurement here is limited, the reader is referred to Refs. 150 to 158, the references in Table 4.2, and the commercial products literature.

4-7.2 *Thermocouples*

(a) *Circuit*

A thermocouple in its typical form as a temperature sensor is the junction of two wires of dissimilar metals as illustrated schematically in Fig. 4.62. The thermocouple circuit develops a voltage that is a function of the temperature difference between the measuring junction (hot) and the reference junction (cold). Ordinarily the reference junction is a thermocouple identical to the measuring couple and is immersed in a constant-temperature medium whose temperature corresponds to the calibration point, usually the ice point of water, 0°C (32°F). When it is not practical or convenient to provide stable reference temperature, a compensator is used. The compensator is connected in series with the thermocouple so that the combined output simulates a constant reference-junction temperature. This concept sometimes is extended to eliminate the ice bath. In most industrial thermocouple indicating instruments, a junction compensator is included so that the extension leads can be connected directly to the indicator terminals. Compensation is discussed in Refs. 159, 160, 205, and, in greater detail, 161.

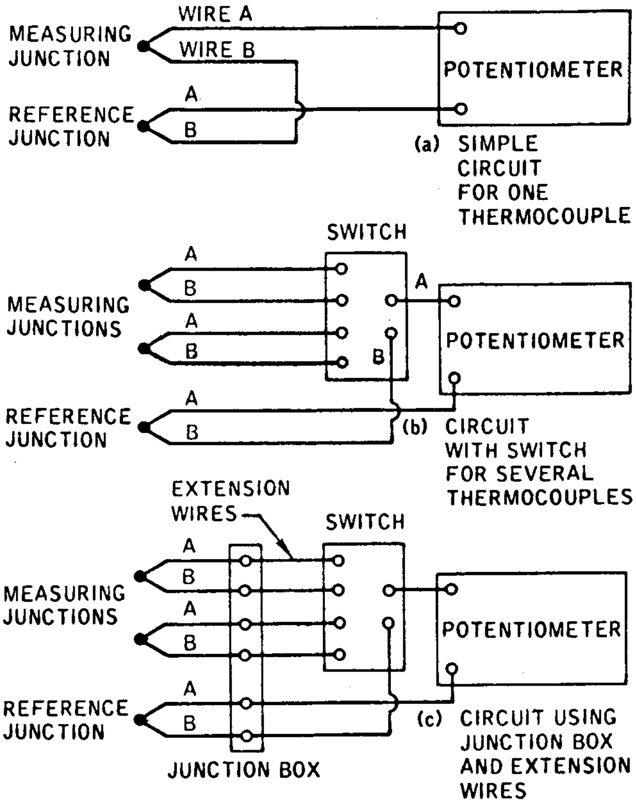

Fig. 4.62 Thermocouple circuits.

The electrical circuit "viewed" by the thermocouple consists of a transmission line containing series and shunt resistances which is terminated by an indicating instrument that can have a finite or an equivalent infinite resistance. If the insulation shunt resistances are very high and an equivalent infinite resistance indicator (e.g., a potentiometer at balance) is used, no current flows, and the reading is independent of the circuit series resistance. Accordingly, effort is made to minimize shunt conductance and the potentiometer (or null method) is the preferred indicator. The insulation conduction ordinarily is negligible except at very high temperatures or when the insulation is contaminated. Figure 4.63 shows the relation between resistivity and tempera-

TABLE 4.2 - Common Techniques of Measuring Temperature*

Technique	Temperature range, °C [153]	Accuracy, % [153]	Location of sensor†	Reference
Thermoelectric voltage				153, 154, 156, 158, 162, 163, 167, 171 to 200
Change with temperature differential of emf generated between dissimilar metals with junctions at different temperatures				
1. Two dissimilar wires	-200 to +1100	1	C,S,B	
2. One wire with body as other material			C,S,B	
3. Thin film(s) deposited on surface			S	
4. Two bodies of different metals in contact				
Electrical resistance				153, 155, 156, 159, 201 to 206
Change of resistance with temperature				
1. Three-dimensional coil	-240 to +600	3/4	B	
2. Two-dimensional grid, coil or tape			C,S,B	
3. One-dimensional wire			S,B	
4. Thermistor (bead or block)	-20 to +300		C,S,B	
5. Thin film deposited on surface	-270 to +400	0.1 or 1	S	
6. Resistance of body itself				
Thermal radiation				153, 157, 207, 208
Change with temperature of heat radiated from surface				
1. Optical comparison with heated reference	600 upward	1 or 2	N	
2. Radiation emitted (total or selective)	20 to 4000	1 or 2	N	
3. Infrared radiation emitted	100 upward	1 or 2	N	
4. Reflection pyrometer	300 upward	1 or 2	C,N	
5. Two-color pyrometer	200 to 4000	1 or 2	N	
6. Color cinematography	800 to 2000	1	N	
7. Evapography			N	

Thermography Change with temperature of luminescence from an excited phosphor, heated by contact or by thermal radiation				155
1. Effect of fluorescence	20 to 200	2	S,N	
2. Effect of phosphorescence	100 to 340		S	
Melting Sudden melting of a substance at a known temperature				153, 155
1. Crayons	40 to 1400	1	C	
2. Paints	40 to 1400	2	S	
3. Papers	40 to 250	1	S	
4. Pellets (metal and nonmetal)	40 to 1500	2	S,B	
Color				153, 155, 157, 158
1. Crayon (sudden change in color of a substance at a known temperature)	40 to 1400	1	C	
2. Paints	40 to 1400		S	
3. Temper color (change with temperature)			N	
4. Thermal radiation (change with temperature)	800 upward	2	N	
Other techniques				154, 158, 209, 210

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*From G. G. Watson, Techniques for Measuring Surface Temperature. Part I, *Instrum. Pract.*, *20*: 218-219 (1966).

†C, contact probe; S, on surface; B, below surface; N, noncontact.

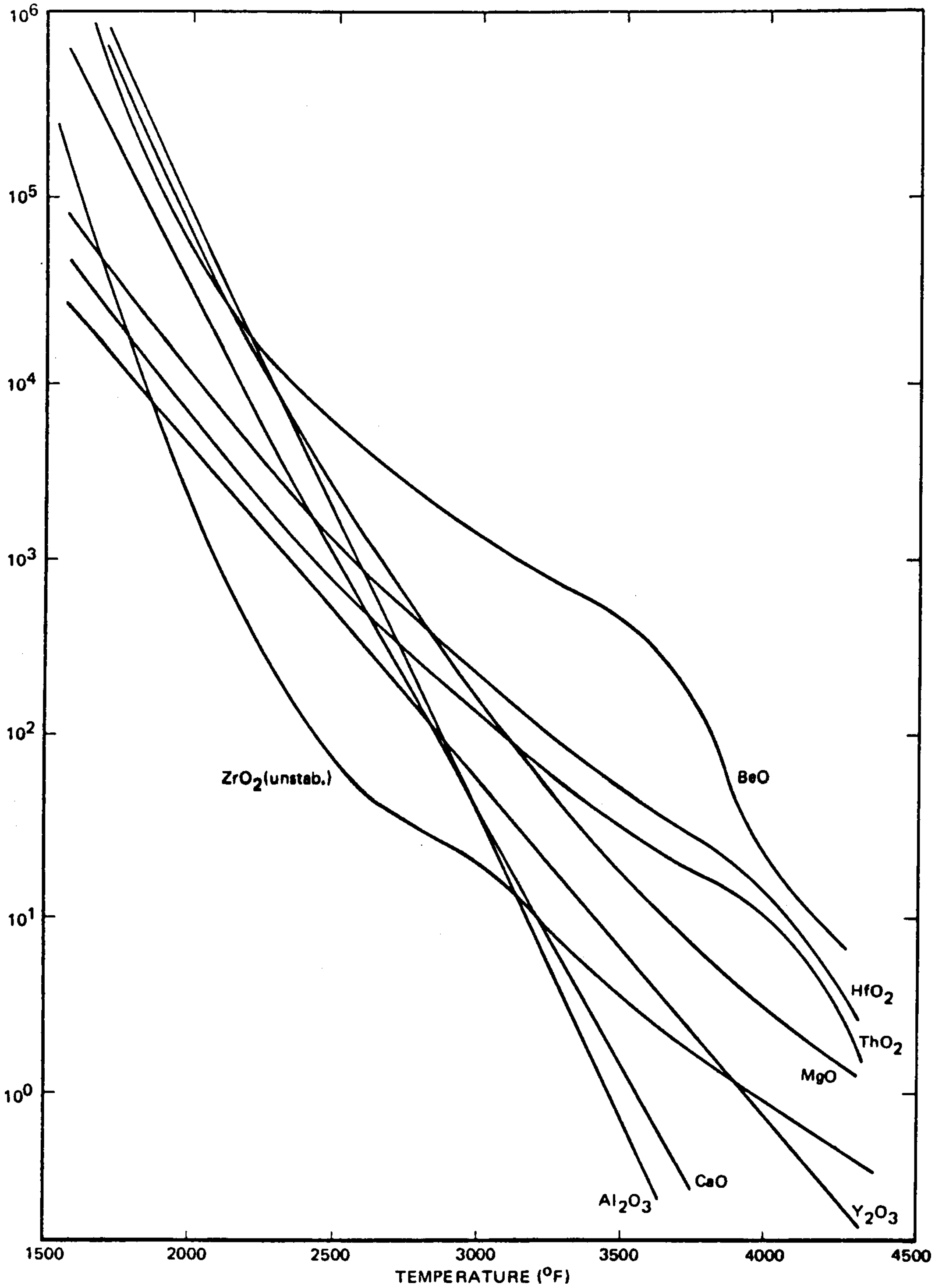


Fig. 4.63 Relative electrical resistance as a function of temperature for various thermocouple insulation materials in helium.

ture for several insulating materials used in thermocouples [162].

A current-drawing indicator can be used, but its use requires a knowledge of the circuit resistance, a function of temperature. This complication is a deterrent to the use of a current-drawing indicator in all but special applications.

Although nearly any combination of dissimilar materials will produce an emf when assembled and operated as a thermocouple, only a few are suitable for ordinary instrumentation applications. Figure 4.64 shows the emf as a function of temperature for several thermocouple materials.

Table 4.3 presents standards adopted for thermocouple fabrication [163]; only thermocouples for which the technology has been well established are included. The limits of error apply for the wire-size temperature limit indicated (limits of error for thermocouples as supplied by the manufacturer). When limits of error are expressed in percent, the percentage applies to the temperature measured. The calibration of a thermocouple can change during use, the magnitude of the change depending on such factors as temperature, length of time, and conditions under which it is used. The recommended upper limit applies to thermocouples in conventional closed-end protecting tubes and does not apply to sheathed thermocouples having compacted mineral-oxide insulation. In actual operation the limit may be higher or lower depending on the specific conditions.

(b) *Types and Mounting*

1. *Surface Mounted.* It is important to have as few welded joints as possible in containment vessels for liquid-metal systems. Vessel fabrication effort, system operating lifetime, reliability, and safety are related to the integrity of the containment vessel. A thermocouple mounted on the surface avoids penetration of the vessel. Moreover, since the surface mounting does not involve any technology peculiar to liquid-metal applications, conventional thermocouple technology applicable to the environment and temperature range is suitable.

Where measurement of the surface temperature is desired, surface mounting is entirely satisfactory. However, in many applications measurement of the liquid-metal temperature is desired; in this case a correction factor must be used. In the usual surface mounting, the thermocouple junction is located in a system of thermal impedances in which heat is flowing. Consequently the temperature indicated at the junction is affected by the values of heat flux and thermal impedances and may differ significantly from the temperature of the source, the liquid metal. In applications in which the temperature of the liquid metal is desired, the temperature is the value of the indicated surface temperature plus the sum of thermal drops in the liquid-to-solid interface, the wall material, and the wall-to-junction material.

The effect of the thermal impedances in the wall-to-junction material can be minimized by improving the conductance in the heat path and by minimizing the heat flux, which can be diminished by reducing the conduction and radiation losses from the junction. This is accomplished by keeping the wires in thermal contact with the vessel wall for a short distance from the junction and, in cases where the junction "views" a lower temperature surface, by shielding or coating the junction and adjacent wire to minimize radiation loss. The device for preserving thermal contact between the thermocouple wires and the vessel surface can be extended to provide mechanical support for the wires. A compensated thermocouple can be used to avoid lead conduction errors. Construction and use of compensated thermocouples are discussed by Watson [153] and Vidadi [164]. Thermal-impedance or heat-transfer aspects of thermocouple measurements are discussed in Refs. 151, 153, 154, 156, 160, 165, and 166.

The thermal impedances in the vessel wall and in the liquid-to-wall interface generally are controlled by design factors other than those pertaining to in-

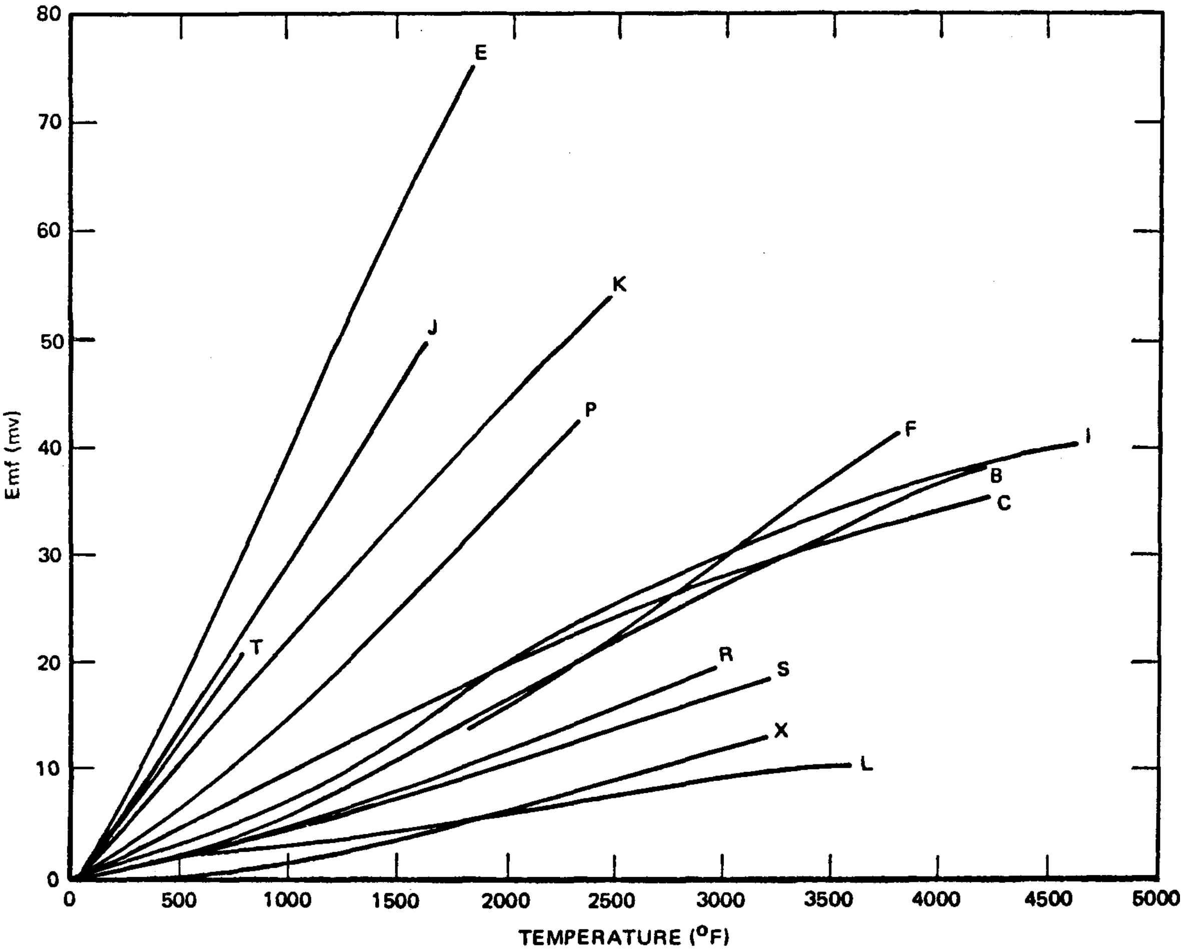


Fig. 4.64 Emf as a function of temperature for several commercial thermocouples. Note that although some of these materials will operate at higher temperatures than those shown, the temperatures on the figure are generally conceded to be the maximum reliable operating temperatures. (From Continental Sensing, Inc., Con-O-Chart 1, 6th printing, June 1967.)

T = Cu vs. Constantan
E = Chromel vs. Constantan
J = Fe vs. Constantan
K = Chromel vs. Alumel
P = Geminol P & N
F = Ir vs. W
B = W vs. W-26% Re
I = W-3% Rh vs. W-25% Rh
C = W-5% Re vs. W-26% Re
R = Pt vs. Pt-13% Rh
S = Pt vs. Pt-10% Rh
X = Pt-6% Rh vs. Pt-30% Rh
L = Ir vs. Ir-40% Rh

strumentation and cannot be minimized for the benefit of instrumentation. If the liquid-metal temperature-measurement uncertainty caused by these thermal drops is unacceptable, immersion techniques can be used.

Unsheathed. An unsheathed thermocouple is one that has no rugged protective cover to prevent environmental or mechanical damage. The pair of wires is electrically insulated by a suitable high-temperature insulation, such as woven Fiberglas, ceramic beads, or ceramic tubes. The unsheathed thermocouple is used when simplicity and economy are dominant factors and a sufficiently low risk of damage is assumed.

A common method of mounting consists in welding the junction to the surface with an electric pulse welder. With this method it is not necessary to form

TABLE 4.3 – Temperatures and Limits of Error for Commercial Thermocouples*

Type (ASTM [163] designation)	Common name	Limits of error			Temperature-wire size relation		
		Standard	Special	Temperature range, °F	Temperature, °F	Wire size	
						AWG no.	Diameter, in.
J	Fe-Constantan				1400	8	0.128
					1100	14	0.064
		±4°F	±2°F	32 to 530	900	20	0.032
		±3/4%	±3/8%	530 to 1400	700	24	0.020
					700	28	0.013
K	Chromel-Alumel				2300	8	0.128
					2000	14	0.064
		±4°F	±2°F	32 to 530	1800	20	0.032
		±3/4%	±3/8%	530 to 2300	1600	24	0.020
					1600	28	0.013
R	Pt-13% Rh vs. Pt	±5°F	±2-1/2%	32 to 1000	2700	24	0.020
S	Pt-10% Rh vs. Pt	±1/2%	±1/4%	1000 to 2700			
T	Cu-Constantan				700	14	0.064
		±1-1/2°F	±3/4°F	-75 to +200	500	20	0.032
		±3/4%	±3/8%	200 to 700	400	24	0.020
					400	28	0.013
E	Chromel-Constantan				1600	8	0.128
					1200	14	0.064
		±3°F	±2-1/4°F	32 to 600	1000	20	0.032
		±1/2%	±3/8%	600 to 1600	800	24	0.020
					800	28	0.013
†	W-5% Re + W-25% Re				4200	18	0.040
					1800	20	0.032
					1600	24	0.020
					1600	28	0.013

*From American Society for Testing Materials, Temperature-Electromotive Force (EMF) Tables for Thermocouples, ASTM E230-68, *1968 ASTM Standards*, Part 30, p. 725.

†No ASTM designation.

a junction weld bead prior to welding to the surface. Each wire can be welded to the surface individually, and there is no impairment of accuracy if the two junctions thus formed are identical and are at the same temperature. This may be the case if the junctions are close together and are not along a path of steep thermal gradient. This method is used when conditions permit since it is simple and economical.

An alternative to welding is the method of imbedding or peening the beaded junctions in a small surface cavity in the vessel wall. This may result in a higher thermal drop between the wall and the junction since the joint is entirely mechanical and an insulating film may form between the wall material and junction. This may introduce a small uncertainty in the measured value.

A fastener to provide mechanical support for the leads is needed for either of these mounting methods.

The size selection of the thermocouple wires depends on a number of factors. For fast response a small wire and a small junction are desirable. Thermocouples with wire diameters as small as 0.0118 cm (0.003 in.) are commercially available. Response times less than 10^{-6} sec are obtained in small sizes. Fragility and handling difficulties are among the main disadvantages of very small wires. Typical wire sizes are 0.013 cm (0.032 in.) or larger.

Sheathed. Thermocouple wires and their electrical insulation (typically MgO) can be enclosed in a metal sheath. The formation of a junction and the method of mounting are essentially the same as that for the unsheathed wire. The sheath provides environmental protection and facilitates mechanical support along the length of the wire.

These two advantages can be extended to include the junction by extending the sheath and closing it over the end of the junction. This constitutes a fully sheathed thermocouple. The junction can be formed in contact with the end closure except in thermocouple systems where it is necessary to insulate the junctions from the sheath. In these cases definite isolation is provided. In such a design the thermal impedance from the sheath wall to the junction may not be particularly detrimental since the junction is surrounded by the sheath and thereby minimizes the thermal losses. Though this is true for steady-state operation, the time constant of the insulated type may be longer than that of the uninsulated type, and this must be taken into account in applications requiring fast response.

The sheathed thermocouple can be mounted in a wall cavity, welded or brazed to the surface, or mounted in a split block or on a stud bonded to the vessel.

The size required depends on a number of factors. Small clearance or fast response requires relatively small thermocouples. Sheathed thermocouple probes with diameters as small as 0.0381 cm (0.015 in.) and response times of 10^{-6} second on the surface are available. Dimensions are discussed in the specifications for thermocouples [167].

(2) *Immersed*. A thermocouple immersed to a sufficient depth into the volume of liquid metal attains the temperature of the liquid metal; this gives a better sampling of temperature than can be obtained by surface mounting. The thermocouple wire itself and its junction ordinarily are not immersed in direct contact with the liquid metal since this causes problems of compatibility of the wire material and the insulation with the liquid metal. Instead it is customary to protect the bare thermocouple from the liquid metal. Two methods of protection are commonly used.

Sheath immersed directly. A fully sheathed thermocouple is immersed through a hole in the vessel wall, and the wall-to-sheath joint is welded closed. This method permits the use of a relatively rugged, tested and calibrated thermocouple and, with adequate depth of immersion, provides an excellent sampling of the liquid-metal temperature. The disadvantages are the difficulty of replacing defective couples while the liquid metal is in the vessel and the additional design, fabrication, and welding required to provide a satisfactory closure at the sheath-to-vessel wall joint.

Sheath immersed in well. A more satisfactory method of immersion involves the use of a well, which is simply a closed-end tube inserted in and projecting into the vessel and welded along the line of penetration. The thermocouple is inserted into the well, and generally some fastener device is provided to hold it in place and in good thermal contact with the well bottom. This has the advantages given for direct immersion, plus that of simplified replacement. Also, a satisfactory well-to-wall closure weld is easier to make than a weld to the thermocouple sheath. For an immersion thermocouple the well technique using a sheathed thermocouple is preferred.

(c) *Thermocouple Location*

The temperature indication can be impaired by the choice of thermocouple location or orientation owing to the following factors:

1. *Electric-Current Gradients.* (The current passes through the junction.) This generally is not a problem with alternating currents [168]. Direct currents flow in several situations in liquid-metal systems, e.g., in d-c conduction pumps and d-c flowmeters. An insulated junction can be used, or the thermocouple can be oriented to minimize the effect of the currents on the junction. A three-wire thermocouple can be used [158].

2. *Fluid-Velocity Effects.* A flow-pattern disturbance can impair the liquid-to-wall heat transfer and thus affect the reading of thermocouples in the region.

3. *Electromagnetic Fields.* Induction heating of the junction and induced currents affect thermocouple readings [169]. In liquid-metal applications the sources of interfering electromagnetic fields include electromagnetic pumps, transformer (induction) heaters, and other sources contributing to noise commonly encountered in instrumentation circuits. Experimental data [170] on the relative effectiveness of different shielding materials, grounding points, and circuit configurations are presented in Table 4.4.

(d) *Junctions, Splices, and Extension Leads*

Some types of junctions are described in relation to methods of installation or mounting. Figure 4.65 presents the metal-sheathed corrosion-resistant thermocouple for nuclear service shown in the ASTM tentative specification [167]. Figures 4.66 and 4.67 show designs for use in a high-temperature liquid-metal (lithium) system [171]. Figure 4.68 is a design for use in fuel rods [172].

A splice between two wires of the same metal or of metals intended to be thermoelectrically equivalent (e.g., extension wires) in a region where the temperature varies along the length can be made by welding the two ends together, by clamping them together directly if good contact is certain, or by mechanically joining them (e.g., twisting and then soldering or brazing). In these various methods parasitic thermoelectric effects caused by intervening material of different composition or structure must be avoided. Gas flames applied to platinum, platinum alloys, and Alumel can cause contamination, which, in turn, causes inhomogeneity and brittleness. Electric welding is preferred for these materials.

TABLE 4.4 – Relative Effectiveness of Various Methods of Reducing Noise in Instrument Circuits [170]

(a) Common-mode noise pickup

Sample	Shield grounded at couple	Shield grounded at control room
Fe-Constantan	3µv	230µv
Chromel-Alumel	2µv	110µv
Cu-Constantan	2µv	290µv

(b) Magnetic-noise test results (twisting vs. shielding)

Test	Ratio	Noise reduction, db
Parallel wires		0
Twisted wires		
4-in. lay	14:1	23
3-in. lay	17:1	37
2-in. lay	112:1	41
1-in. lay	141:1	43
Parallel wires in 1-in. rigid steel conduit	22:1	27

(c) Magnetic-field reduction by shielding

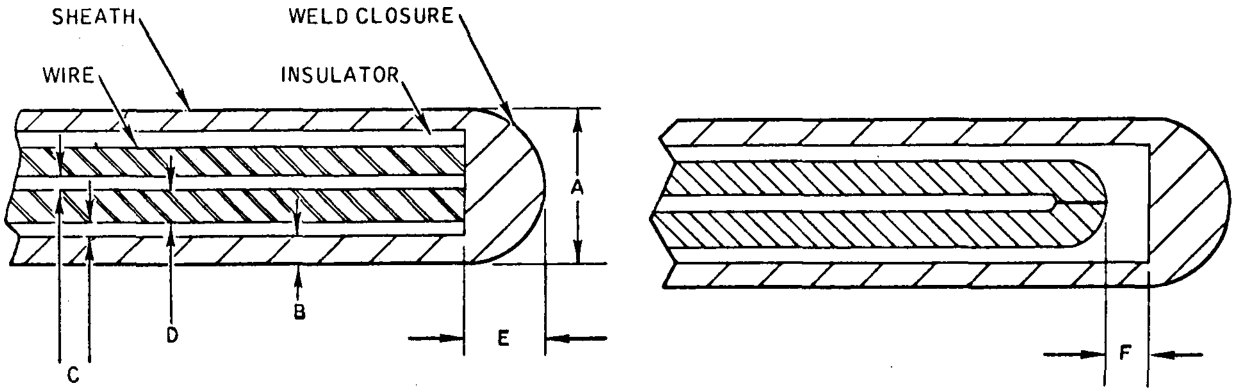
Shield material	Ratio	Reduction, db
1/2-in.-OD aluminum tube	1:1	0
1-in. rigid steel conduit	138:1	42.8
1-in.-ID BX armor steel	28:1	28.8
1-in.-ID magnetic shielding tape		
Type A 1 layer	3.5:1	10.8
5 layers	966:1	59.7
Type B 1 layer	5.3:1	14.5
5 layers	12:1	21.6

(d) Static-noise test results

Shield	Noise-reduction ratio	Shield efficiency, db
Tinned copper braid (85% coverage)	103:1	40.3
Spiral-wrapped copper tape (90% coverage)	376:1	51.5
Aluminum-Mylar tape with drain wire (total coverage)	6610:1	76.4

(e) Cross-talk noise pickup

Test	Voltage pickup on receiving pair	Circuit isolation, db
Nonshielded pair cable		
Unbalanced termination	100mv	46
Balanced termination	50µv	112
Shielded pair cable		
Unbalanced termination No shields grounded	100mv	46
Balanced termination No shields grounded	10µv	126
Unbalanced termination		
Driving pair shield grounded	80µv	108
Receiving pair shield grounded	40µv	114
Both pair shields grounded	10µv	126



GROUNDED MEASURING JUNCTION, CLASS 1

UNGROUNDED MEASURING JUNCTION, CLASS 2

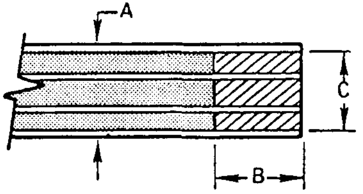
DIMENSIONS

SHEATH OUTSIDE DIAMETER, A			MINIMUM SHEATH WALL, B (in.)	MINIMUM INSULATION THICKNESS, C (in.)	MINIMUM WIRE DIAMETER, D (in.)	TOLERANCE, E (in.)		TOLERANCE, F (in.)	
NOMINAL (in.)	TOLERANCE (in.)								
	min.	max.				min.	max.	min.	max.
1/25	0.0390	0.0415	0.006	0.004	0.005	0.006	0.020	0.004	0.021
1/16	0.0615	0.0640	0.009	0.005	0.010	0.009	0.032	0.005	0.032
1/8	0.1240	0.1265	0.012	0.012	0.020	0.012	0.062	0.012	0.063
3/16	0.1865	0.1890	0.020	0.022	0.031	0.020	0.093	0.022	0.095

Fig. 4.65 Metal-sheathed corrosion-resistant thermocouples for nuclear service. (From American Society for Testing Materials, Metal-Sheathed Corrosion-Resistant Thermocouples for Nuclear Service, ASTM E235-67, *1968 ASTM Standards*, Part 30.)

(e) *Sensor Response as a Function of Temperature*

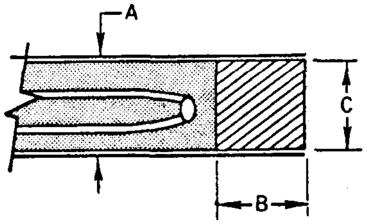
Comparative values of emf as a function of temperature for various common thermocouple materials are shown in Fig. 4.64. Tables of emf as a function of temperature are available from several sources. Reference 163 presents tables for Types E, J, K, R, S, and T thermocouples, the types most commonly used in industry. Tables are available from manufacturers of thermocouples and thermocouple wire.



DIMENSIONS (in.)

A	B	C
1/16	0.145 0.135	0.057 0.055
1/8	0.150 0.140	0.118 0.116

GROUNDED JUNCTION, W-Re DESIGN



DIMENSIONS (in.)

A	B	C
1/16	0.125 0.115	0.054 0.052
1/8	0.125 0.115	0.113 0.111

UNGROUNDED JUNCTION, CHROMEL-ALUMEL DESIGN

Fig. 4.66 Designs for thermocouple junctions for liquid metal (closure weld not shown). Dimensions are in inches.

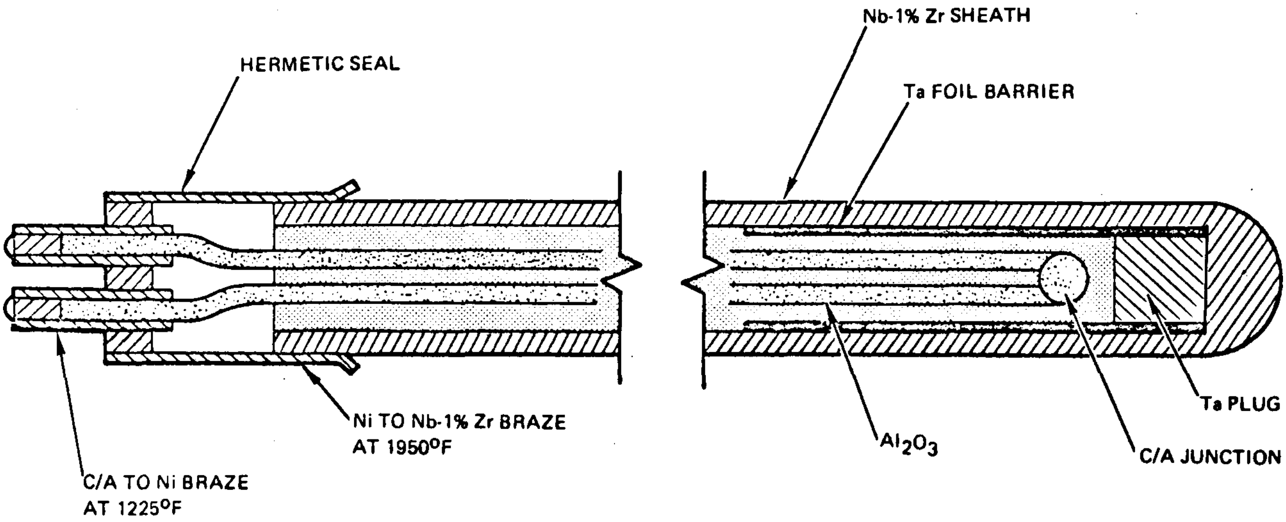


Fig. 4.67 Construction of Nb-1% Zr-sheathed Chromel-Alumel thermocouple for use in liquid metal.

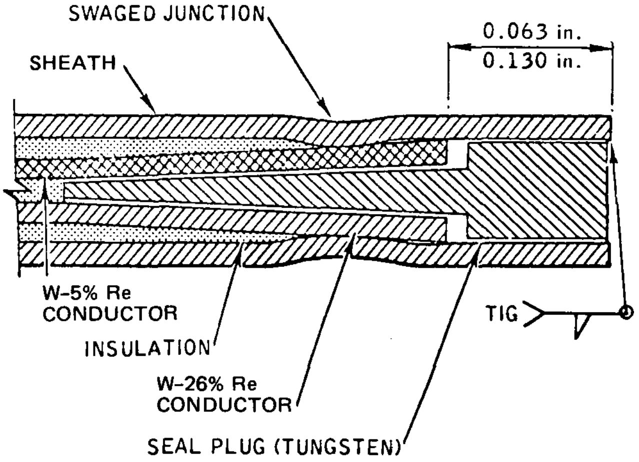


Fig. 4.68 Idealized hot-junction construction for W-Re thermocouple or Borax V (longitudinal section). The sheath is W-26% Re, 0.062 ± 0.003 in. OD, 0.010 ± 0.002 in. wall; the wires are 30 AWG tungsten, W-5% Re, or W-26% Re; and the insulation is hard-fired thoria of 99.94% purity. [From E. J. Brooks, Reactor Fuel Temperature and Thermal Time Constant Measurements with Tungsten-Rhenium Thermocouples, *ISA (Instrum. Soc. Amer.) Trans.*, *5*(3): (1966).]

(f) *Time Response*

Thermocouple time response to liquid-metal temperature changes is expressed by well-known heat-transfer relations treated in such standard texts as Kreith [165] and McAdams [166]. Design objectives for fast response for the general sensor (and protective cover) are high liquid-metal-to-junction heat-transfer factors, low mass and specific heat, and low junction-to-heat-sink heat-transfer factors. Experimental studies of the response time of sheathed mineral-insulated thermocouples in liquid metal are reported by Bentley and Rowley [173] and Thomson [174]. The experiments showed that the response is the same in flowing sodium as in flowing water [173, 174]; response is relatively insensitive to flow rate except at a very low Reynolds number [174] and is independent of temperature at 30 to 370°C (86 to 698°F). The time constants were found to vary as the square of the sheath diameter predicted theoretically [173,174]. Figure 4.69 shows the response time as a function of sheath diameter. The data [174] indicated that, contrary to generally accepted belief, "response time of bonded junctions in liquid will be no better than can be obtained with a well-made insulated hot junction." Other experimental work on thermocouple response time was reported by Brooks [172], Brooks and

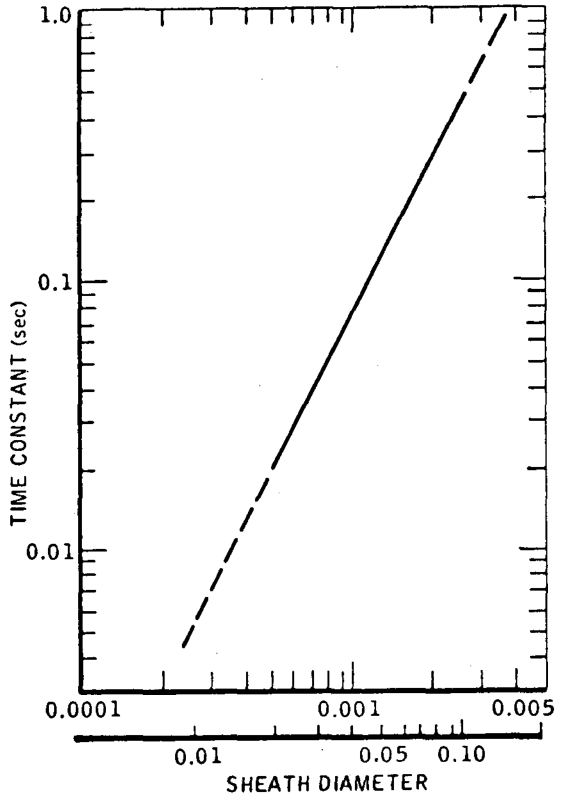


Fig. 4.69 Response time of mineral-insulated, sheathed thermocouple as a function of sheath diameter. [From P. G. Bentley and R. Rowley, Comparison of the Frequency Responses and Time Constants of Mineral-Insulated Thermocouples in Sodium and Water, *J. Inst. Measurement and Control, 1*(5): T103 (1968).]

Kramer [175], and Bumpus *et al.* [176].

(g) *Stability*

The thermocouple terminal voltage is the algebraic sum of the emf's generated throughout the circuit and the voltage losses caused by shunt resistance, which was discussed previously. The emf's are those intended (at the measuring and reference junctions) and those of a parasitic nature caused by such electrolytic action as may occur when the wires are exposed to chemical attack, and by the thermal emf's generated due to inhomogeneities in the wire when the inhomogeneities are in a thermal gradient. The emf's of electrolytic origin are readily identified, one characteristic being their significantly higher voltage. The thermoelectric parasitic emf's due to inhomogeneities are not so readily discernible since their origin is of the same nature as the measuring and reference junctions.

The thermoelectric voltage is the product of the Seebeck coefficient, which is a temperature dependent material property, and the temperature. Factors contributing to changes in the Seebeck coefficient include [177]:

Composition:

1. Batch-to-batch variations in alloys.
2. Local variations in impurity and alloy composition.
3. Absorption, by solution or chemical combination, of materials from the environment.
4. Loss of constituents by selective evaporation or chemical attack.
5. Solution of elements produced by nuclear transmutation.

Metallurgical state:

1. Work hardening, annealing.
2. Recrystallization.
3. Solution and precipitation of constituents.
4. Ordering effects.
5. Dislocations (permanent or temporary) caused by nuclear radiation.

Physical forces:

1. Elastic strain.
2. Static pressure.
3. Magnetic flux.

Certain of these factors, such as batch variations in composition and local impurities, can be regarded as fixed in the material and likely to remain so, and the others can be regarded as imposed on the material. Some of the metallurgical changes occur systematically as a function of temperature and time when the material is heated. The effects of fixed and systematic factors will always be present in a thermocouple in use and will form part of its inherent properties. Other factors such as chemical attack or cold working can be regarded as superimposed on the inherent properties.

A study [178] of calibration drift in stainless-steel-sheathed magnesia-insulated, ungrounded, type K (Chromel-Alumel) thermocouples showed the following effects:

1. The initial calibration drift occurs at or above 400°C (752°F).
2. The thermocouple output is always higher than its original value.
3. Drift occurs in simple thermal gradients and in simulated reactor thermal conditions.
4. No drift is apparent at temperatures up to 280°C (536°F).
5. At 400°C (752°F) most drift occurs within the first 30 days of operation and is complete by about 100 days.
6. The drift appears to occur in the Chromel leg of the thermocouple.
7. Varying temperature distributions along the cable produce varying errors, even when the hot junction is at a constant temperature.
8. Changes in the cold-junction temperature appear to produce small calibration shifts.
9. The drifts from the original calibrations can be as much as 4°C (7.2°F), although they are not usually more than 2°C (3.6°F).
10. Heat treatment of the entire cable has been successful in preventing initial drift at 400°C (752°F).
11. At 650°C (1202°F) there is a positive drift of 5°C (9.0°F) in 25 days.

Stability of the type K thermocouple in nuclear radiation, as reported in numerous studies, has been excellent.

A type J (iron-Constantan) thermocouple showed negligible drift in a test at 400°C [178].

Stability and other characteristics of the higher temperature thermocouples, mainly tungsten-rhenium types, are treated in Refs. 172 and 179 to 195. Generally, the very high temperature thermocouples and associated technology are of interest primarily in applications above the usual temperature range of sodium and NaK systems.

REFERENCES

1. D. M. Considine (Ed.), *Handbook of Applied Instrumentation*, McGraw-Hill Book Company, Inc., New York, 1966.

2. D. M. Considine, *Process Instruments and Controls Handbook*, McGraw-Hill Book Company, Inc., New York, 1957.

3. G. C. Carroll, *Industrial Process Measuring Instruments*, McGraw-Hill Book Company, Inc., New York, 1962.

4. P. J. O'Higgins, *Basic Instrumentation, Industrial Measurement*, McGraw-Hill Book Company, Inc., New York, 1966.

5. A. E. Fribance, *Industrial Instrumentation Fundamentals*, McGraw-Hill Book Company, Inc., New York, 1962.

6. R. H. Cerni and L. E. Foster, *Instrumentation for Engineering Measurement*, John Wiley & Sons, Inc., New York, 1962.

7. H. K. P. Neubert, *Instrument Transducers*, Oxford University Press, Inc., New York, 1963.

8. N. H. Cook and E. Rabinowics, *Physical Measurement and Analysis*, Addison-Wesley Publishing Company, Inc., Reading, Mass., 1963.

9. H. S. Kindler and H. K. Owens, *Standards and Practices for Instrumentation*, Instrument Society of America, Pittsburgh, 1963.

10. E. B. Jones, *Instrument Technology*, Butterworth & Co. (Publishers) Ltd., London, 1965.

11. J. A. Shercliff, *The Theory of Electromagnetic Flow-Measurement*, Cambridge University Press, New York, 1962.

12. H. G. Elrod and R. R. Fouse, An Investigation of Electromagnetic Flowmeters, *Trans. Am. Soc. Mech. Eng.*, *74*: 589-594 (1952).

13. W. C. Gray and E. R. Astley, Liquid Metal Magnetic Flowmeters, *J. Instr. Soc. Am.* *1*(6): 15-23 (1954).

14. P. L. Kirillov, V. D. Kolesnikov, V. A. Kuznetsov and N. M. Turchin, Instruments for Measuring the Pressure, Flow, and Level of Fused Alkali Metals, *At. Energ. (USSR)*, *9*(3): 173-181 (1960).

15. Argonne National Laboratory, *Reactor Development Program Progress Report; May 1966*, USAEC Report ANL-7219, June 1966.

16. R. G. Affel, G. H. Burger and C. L. Pearce, *Calibration and Testing of 2- and 3½-in. Magnetic Flowmeters for High-Temperature NaK Service*, USAEC Report ORNL-2793, Oak Ridge National Laboratory, March 1960.

17. D. Hadfield, *Permanent Magnets and Magnetism*, John Wiley & Sons, Inc., New York, 1962.

18. R. J. Parker and R. J. Studders, *Permanent Magnets and Their Application*, John Wiley & Sons, Inc., New York, 1962.

19. Thomas & Skinner, Inc., *Permanent Magnet Design*, Bulletin M303, Indianapolis, Ind.

20. The Carpenter Steel Co., *Alloys for Electronic, Magnetic, and Electrical Applications*, Reading, Pa., 1965.

21. Indiana General Corp., Magnet Div., *Design and Application of Permanent Magnets*, Manual 7, Valparaiso, Ind.

22. E. R. Cronk, Recent Developments in High-Energy Alnico Alloys, *J. Appl. Phys.*, *37*(3): 1097-1100 (1966).

23. W. L. Zingery, W. B. Whalley, E. B. Romberg and F. W. Wheeler, Evaluation of Long-Term Magnet Stability, *J. Appl. Phys.*, *37*(3): 1101-1103 (1966).

24. G. E. Turner, *The Nonlinear Behavior of Large Permanent-Magnet Flowmeters*, USAEC Report NAA-SR-4544, Atomics International, April 1960.

25. C. G. Pfister and R. J. Dunham, D-C Magnetic Flowmeter for Liquid Sodium Loops, *Nucleonics*, *15*(10): 122-123 (1957).

26. C. E. Webb, The Stability of Permanent Magnets, *Proc. Inst. Elec. Engrs. (London)*, *Part C*, *108*: 317-324 (1961).

27. General Electric Company, *Permanent Magnet Manual*, PM-200, 1963.

28. General Magnetic Corp., *Temperature and Radiation Effects on Permanent Magnets*, Detroit, 1966.

29. D. I. Gordon and R. S. Sery, Effects of Charged Particles and Neutrons on Magnetic Materials, *IEEE (Inst. Elec. Electron. Eng.)*, *Trans. Commun. Electron.*, *83*(73): 357-361 (1964).

30. R. K. Tenzer, *Temperature Effects on the Remanence of Permanent Magnets*, Report ASD-TDR-63-500; Indiana General Corp., May 1963.

31. Argonne National Laboratory, *Reactor Development Program Progress Report, October 1967*, USAEC Report ANL-7391, November 1967.

32. Argonne National Laboratory,

Reactor Development Program Progress Report, September 1967, USAEC Report ANL-7382, October 1967.

33. J. A. Shercliff, Experiments on the Dependence of Sensitivity on Velocity Profile in Electromagnetic Flowmeters, *J. Sci. Instr.*, *32*: 441-442 (1955).

34. J. F. McCarthy, *Compilation of Current Technical Experience at Enrico Fermi Atomic Power Plant, Monthly Report No. 1, August 1966*, USAEC Report APDA-CFE-1, Atomic Power Development Associates, Inc., 1966.

35. R. A. Boucher and D. B. Ames, End Effect Losses in D-C Magnetohydrodynamic Generators, *J. Appl. Phys.*, *32*(5): 755-759 (1961).

36. G. W. Sutton, H. Hurwitz and H. Poritsky, Electrical and Pressure Losses in a Magnetohydrodynamic Channel Due to End Current Loops, *IEEE (Inst. Elec. Electron. Eng.), Trans. Commun. Electron.*, *80*: 687-695 (1962).

37. F. E. Terman, *Radio Engineers Handbook*, McGraw-Hill Book Company, Inc., New York, 1943.

38. J. A. Shercliff, *A Textbook of Magnetohydrodynamics*, Pergamon Press, Inc., New York, 1965.

39. G. F. Popper and M. C. Glass, The Design and Performance of a 1200°F Magnetic Flowmeter for In-Core Application in Sodium Cooled Reactors, *IEEE (Inst. Elec. Electron. Eng.), Trans. Nucl. Sci.*, *NS-14*(1): 342-347 (1967).

40. G. F. Popper, D. E. Wiegand and M. C. Glass, *Summary Review of Flowmeters Suitable for Measuring Sodium Flow at Temperatures Up to 1200°F in the Fast Flux Test Facility (FFTF)*, USAEC Report ANL-7340, Argonne National Laboratory, December 1967.

41. K. A. Davis, *SNAP-10A Thermoelectric Pump. Final Report*, USAEC Report NAA-SR-11879, Atomics International, July 15, 1966.

42. G. E. Berg, *Final SNAPSHOT Performance Report*, USAEC Report NAA-SR-11934, Atomics International, Aug. 15, 1966.

43. E. Duncombe, R. A. Davies, D. F. Davidson and R. Dehn, Some Analytical and Process Instruments for Measurements in Sodium, in *Alkali Metal Coolants*, Symposium Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/143).

44. P. B. F. Evans, D. Harrison, E. J. Burton, G. O. Jackson, E. Duncombe and N. T. C. McAffer, Control and Instrumentation of Prototype Fast Reactor, in *Fast Breeder Reactors*, Conference Proceedings, London, May 17-19, 1966, p. 765, Pergamon Press, Inc., New York, 1966.

45. M. N. Karpov, Magnetic System of a Transducer in an Inductive Flowmeter with a Large Diameter, *Meas. Tech. (USSR) (Engl. Transl.)*, No. *6*: 828-832 (June 1966).

46. D. F. Davidson and E. Duncombe, Some Electromagnetic Transducer Techniques for Use at Elevated Temperatures, *Trans. Soc. Instrum. Technol.*, *18*(2): 51-61 (1966).

47. D. E. Wiegand, Summary of an Analysis of the Eddy-Current Flowmeter, *IEEE (Inst. Elec. Electron. Eng.), Trans. Nucl. Sci.*, *NS-15*(1): 28-36 (1968).

48. M. D. Cowley, Flowmetering by a Motion-Induced Magnetic Field, *J. Sci. Instr.*, *42*: 406-409 (1965).

49. P. G. Bentley and D. G. Dawson, Fluid Flow Measurement by Transit Time Analysis of Temperature Fluctuations,

Trans. Soc. Instrum. Technol, *18*(3): 183-193 (1966).

50. R. L. Randall and D. Logan, Atomics International, Application of Noise-Analysis Techniques to Hydraulic Measurements in Liquid-Metal Systems, in *Proceedings of the Symposium on Liquid Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 183-188, Argonne National Laboratory.

51. L. K. Spink, *Principles and Practice of Flow Meter Engineering*, The Foxboro Company, Foxboro, Mass., 1967.

52. H. J. Bomelberg, *Evaluation of the Applicability of Water-Model Testing to Liquid-Metal Engineering Problems*, USAEC Report LMEC-68-4, Atomics International, Feb. 26, 1968.

53. W. A. Wildhack, R. F. Dressler and E. C. Lloyd, Investigation of the Properties of Corrugated Diaphragms, *Trans. Am. Soc. Mech. Engrs.*, *79*(1): 65-82 (1957).

54. A. Wolf, An Elementary Theory of the Bourdon Gage, *J. Appl. Mech.*, *13*: A-207-210 (1946).

55. F. B. Jennings, Theories on Bourdon Tubes, *Trans. Am. Soc. Mech. Engrs.*, *78*: 55-64 (1956).

56. H. L. Mason, Sensitivity and Life Data on Bourdon Tubes, *Trans. Am. Soc. Mech. Engrs.*, *78*: 65-77 (1956).

57. H. J. Van Kuyk and W. D. Huston, Spiral and Helical Pressure Gages, Instrument and Control Systems, *Instrum. Contr. Syst.*, *38*: 121-126 (September 1965).

58. J. A. Haringx, Design of Corrugated Diaphragms, *Trans. Am. Soc. Mech. Engrs.*, *79*(1): 55-64 (1957).

59. A. M. Wahl, Recent Research on Flat Diaphragms and Circular Plates with Particular Reference to Instrument Applications, *Trans. Am. Soc. Mech. Engrs.*, *79*(1): 83-87 (1957).

60. Kaman Nuclear, Data Sheet K-1900, Colorado Springs, Colo.

61. R. A. Clark, Operational Experience and Developmental Activities in LASL Sodium Systems, in *Proceedings of the Sodium Components Information Meeting, Palo Alto, Calif., Aug. 20-21, 1963*, USAEC Report SAN-8002, pp. 286-306, San Francisco Operations Office (AEC), May 1964.

62. W. R. Miller, *High-Temperature Pressure Transmitter Evaluation*, USAEC Report ORNL-2483, Oak Ridge National Laboratory, July 1958.

63. R. D. Brooks (Ed.), *Alkali Metals Boiling and Condensing Investigations. Vol. I. Experimental Program. Final Report*, Report NASA-CR-54050, General Electric Company, June 1962.

64. G. H. Reicks, *Sodium Level Detectors in the Enrico Fermi Atomic Power Plant*, USAEC Report APDA-300, Atomic Power Development Associates, Inc., Nov. 30, 1965.

65. G. E. Turner, Atomics International, SCTI Sodium Instrument Operating Experience, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 40-42, Argonne National Laboratory.

66. H. Strahl, Atomics International, SNAP System Instrumentation, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 37-39, Argonne National Laboratory.

67. C. C. Scott, Atomic Power De-

velopment Associates, Inc., Fermi Process Instrumentation, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 29-36, Argonne National Laboratory.

68. Oak Ridge National Laboratory, *Molten-Salt Reactor Program. Semiannual Progress Report for Period Ending Jan. 31, 1963*, USAEC Report ORNL-3419, June 3, 1963.

69. S. A. Hluchan, Pressure and Temperature Transducers for High Temperature and Nuclear Radiation Environments, paper presented at the National Telemetering Conference, June 2-4, 1964, Los Angeles, USAEC Report CONF-658-1.

70. Moore Products Co., commercial literature, 1967.

71. J. E. Kinzer, Atomics International, Miniaturized Pressure Sensor for LMFBR Environment, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 63-64, Argonne National Laboratory.

72. E. C. King, Mine Safety Appliances Research Corp., Pressure Transducers for Nuclear Reactor Applications, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 65-69, Argonne National Laboratory.

73. Mine Safety Appliances Co., commercial literature, August 1966.

74. L. H. Thacker, *High-Temperature Pressure Transducer*, USAEC Report LA-2727, Los Alamos Scientific Laboratory, June 1962.

75. J. Delisle and N. Lions, *Instrumentation in the RAPSODIE Test Circuits of 1 and 10 Mw - Flowmeters, Manometers, Level Indicators, and Blockage Indicators* (Engl. Transl.), French Report CEA-R-2522, Commissariat à l'Energie Atomique, August 1964.

76. V. N. Lawford, NaK-Filled Differential-Pressure Instruments for High-Temperature Measurements, paper presented at the Winter Annual Meeting and Energy Systems Exposition, New York, Nov. 27 - Dec. 1, 1966, The American Society of Mechanical Engineers, ASME Preprint 66-WA/NE-16, CONF-661102-21.

77. H. E. Flotow, B. M. Abraham and R. D. Carlson, A Differential Pressure Gauge to Determine the Densities of UO_2-NaK Slurries, in *Papers Presented at Reactor Fuel Measurement Techniques Symposium, Lansing, Mich., June 18-20, 1958*, USAEC Report TID-7560, pp. 164-171, 1958.

78. S. J. Fanciullo, *Development of Liquid-Metal Level Probes*, USAEC Report PWAC-423, Pratt and Whitney Aircraft, Apr. 27, 1964.

79. D. O. Jordan and J. E. Lane, The Wetting of Solid Metals by Liquid Alkali Metals, in *The Alkali Metals*, Symposium Proceedings, Nottingham, England, July 19-22, 1966, Special Publication No. 22, pp. 147-152, The Chemical Society, London, 1967.

80. M. H. Wahl, *Wetting with Sodium*, USAEC file No. NP-5811, Mine Safety Appliances Co., Nov. 7, 1955.

81. H. J. Metz and M. M. Yarosh, Oak Ridge National Laboratory, Experiences and Developments in Instrumentation for Liquid-Metal Experiments, in *Proceedings of the Conference on Application of High-Temperature Instrumentation to Liquid-Metal Experiments, Sept. 28-29, 1965*, USAEC Report ANL-7100, pp. 379-412, Argonne National Laboratory.

82. N. H. Briggs, G. W. Greene and R. F. Hyland, Resistance-Type Liquid-Metal Level Elements, in *Instrumentation and Controls Division Annual Progress Report for Period Ending Sept. 1, 1965*, USAEC Report ORNL-3875, pp. 116-118, Oak Ridge National Laboratory, August 1966.

83. N. H. Briggs, G. W. Greene and R. F. Hyland, Development of Resistance-Type Liquid Metal Level Elements, *Trans. Amer. Nucl. Soc.*, *9*(1): 318-319 (1966).

84. G. W. Greene, N. H. Briggs, C. M. Burton and E. G. Meyer, Present Status of Resistance-Type Liquid-Metal Level Detectors, in *Instrumentation and Controls Division Annual Progress Report for Period Ending Sept. 1, 1966*, USAEC Report ORNL-4091, pp. 120-121, Oak Ridge National Laboratory, June 1967.

85. A. F. Popov, Level Meter for Liquid Metals, *Instr. Construct. (USSR) (Engl. Transl.)*, No. *7*: 16-18 (1962).

86. R. G. Affel, G. H. Burger and R. E. Pidgeon, *Level Transducers for Liquid Metal*, USAEC Report ORNL-2792, Oak Ridge National Laboratory, Apr. 28, 1960.

87. L. Reed, Nonmetallic Containment Materials for Alkali Metals and Their Compounds, in *The Alkali Metals*, Symposium Proceedings, Nottingham, England, July 19-22, 1966, Special Publication No. 22, pp. 45-52, The Chemical Society, London, 1967.

88. J. W. Krewson and R. L. Moore, Single-Point Molten-Salt-Level Indicators, in *Instrumentation and Controls Division Annual Progress Report for Period Ending Sept. 1, 1962*, USAEC Report ORNL-3378, pp. 54-57, Oak Ridge National Laboratory, February 1963.

89. E. C. King, MSA Research Corp., Liquid-Level Detectors for Liquid Metals, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 70-74, Argonne National Laboratory.

90. J. F. McCarthy, *Compilation of Current Technical Experience at Enrico Fermi Atomic Power Plant. Monthly Report No. 9, April 1967*, USAEC Report APDA-CFE-9, Atomic Power Development Associates, Inc., June 1967.

91. R. C. Jackson, *Liquid Metal Level Measurements*, Instrumentation Society of America, Preprint-1.1-4-66, 1966.

92. D. Bradstreet and W. A. Somerville, UKAE Internal Memorandum, Dounreay Experimental Reactor Establishment, June 1966.

93. R. D. Peak, *Thermocouple Liquid-Level Indicator Used on Cold-Trap Stands*, USAEC Report CF-58-10-13, Oak Ridge National Laboratory, Oct. 3, 1958.

94. Oak Ridge National Laboratory, *Molten-Salt Reactor Program Semiannual Progress Report for Period Ending July 1, 1964*, USAEC Report ORNL-3708, November 1964.

95. Oak Ridge National Laboratory, *Molten-Salt Reactor Program Semiannual Progress Report for Period Ending Jan. 31, 1964*, USAEC Report ORNL-3626, July 1964.

96. Oak Ridge National Laboratory, *Molten-Salt Reactor Program Semiannual Progress Report for Period Ending July 1, 1964*, USAEC Report ORNL-3708, November 1964.

97. A. L. Southern, *Closed-Loop Level Indicator for Corrosive Liquids Operating at High Temperatures*, USAEC Report ORNL-2093, Oak Ridge National Laboratory, June 1956.

98. Oak Ridge National Laboratory, *Molten-Salt Reactor Program Semiannual Progress Report for Period Ending Feb. 18, 1965*, USAEC Report ORNL-3812, June 1965.

99. G. E. Turner, *A Coil-Type Level Gage for High-Temperature Liquid Metals*, USAEC Report NAA-SR-4195, Atomics International, Nov. 15, 1959.

100. A. G. Hosler and F. A. Smith, Impurity and Liquid-Level Measurements for the Faret Loop, in *Proceedings of the Conference on Application of High-Temperature Instrumentation to Liquid-Metal Experiments, Sept. 28-29, 1965*, USAEC Report ANL-7100, pp. 413-425, Argonne National Laboratory.

101. T. R. Johnson, F. G. Teats and R. D. Pierce, *Induction Probe for Measuring Liquid Metals*, USAEC Report ANL-7153, Argonne National Laboratory, February 1966.

102. D. F. Davidson, *Measurement of Liquid-Metal Levels by the Effect of Eddy Currents on an Inductance*, British Report IGR-R/CA-255, December 1957.

103. L. W. Stilwell, Garret Corp., Liquid-Metal Level Detector and Indicator, in *Proceedings of the Conference on Application of High-Temperature Instrumentation to Liquid-Metal Experiments, Sept. 28-29, 1965*, USAEC Report ANL-7100, pp. 367-378, Argonne National Laboratory.

104. M. A. Ziniuk, A Delay-Line-Type Level Sensor for High-Temperature Liquid Metals, *Trans. Amer. Nucl. Soc.*, *10*(1): 309 (1967).

105. M. A. Ziniuk, *A Delay-Line-Type Level Sensor for High-Temperature Liquid Sodium*, Report APDA-191, Atomic Power Development Associates, Inc., July 1966.

106. A. A. Petrenko, Experiment Using Instruments for Measuring Pressure and Level with Apparatus Containing Fast Neutron Reactors, *Instr. Construct. (USSR) (Engl. Transl.)*, No. *1*: 23-25 (January 1965).

107. D. F. Davidson and J. Pilling, *A High-Frequency Induction Level Gauge for Liquids in Inaccessible Locations*, British Report IGR-R/CA-234, October 1957.

108. D. R. Grieser, G. G. Cocks, E. H. Hall, W. M. Henry and J. McCallum, *Determination of Oxygen in Sodium at Concentrations Below 10 ppm*, USAEC Report BMI-1538, Battelle Memorial Institute, Aug. 23, 1961.

109. Mine Safety Appliances Research Corp., *Development of Techniques for Measurement of Impurities in Sodium. Quarterly Progress Report, April-June, 1965*, USAEC Report MSAR-65-95, July 30, 1965.

110. R. C. Andrews, S. J. Rodgers, R. Tepper and R. J. Udavcak, *A Critical Review of the Development of Techniques for the Measurement of Impurities in Sodium. Quarterly Progress Report, April-June, 1967*, USAEC Report MSAR-67-213, Mine Safety Appliances Research Corp., December 1967.

111. K. A. Davis, *Liquid Metal In-Line Impurity Measuring Instruments (Sodium) State-of-the-Art Study*, USAEC Report LMEC-Memo-68-3, Atomics International, January 1968.

112. B. Minushkin and M. Kolodney, *Development of a Continuous Electrochemical Meter for Oxygen in Sodium*, USAEC Report UNC-5131, United Nuclear Corp., December 1967.

113. B. Minushkin, *Electrochemical Oxygen Meter Operating Manual*, USAEC Report 5113, United Nuclear Corp., Aug. 31, 1965.

114. B. Minushkin and J. McKee, United Nuclear Corp., Development of Electrochemical Methods for Oxygen Monitoring and Removal in Sodium, *AEC-NASA Liquid Metals Information Meeting, Gatlinburg, Tenn., Apr. 21-23, 1965*, USAEC Report CONF-650411, pp. 16-34, Oak Ridge National Laboratory.

115. C. C. McPheeters and J. M. Williams, *A Comparison of Three Methods of Oxygen Concentration Measurement in Sodium*, USAEC Report LADC-7743, Los Alamos Scientific Laboratory, 1966.

116. Atomic Power Development Associates, Inc., *Quarterly Technical Progress Report on AEC-Sponsored Activities, June 15 - Sept. 15, 1966*, USAEC Report APDA-195, 1966.

117. M. Kolodney, B. Minushkin and B. Steinmetz, United Nuclear Corp., Electrolytic Method for the Continuous Measurement of Oxygen in Liquid Sodium, paper presented at the 126th Meeting of the Electrochemical Society, Washington, D.C., Oct. 11-15, 1964, USAEC Report CONF-641018-4.

118. Atomic Power Development Associates, Inc., Sodium Technology Loop Project, in *Quarterly Technical Progress Report on AEC-Sponsored Activities, Mar. 15 - June 15, 1966*, USAEC Report APDA-193, 1966.

119. Atomic Power Development Associates, Inc., *Operation of the Sodium Technology Loop for Contamination Meter Evaluations*, USAEC Report APDA-163, Mar. 25, 1964.

120. H. Strahl, *A Device for Continuous Detection of Hydrogen in Sodium*, USAEC Report NAA-SR-6986, Atomics International, May 31, 1962.

121. V. I. Subbotin, F. A. Kozlov, N. N. Ivanovstii and V. M. Makarov, Leak Finding in a Sodium-Water Steam Generator, *At. Energ. (USSR), 20*(6): 557-560 (1966).

122. E. F. Hill, Atomic Power Development Associates, Sodium Technology Loop Evaluation of In-Line Instruments and Purification Devices, in *Proceedings of Sodium Components Development Program Information Meeting, Chicago, June 16-17, 1965*, USAEC Report CONF-650620, pp. 255-270, Chicago Operations Office (AEC).

123. J. P. Petrek, Atomic Power Development Associates, Inc., Sodium-Purity Instrumentation, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 102-110, Argonne National Laboratory.

124. United Nuclear Corp., *Carbon Meter for Sodium. Progress Report Feb. 21 - June 30, 1966*, USAEC Report UNC-5160, July 31, 1966.

125. K. T. Claxton, Review of Solubility Data for the Liquid Sodium-Oxygen System, *J. Nucl. Energy, Parts A & B, 19*(11): 849-889 (1965).

126. D. D. Williams, J. A. Grand and R. R. Miller, The Solubility of Sodium Hydride in Sodium, *J. Phys. Chem., 61*:379-381 (1957).

127. I. L. Gray, R. L. Neal and B. G. Voorhees, Control of Oxygen in Sodium Heat Transfer Systems, *Liquid Metals Technology. Part I*, Chemical Engineering Progress Symposium Series, No. 20, pp. 11-18, American Institute of Chemical Engineers, 1957.

128. H. W. Savage, E. L. Compere, W. R. Huntly, B. Fleischer, R. E. MacPherson and A. Taboada, *SNAP-8 Corrosion Program Summary Report*, USAEC Report ORNL-3898, Oak Ridge National Laboratory, December 1965.

129. K. Furukawa, K. Yamamoto, I.

Nihei and Y. Iguchi, *Liquid Sodium Technology Development. I. Test Loops, Purification Methods and Supplementary Techniques*, Japanese Report JAERI-1129, 1965.

130. J. P. Delisle, *Automatic Measurement of the Plugging Temperature of Sodium and of NaK*, translated from a paper presented at Liquid Metals Colloquium of the European Society of Atomic Energy, Aix-en-Provence - Cadarache, Sept. 30 - Oct. 2, 1963, USAEC Report AEC-tr-6353, Oak Ridge National Laboratory.

131. V. I. Subbotin, P. L. Kirillov and F. A. Kozlov, *The Purification of Sodium from Oxygen and Monitoring of the Oxygen Content in Sodium*, translated from USSR Report 701, by J. G. Lomaz, UKAEA, Capenhurst, PG Information Series 10 (R).

132. R. B. Hinze, *Control of Oxygen Concentration in a Large Sodium System*, USAEC Report NAA-SR-3638, Atomics International, Dec. 1, 1959.

133. E. F. Batutis, Operating Experiences with Oxide Monitors for Sodium Systems, in *Analytical Chemistry in Nuclear Reactor Technology. Part 2. Instrumentation, Remote-Control Techniques and Nucleonics, Second Conference, Gatlinburg, Tenn., Sept. 29 - Oct. 1, 1958*, USAEC Report TID-7568 (Pt. 2), pp. 24-32, Oak Ridge National Laboratory, April 1959.

134. A. G. Hosler and F. A. Smith, Impurity and Liquid-Level Measurements for the Faret Loop, in *Proceedings of the Conference on Application of High-Temperature Instrumentation to Liquid-Metal Experiments, Sept. 28-29, 1965*, USAEC Report ANL-7100, pp. 413-425, Argonne National Laboratory.

135. W. M. Hoschouer and D. F. Casey, *Design and Thermal Analysis of Sodium Specialties Components for HNPF*, USAEC Report NAA-SR-5445, Atomics International, Feb. 15, 1961.

136. P. B. F. Evans, D. Harrison, E. J. Burton, G. O. Jackson, E. Duncombe and N. T. C. McAffer, Control and Instrumentation of Prototype Fast Reactor, in *Fast Breeder Reactors*: Conference Proceedings, London, May 17-19, 1966, p. 765, Pergamon Press, Inc., New York, 1966.

137. Argonne National Laboratory, *Reactor Development Program Progress Report, May 1966*, USAEC Report ANL-7219, June 30, 1966.

138. Los Alamos Scientific Laboratory, *Quarterly Status Report on Advanced Reactor Technology (ART) for Period Ending Jan. 31, 1966*, USAEC Report LA-3482, February 1966.

139. K. A. Davis, *Development of a Rapid-Operating Plugging Meter*, USAEC Report NAA-SR-4537, Atomics International, Aug. 1, 1959.

140. P. L. Kirillov, F. A. Kozlov, V. I. Subbotin and N. M. Turchin, Removal of Oxides from Sodium and Tests for the Oxide Content, *At. Energ. (USSR)*, *7*(1): 30-36 (1960).

141. J. W. Mausteller (Ed.), *Progress Report No. 27 for February and March*, USAEC file No. NP-5601, Mine Safety Appliances Co., Apr. 22, 1955.

142. L. R. Blake, Resistivity Monitor to Indicate Oxide Content of Sodium, *Institute of Electrical Engineers, Proceedings*, Pt. A, *107*(34): 383-394 (1960).

143. Atomic Power Development Associates, Inc., *Evaluation of the Blake Sodium Resistivity Meter*, USAEC Report APDA-149, Oct. 15, 1962.

144. R. Dehn and A. R. Eames, The Rhometer: A Continuous Impurity Monitor

for Liquid Metal Circuits, *Radio Electron. Eng.*, *29*(6): 331-343 (1965).

145. V. I. Subbotin, M. N. Ivanovskii, M. N. Arnol'dov, B. A. Shmatko and A. D. Pleshivtsev, Monitoring the Oxygen and Hydrogen Contents of Fused Sodium by Measuring Its Electrical Resistance, *At.Energ. (USSR)*, *21*: 511-512 (1966).

146. M. N. Arnol'dov, M. N. Ivanovskii, V. I. Subbotin and B. A. Shmatko, Investigation of the Possibility of Monitoring Impurities in Liquid-Metal Coolants by Measurement of the Electrical Resistance, in *Alkali Metal Coolants*, Symposium Proceedings, Vienna, 1966, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/143).

147. K. A. Davis, *Detection Device for Hydrogen in Sodium*, USAEC Report NAA-SR-5732, Atomics International, Jan. 15, 1962.

148. W. L. Chase, J. A. Ford, A. J. Friedland, D. M. Green, L. R. Kovac and J. E. Meyers, *Analysis of the Babcock and Wilcox Full-Size Steam Generator for a Sodium-Water Reaction*, USAEC Report APDA-176, Atomic Power Development Associates, Inc., Nov. 30, 1965.

149. H. V. Chamberlain, Leak Detection: Sodium-Water Reactions, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 75-78, Argonne National Laboratory.

150. C. M. Herzfeld, *Temperature, Its Measurement and Control in Science and Industry*, Vol. 3, Parts 1 and 3, Reinhold Publishing Corporation, New York, 1962.

151. H. D. Baker, E. A. Ryder and N. H. Baker, *Temperature Measurement in Engineering*, Vol. I, John Wiley & Sons, Inc., New York, 1953.

152. H. D. Baker, E. A. Ryder and N. H. Baker, *Temperature Measurement in Engineering*, Vol. II, John Wiley & Sons, Inc., New York, 1961.

153. G. G. Watson, Techniques for Measuring Surface Temperature. Part 1, *Instrum. Pract.*, *20*: 217-255 (1966).

154. G. G. Watson, Techniques for Measuring Surface Temperature. Part 2, *Instrum. Pract.*, *20*: 335-341 (1966).

155. G. G. Watson, Techniques for Measuring Surface Temperature. Part 3, *Instrum. Pract.*, *20*: 447-451 (1966).

156. G. G. Watson, Techniques for Measuring Surface Temperature. Part 4, *Instrum. Pract.*, *20*: 517-524 (1966).

157. G. G. Watson, Techniques for Measuring Surface Temperature. Part 5, *Instrum. Pract.*, *20*: 679-684 (1966).

158. G. G. Watson, Techniques for Measuring Surface Temperature. Part 6, *Instrum. Pract.*, *20*: 751-758 (1966).

159. G. Boom and F. van der Woude, Very Stable and Simple Compensator for Thermocouples, *Rev. Sci. Instrum.*, *36* (6): 857 (1965).

160. D. L. Rall and D. R. Hornbaker, Taking Meaningful Temperature Measurements, *Instrum. Technol.*, *14*(10): 63-68 (1957).

161. T. J. Claggett, External Thermocouple Compensation, *Instrumentation*, *18*(2): 24-27 (1965).

162. W. C. Kuhlman, *Thermocouple Research at GE-NMPO*, USAEC Report CONF-650204-9, General Electric Company, Feb. 10, 1965.

163. American Society for Testing Materials, Temperature-Electromotive

Force (EMF) Tables for Thermocouples, ASTM, E230-68, *1968 ASTM Standards*, Part 30.

164. Yu. A. Vidadi, A Thermocouple with a Compensating Heater, *Instrum. Exp. Tech. (USSR) (Engl. Transl.)*, No. *6*: 1301-1302 (November - December 1964).

165. F. Kreith, *Principles of Heat Transfer*, (2nd ed.), International Textbook Co., Scranton, Pa., 1965.

166. W. H. McAdams, *Heat Transmission*, McGraw-Hill Book Company, Inc., New York, 1954.

167. American Society for Testing Materials, Metal-Sheathed Corrosion-Resistant Thermocouples for Nuclear Service, ASTM, E235-67, *1968 ASTM Standards*, Part 30.

168. R. Dutton and E. C. Lee, Surface-Temperature Measurement of Current Carrying Objects, *ISA (Instrum. Soc. Amer.) J.*, *6*: 49-51 (1959).

169. H. J. Saver, R. E. Schowalter and R. S. Patel, Induction Field Effects on Temperature Transducers, *ISA (Instrum. Soc. Amer.) J.*, *13*(3) 44-47 (1966).

170. B. Klipec, Controlling Noise in Instrument Circuits, *Contr. Eng.*, *14*(3): 75-76 (1968).

171. P. Bliss, *Status of Instrument Development for the SNAP-50 Reactor Test Program*, USAEC Report PWAC-473, Pratt and Whitney Aircraft, July 16, 1965.

172. E. J. Brooks, Reactor Fuel Temperature and Thermal Time Constant Measurements with Tungsten-Rhenium Thermocouples, *ISA (Instrum. Soc. Amer.) Trans.*, *5*(3): 217-222 (1966).

173. P. G. Bentley and R. Rowley, Comparison of the Frequency Responses and Time Constants of Mineral-Insulated Thermocouples in Sodium and Water, *J. Inst. Measurement and Control*, *1*(5): T100-T104 (1968).

174. A. Thomson, The Thermal Response Time of Sheathed Mineral-Insulated Thermocouples, *Trans. Soc. Instrum. Technol.*, *17*(2): 49-56 (1965).

175. E. J. Brooks and W. C. Kramer, *Tungsten-Rhenium Alloy Thermocouples and Their Use in a UO_2-Fueled Reactor*, USAEC Report ANL-6981, Argonne National Laboratory, November 1965.

176. C. F. Bumpus, M. Silberberg, R. N. Cordy and W. N. Briggs, *Development of Techniques for In-Pile Capsule Transient Heating Experiments*, USAEC Report NAA-SR-9009, Atomics International, Jan. 30, 1964.

177. A. W. Fenton, R. Dacey and E. J. Evans, *Thermocouples: Instabilities of the Seebeck Coefficient*, British Report TRG-Report-1447, 1967.

178. R. A. Evans and J. Holt, *Calibration Drift Effects in Nickel-Alloy Thermocouples*, British Report TRG-Report-1510, 1967.

179. F. R. McQuilkin, N. H. Briggs and E. L. Long, Summary of Experience with High-Temperature Thermocouples Used in the ORNL-GCR Program Fuel Irradiation Experiments, *Trans. Amer. Nucl. Soc.*, *8*(1): 69-70 (1965).

180. G. F. Popper and A. E. Knox, Reactor Fuel Pin Temperatures, *IEEE (Inst. Elec. Electron. Eng.), Trans. Nucl. Sci.*, *NS-14*(1): 333-341 (1967).

181. S. R. Skaggs, W. A. Ranken and A. J. Patrick, *Decalibration of a Tungsten-Tungsten 25% Rhenium Thermocouple in a Neutron Flux*, USAEC Report LA-3662, Los Alamos Scientific Laboratory, January 1967.

182. G. A. Remley, Westinghouse Electric Corp., High-Temperature Thermometry, in *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 52-62, Argonne National Laboratory.

183. N. H. Briggs, E. L. Long and F. R. McQuilkin, *Summary of Experience with High-Temperature Thermocouples Used in the ORNL-GCR Program Fuel-Irradiation Experiments*, USAEC Report ORNL-P-1065, Oak Ridge National Laboratory, 1964.

184. P. Bliss and S. Fanciullo, *High-Temperature Thermometry at Pratt and Whitney Aircraft-CANEL*, USAEC Report PWAC-462, Pratt and Whitney Aircraft, June 1965.

185. P. Bliss and S. Fanciullo, High Temperature Thermometry at CANEL, *IEEE (Inst. Elec. Electron. Eng.), Trans. Nucl. Sci., NS-13*(1): 643-651 (1965).

186. K. M. Horst, General Electric Company, SEFOR Preoperational Development Program, in *Fast Reactors*, National Topical Meeting, San Francisco, Apr. 10-12, 1967, Report CONF-670413, pp. 5-31-5-54, American Nuclear Society, 1967.

187. R. R. Asamoto and P. E. Novak, Tungsten-Rhenium Thermocouples for Use at High Temperatures, *Rev. Sci. Instrum., 38*(8): 1047-1052 (1967).

188. S. Fanciullo, *Thermocouple Development, Lithium-Cooled Reactor Experiment*, USAEC Report PWAC-442, Pratt and Whitney Aircraft, Mar. 5, 1964.

189. W. C. Kuhlman, *Status Report of the Investigation of Thermocouple Materials for Use at Temperatures Above 4500°F*, Society of Automotive Engineers, Preprint 750D, 1963.

190. C. E. Huck, *Thermocouple Development for the Fast Flux Test Facility*, USAEC Report BNWL-SA-1227, Battelle-Northwest Laboratories, Aug. 21, 1967.

191. A. E. Knox and G. F. Popper, Fuel-Pin Thermocouple Hot-Zone Errors at Temperatures Up to 2400°C, *Trans. Amer. Nucl. Soc., 10*(1): 309, 310 (1967).

192. B. E. Walker, C. T. Ewing and R. R. Miller, Thermoelectric Instability of Some Noble Metal Thermocouples at High Temperature, *Rev. Sci. Instrum., 33*(10): 1029-1040 (1962).

193. S. Fanciullo, *Thermocouple Development, Lithium-Cooled Reactor Experiment*, USAEC Report PWAC-422, Pratt and Whitney Aircraft, Mar. 5, 1964.

194. J. W. Hendricks and D. L. McElroy, High Temperature-High Vacuum Thermocouple Drift Tests, *Environ. Quart., 13*(1): 34-38 (1967).

195. J. Nanigian, Ribbon Thermocouples in the 3000°F to 5000°F Range, *Instrum. Contr. Syst., 39*(5): 93-99 (1966).

196. K. J. Salt and C. A. Wintle, *Improved Accuracy of Temperature Measurement with Thermocouples*, British Report AEEW-R-522, June 1967.

197. T. Sannes, Tiny Thermocouples, *Instrum. Technol., 14*(3): 35-38 (1967).

198. R. Marshall, L. Atlas and T. Putner, The Preparation and Performance of Thin Film Thermocouples, *J. Sci. Instrum., 43*(3): 144-149 (1966).

199. R. F. Loeffler, Thermocouples, Resistance Temperature Detectors, Thermistors - Which? *Instrum. Contr. Syst., 40*(5): 89-93 (1967).

200. T. P. Wong, Temperature Sensors, *Instrum. Contr. Syst., 40*(5): 103-107 (1967).

201. H. L. Daneman and G. C. Mergner, Precise Resistance Thermometry - A Review. Part I: D-C Methods, *Instrum. Technol.*, *14*(5): 51-56 (1967).

202. H. L. Daneman and G. C. Mergner, Precise Resistance Thermometry - A Review. Part II: A-C Methods, *Instrum. Technol.*, *14*(6): 65-69 (1967).

203. J. S. Johnson, Recent Advances in Industrial Platinum Resistance Thermometry, *Platinum Metals Rev.*, *10*(2): 42-47 (1966).

204. O. P. Steele III, Atomics International, Stable High-Temperature Detection, *Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, Mar. 1-2, 1967*, USAEC Report ANL-7380, pp. 47, Argonne National Laboratory.

205. H. E. Sostman, Resistance Thermometers, *Instrum. Contr. Syst.*, *39*(10): 117-120 (1966).

206. D. A. Toenshaff and E. D. Zysk, "Birdcage" Resistance Thermometer, *Instrum. Contr. Syst.*, *40*(5): 109-111 (1967).

207. R. H. Muller, Automatic Optical Pyrometers Measure High Temperatures, *Anal. Chem.*, *38*(9): 93A-94A (1966).

208. L. D. Berringer, Pyrometers, *Instrum. Contr. Syst.*, *39*(9): 119-122 (1966).

209. Aeroprojects, Inc., *Applications of Ultrasonic Energy: Ultrasonic Instrumentation for Nuclear Applications. Bimonthly Progress Report No. 31, Oct. 1-Nov. 30, 1966*, USAEC Report NYO-3622-6, December 1966.

210. V. I. Kutovoi and V. I. Stetsenko, Checking the Temperature of Liquid Metals by Means of the Radioisotope Method, *Meas. Tech. (USSR) (Engl. Transl.)*, No. *8*: 720-723 (1965).

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