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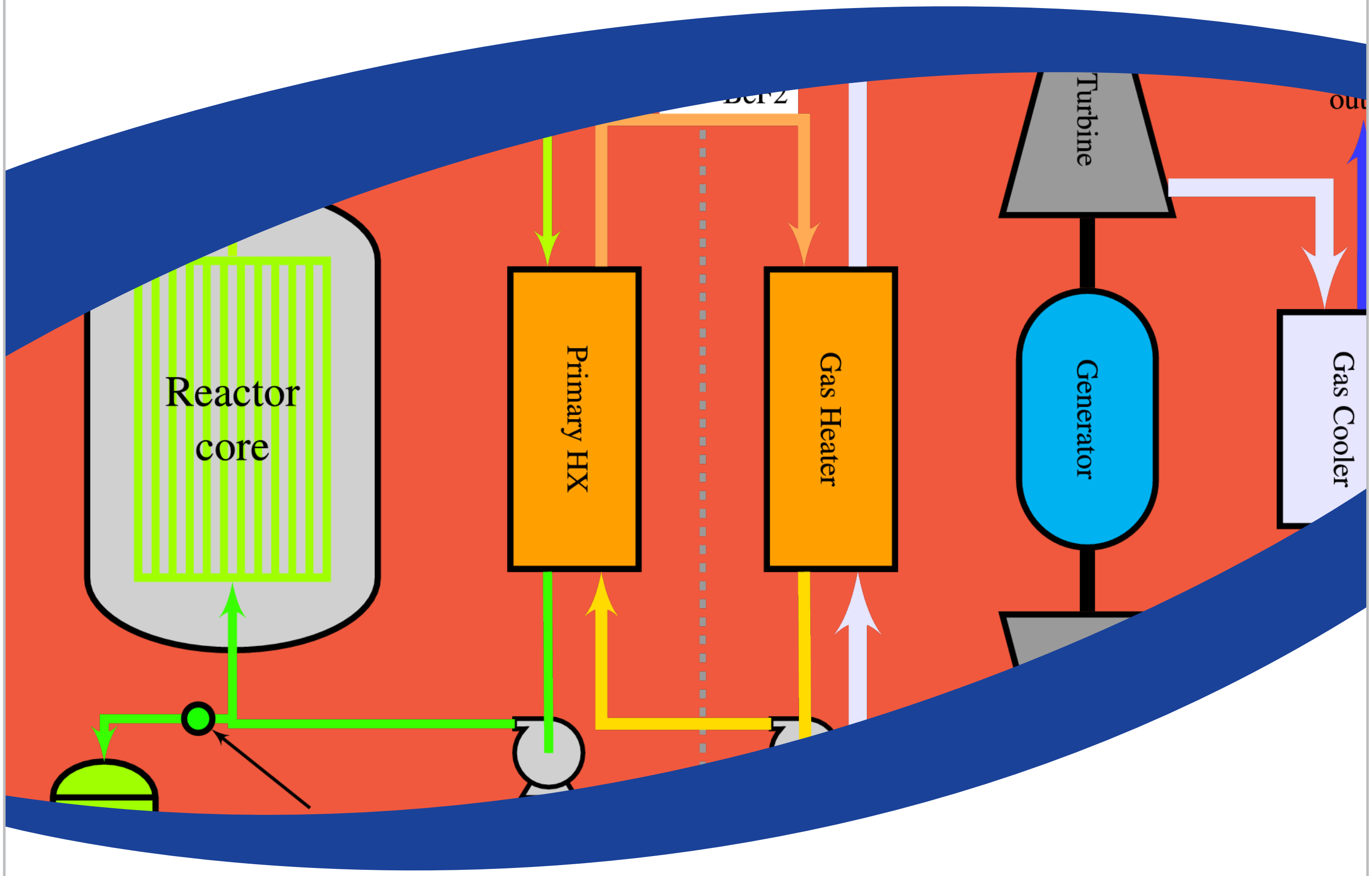
Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design

The Liquid-Fluoride Thorium Reactor (LFTR)



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The Liquid-Fluoride Thorium Reactor (LFTR)

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Final Report, October 2015

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Cover Image: LFTR schematic courtesy of Flibe Energy [2015].

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ABSTRACT

EPRI collaborated with Southern Company on an independent technology assessment of an innovative molten salt reactor (MSR) design—the liquid-fluoride thorium reactor (LFTR)—as a potentially transformational technology for meeting future energy needs in the face of uncertain market, policy, and regulatory constraints. The LFTR is a liquid-fueled, graphite-moderated thermal spectrum breeder reactor optimized for operation on a Th-^{233}U fuel cycle. The LFTR design considered in this work draws heavily from the 1960s-era Molten Salt Reactor Experiment and subsequent design work on a similar two-fluid molten salt breeder reactor design. Enhanced safety characteristics, increased natural resource utilization, and high operating temperatures, among other features, offer utilities and other potential owners/operators access to new products, markets, applications, and modes of operation. The LFTR represents a dramatic departure from today's dominant and proven commercial light water reactor technology. Accordingly, the innovative and commercially unproven nature of MSRs, as with many other advanced reactor concepts, presents significant challenges and risks in terms of financing, licensing, construction, operation, and maintenance.

This technology assessment comprises three principal activities based on adaptation of standardized methods and guidelines: 1) rendering of preliminary LFTR design information into a standardized system design description format; 2) performance of a preliminary process hazards analysis; and 3) determination of technology readiness levels for key systems and components. The results of the assessment provide value for a number of stakeholders. For utility or other technology customers, the study presents structured information on the LFTR design status that can directly inform a broader technology feasibility assessment in terms of safety and technology maturity. For the developer, the assessment can focus and drive further design development and documentation and establish a baseline for the technological maturity of key MSR systems and components. For EPRI, the study offers an opportunity to exercise and further develop advanced nuclear technology assessment tools and expertise through application to a specific reactor design.

The early design stage of the LFTR concept indicates the need for significant investment in further development and demonstration of novel systems and components. The application of technology assessment tools early in reactor system design can provide real value and facilitate advancement by identifying important knowledge and design performance gaps at a stage when changes can be incorporated with the least impact to cost, schedule, and licensing.

Keywords

Advanced nuclear reactor
System design description (SDD)
Process hazards analysis (PHA)
Molten salt reactor (MSR)
Liquid-fluoride thorium reactor (LFTR)
Technology readiness level (TRL)

EXECUTIVE SUMMARY

Planning for new or replacement power generation capacity requires a decade or more of lead time due to the large capital investment at stake, long queues for fabrication of large components, and licensing requirements. Given the large uncertainty associated with the magnitude of future energy demand and capacity requirements, utilities are interested in identifying technology options that can mitigate the business risks associated with equally uncertain economic, policy, and regulatory futures. It is in this context that electric utilities are taking notice of advanced nuclear generation technologies as options for the 2035 time horizon—a period during which existing nuclear plants in the United States will reach 60 years of operation and a substantial fraction of coal generation will require replacement.

While current and new light water reactors (LWRs) will continue to provide much of the technology backbone for global nuclear generation throughout the 21st century, changing and challenging market, regulatory, and policy environments are placing the role of new nuclear development at risk in many countries and regions. Advanced Generation IV1 reactor technologies may offer new opportunities and missions beyond traditional power generation derived from their unique attributes such as

- Increased asset flexibility in terms of deployment, operations, and products
- Enhanced passive safety from inherent physical properties of the design
- Extension of fuel resources with high conversion or breeding

Working with Vanderbilt University, EPRI has developed decision analysis tools to inform RD&D planning and investment for alignment with utility needs, innovation opportunities, and resource limits. In a pilot application of these tools, EPRI collaborated with Southern Company on an independent technology assessment of an innovative molten salt reactor (MSR) design—Flibe Energy's liquid-fluoride thorium reactor (LFTR).

The LFTR is a liquid-fueled, graphite-moderated, thermal spectrum breeder reactor optimized for operation on a thorium-supported uranium-233 (Th-^{233}U) fuel cycle. Natural thorium is relatively abundant in many parts of the world, including those lacking uranium resources. Furthermore, while thorium cannot be used to directly fuel a reactor, thorium can be converted into fissile ^{233}U via neutron absorption in an operating reactor fueled with existing fissile

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[1] Advanced Generation IV reactors are generally characterized as reactor designs that offer significant improvements with respect to current nuclear technologies in terms of potential for enhanced resource utilization, inherent safety, economic competitiveness, proliferation resistance, and security. Most employ coolants other than water. The term Generation IV more narrowly refers to six advanced reactor design classes designated under the Generation IV International Forum (GIF). Reference: *A Technology Roadmap for Generation IV Nuclear Energy Systems*. GIF-002-00. 2002.

material. Once "jump-started," a thorium-supported self-sustaining fuel cycle can be achieved.[2] The LFTR design considered in this work draws heavily from work during the 1960s era at Oak Ridge National Laboratory (ORNL) on the Molten Salt Reactor Experiment (MSRE). It also draws from subsequent ORNL design work on a two-fluid molten salt breeder reactor design derivative, the molten salt breeder reactor (MSBR).[3,4] The overall goal of the LFTR concept from the developer's perspective is a reactor that can produce economical electric power through a combination of reduced capital cost, enhanced safety, operational reliability and responsiveness, and additional revenue-generating products from nuclear fission.

The LFTR represents a dramatic departure from today's dominant and proven commercial LWR technology. Accordingly, the innovative and commercially unproven nature of MSRs, as with many other advanced reactor concepts, presents significant challenges and risks in terms of financing, licensing, construction, operation, and maintenance. Standard methods and tools were adapted to match the early developmental stage of the LFTR design for conducting the technology assessment described herein. This assessment involved three principal activities:

1) Rendering of preliminary LFTR design information into a standardized system design description format
2) Performance of a preliminary process hazards analysis
3) Determination of technology readiness levels (TRLs) for key systems and components

ES.1 Development of the LFTR System Design Description (SDD)

Following recommendations from the EPRI – Vanderbilt University assessment team, the technology development team (comprising developer Flibe Energy and systems architect/engineer Teledyne Brown Engineering) produced preliminary system descriptions of the LFTR design based on the system design description (SDD) format.[5] This format allows design teams to 1) clearly identify system components, 2) describe how those components are arranged physically and interconnected, 3) explain the system flow paths, 4) identify the indicators, controls, and alarms provided, 5) define the acceptable ranges for system performance and set points, and 6) explain the operational and safety functions that each system performs.

Use of the SDD structure and format streamlines input into more detailed future probabilistic risk analyses, safety analyses, and reliability studies while simultaneously incorporating safety considerations throughout the design life. This is a better option than leaving safety to be

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[2] Nuclear fuel cycles that extract energy from thorium resources using a thermal energy spectrum are proposed as a means to achieve greater resource and energy sustainability relative to traditional LWR fuel cycles. This benefit results from the opportunity for increased fuel utilization in the thorium-^{233}U fuel cycle afforded by the associated neutronic properties. The fission of ^{233}U in the thermal neutron energy spectrum produces enough neutrons to keep the chain reaction going while also converting enough thorium-232 (^{232}Th) into new ^{233}U to realize a net production of fissile fuel during operation. This mode of operation is known as breeding, as opposed to the net consumption of fissile fuel known as burning.

[3] Greene, S.R. (2001). *Molten Salt Reactors: Technology History, Status, and Promise*. Oak Ridge National Laboratory (ORNL).

[4] Robertson, R., O. Smith, R. Briggs, and E. Bettis (1970). *Two-Fluid Molten-Salt Breeder Reactor Design Study* (status as of January 1, 1968). ORNL-4528.

[5] Guidance on the SDD structure and its use can be found within DOE-STD-3024-2011 and DOE-STD-3009-2014.

addressed at advanced design stages when changes are generally more costly and disruptive. The LFTR system descriptions identify the requirements associated with system structures and components, explain why those requirements exist, and describe the system design features that meet those requirements.

As shown in Figure 1, the evaluated LFTR system can be divided into the following systems:

- The reactor core
- The primary loop, including the primary pump and heat exchanger
- The intermediate loop, including the coolant pump and gas heater
- The power conversion system, including its turbomachinery and recuperators
- The external cooling system, including the gas cooler and cooling towers
- The chemical processing system for the reactor fluids
- The off-gas handling system for managing gases released from the reactor

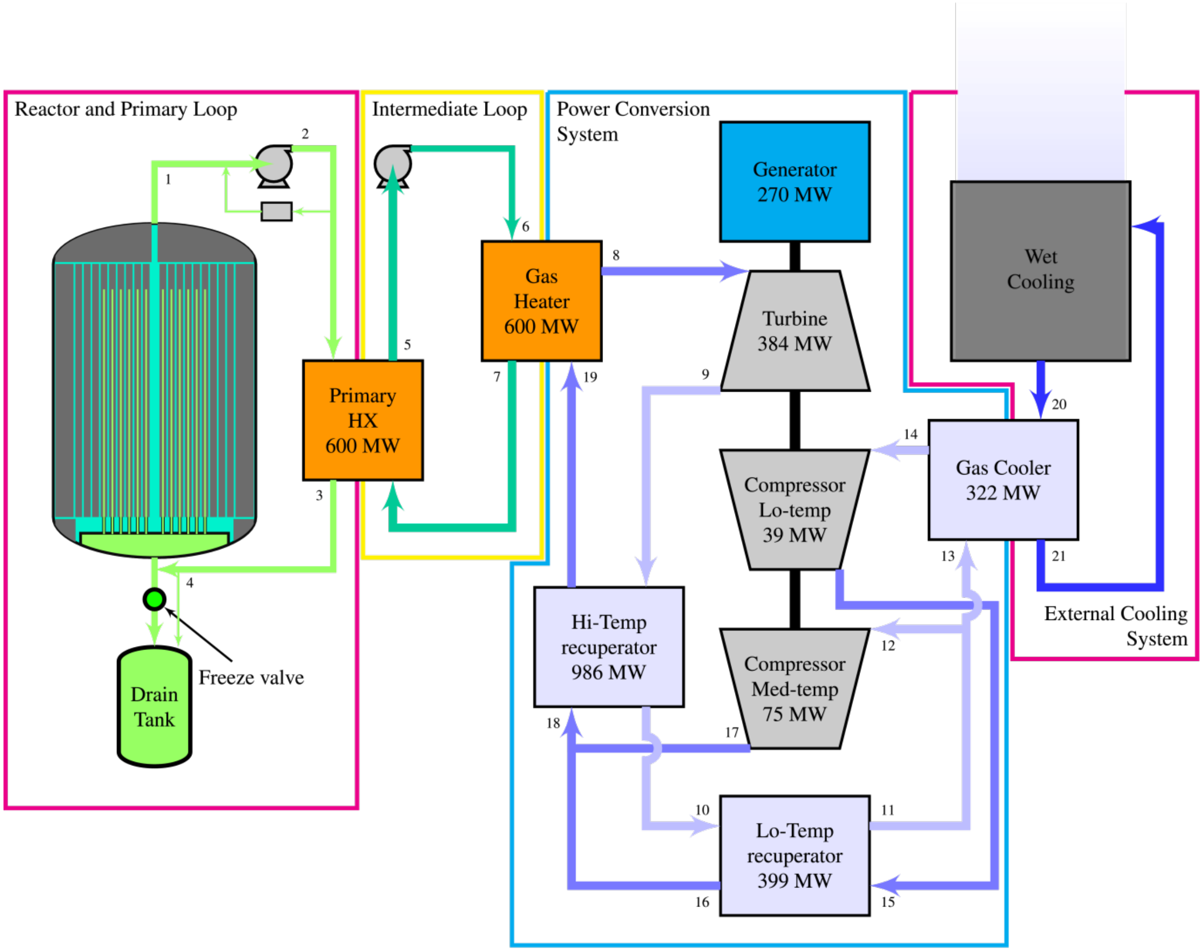

Figure 1
LFTR reference design, showing reactor and primary loop, intermediate loop, power conversion system, and external cooling system simplified flow diagram [Flibe Energy, 2015].

Flibe Energy’s LFTR design seeks to exploit the following properties and attributes to the maximum possible extent:

- Inherent safety
- Improved utilization of an abundant resource, namely, thorium
- Economic viability
- Environmental sustainability
- Significant and high-value cogeneration
- Reduced quantity and optimized characteristics of materials requiring management and permanent disposal as nuclear waste

As shown in Figure 2, the LFTR incorporates extensive chemical processing systems in addition to the more traditional mechanical systems involving solid-fueled reactor designs.

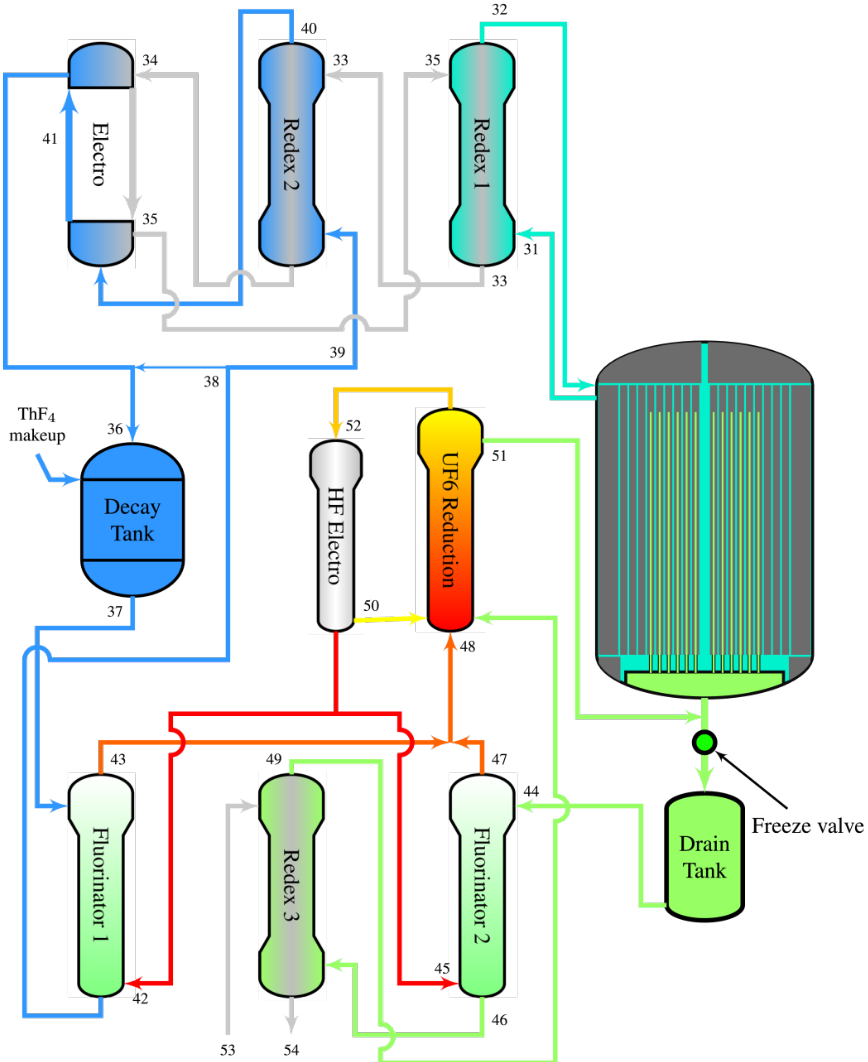

Figure 2
Reactor and chemical processing system simplified flow diagram [Flibe Energy, 2015].

Figure 3 depicts six subsystems (which will be referred to simply as “systems”). While most systems are themselves comprised of subsystems, this additional detail is excluded here for simplicity and clarity. A description of boundaries and interfaces can provide insights into how these systems function in context of the overall design. Boundaries define the furthest extents of a given system, while interfaces define how each system interacts with other systems or the outside world. Radioactivity is present in significant amounts in the reactor, blanket, and chemical processing and decay systems (colored orange), while the remaining systems (colored blue) are relatively uncontaminated. Due to the radioactivity of the fuel salt, the intermediate salt loop will also have some radioactivity, though this will be much less than the reactor and other primary system components.

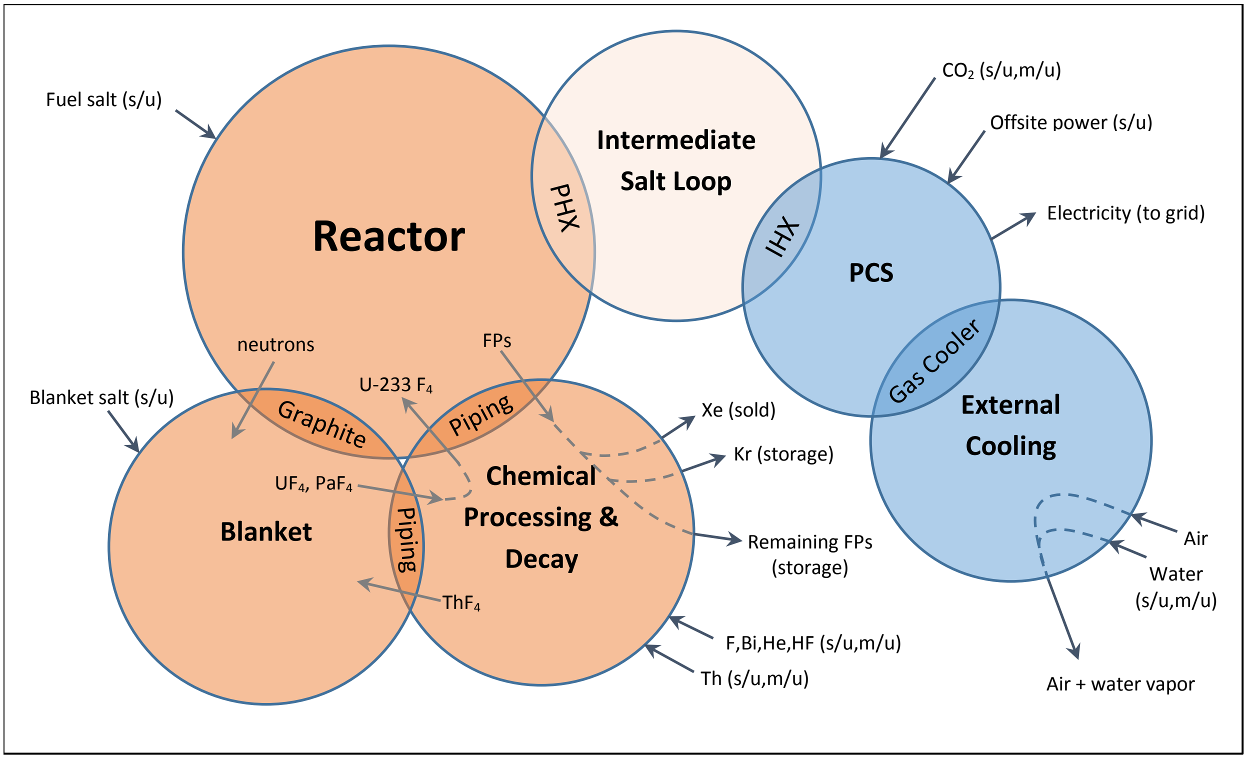

Figure 3
LFTR system/subsystem boundaries and interfaces [Flibe Energy, 2015].

Note: Inputs and outputs across boundaries are indicated with arrows. The abbreviations “s/u” and “m/u” indicate startup and makeup, respectively. C, O, U, Pa, and Th, for example, are the chemical symbols for carbon, oxygen, uranium, protactinium, and thorium, respectively, while “FPs” refers to fission products.

The fuel salt and blanket salt consist of $2LiF_2$-BeF_2-XF_4, where “X” is ^{233}U for the fuel and ^{232}Th for the blanket. Some inputs to the system are only for startup, such as the initial fuel for the blanket and reactor, CO_2 for the primary coolant system (PCS), and startup power. At steady-state, the main inputs are thorium makeup for the blanket and air and water as heat sinks for the thermodynamic cycle. The remaining inputs provide makeup for the inevitable losses that characterize real systems (CO_2 loss from the PCS as well as F, He, Bi, and H loss from the chemical processing). Steady-state outputs are fission products, electricity, air, and water vapor.

ES.2 Preliminary Process Hazards Analysis (PPHA)

Liquid-fuel MSRs such as LFTR essentially result in co-location of a critical nuclear reactor and a small chemical processing plant for fuel and blanket salt conditioning. Consequently, application of standard industry integrated safety analyses and implementation of process safety management practices represent a logical path to achieve balanced plant safety. Learning from such analyses can be more easily incorporated into reactor design earlier in the project life cycle.

Process hazards analysis (PHA) methods were developed by the chemical industry to assess the significance of hazardous situations associated with complex engineered systems, processes, and activities, especially those comprising complex engineered systems.[6,7] The U.S. Department of Energy (DOE) adapted PHA for evaluating its own unique chemical-nuclear process hazards and has identified seven acceptable PHA methodologies.[8] Of these, the aptly named "What-If" analysis requires the least design and operational information, making it useful for application to the LFTR perceptual design where experience and data are limited. Given the preliminary nature of the LFTR SDD, this PHA is also preliminary in nature and is therefore described hereafter as a preliminary process hazards analysis (PPHA).

The What-If PPHA method involves identification and resolution of a series of open-ended questions that begin with the words "What If…" (for example, What if the primary pump fails?). One of the strengths of this method is that it can be applied to a system at any stage of its development.

The LFTR PPHA was conducted through a structured iterative discussion with the LFTR design team followed by systematic review of each question, potential consequences, mitigation measures, preventive actions, and control systems. The PPHA dialog identified a preliminary set of safety systems, engineering controls, and administrative controls and laid the groundwork for more advanced safety analyses. The PPHA process also proved useful to advancing and enhancing the LFTR design itself, as the structured dialog revealed gaps in the design description, resulting in addition of an operational and maintenance philosophy and definition of top-level system requirements. The in-person dialog with the developer also revealed additional questions and scenarios, resulting in an enhanced, more complete PPHA.

Out of the PPHA discussion came a preliminary set of safety systems, engineering controls, and administrative controls designated for particular events such as loss of blanket salt. A preliminary ranking of the subsystems was developed to account for experience, hazardous chemical inventories, activities, temperatures, frequency of use, opportunities for initiating events, and the consequences of those events. In descending order of risk, the ranked subsystems are as follows:

1) Reactor vessel and containment cell
2) Fuel salt processing system
3) Primary heat exchanger

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[6] Center for Chemical Process Safety (CCPS) (1992). *Guidelines for Hazard Evaluation Procedures, Second Edition with Worked Examples*. New York, American Institute of Chemical Engineers. ISBN: 0-8169-0491-X.

[7] American Institute of Chemical Engineers (AIChE). (2015, Last Revised September 2015). *Institute Milestones*.

[8] U.S. Department of Energy (DOE) (2004). *DOE Handbook: Chemical Process Hazards Analysis*. DOE-HDBK-1100-2004.

4) Blanket salt processing system

5) Off-gas handling system

6) Drain tank

The reviewed What-If questions generally fall within four categories: 1) unintentional removal, addition, or accumulation of material in the LFTR system, 2) equipment failure, 3) human/operational error, and 4) an internally initiated event such as fire or explosion. A short list of the hazards spanning the evaluated LFTR systems and components that were deemed most significant in terms of consequences (based on expert judgment and technical documentation) is presented in Table 1. A number of the reviewed What-If questions are related to the technical challenges identified in the 1960s MSRE era, when safety studies focused on reactivity control and reactor operations.[9] Other significant hazards include those related to stresses on and corrosion of primary loop system components operating at high temperatures and in contact with molten salt fluids.

Table 1
Important hazards identified during the PPHA process with the most significant consequences for safety or integrity of the LFTR system (derived from corresponding What If questions).

LFTR System or Component	Hazard Scenario
Reactor Vessel/ Containment Cell	Unintentional control rod withdrawal
	Loss of blanket salt
	Premature criticality during filling
	Inflow of contaminants or unexpected isotopic ratio in the fuel salt
	Breakage of one or more graphite tubes
	Inadvertent release of fission gas from reactor cell and/or containment
Fuel Salt Processing	Hydrogen reacts with fluorine in chemical processing system
	Excess pressure in the helium bubbler
Primary Heat Exchanger	Minor failure in the primary heat exchanger
	Major failure within the primary heat exchanger occurs
	Sealed housing for the electric drive motors for pumps fail
Blanket Salt Processing	Inadequate removal of Pa or U in the blanket salt
	Electrolytic cell is improperly operated
Off-Gas Processing and Treatment	Potassium hydroxide (KOH) is released
Drain Tank	Improper or inadequate cooling of the drained fuel salt
	A partially thawed piece of the salt plug or other solid mass obstructs piping to the drain tank

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[9] Beall, S., P. Haubenreich, R. Lindauer, and J. Tallackson (1964). *MSRE Design and Operations Report: Part V, Reactor Safety Analysis Report*. ORNL-TM-0732.

An important insight from the PPHA activity was the value such an integrated, systematic review can provide to multiple stakeholders, even at the earliest stages of design development. The PPHA injects fresh perspectives into the design process, which developers can use to refine and enhance the next design iteration. The evaluation and review team benefits from familiarization with the proposed design and insights into technology gaps and pathways to commercialization.

ES.3 Technology Readiness Level (TRL) Determination

Liquid-fueled MSRs such as the LFTR represent a dramatic departure from traditional solid-fueled reactors that have operated and are operating at demonstration and commercial scales globally. The LFTR incorporates systems and components for novel functions, including online cleanup and processing of molten fuel and blanket salts. Similar to other advanced Generation IV concepts, operation with new coolants (heat transfer fluids) at temperatures above 500°C presents a new set of reliability, performance, inspection, and maintenance challenges to be addressed for successful commercialization. Consequently, a measure of technological maturity is required that can accommodate this complexity, novelty, and wide variation in the quality and nature of supporting evidence. The TRL scale, as shown in Figure 4, represents such a measure of maturity.

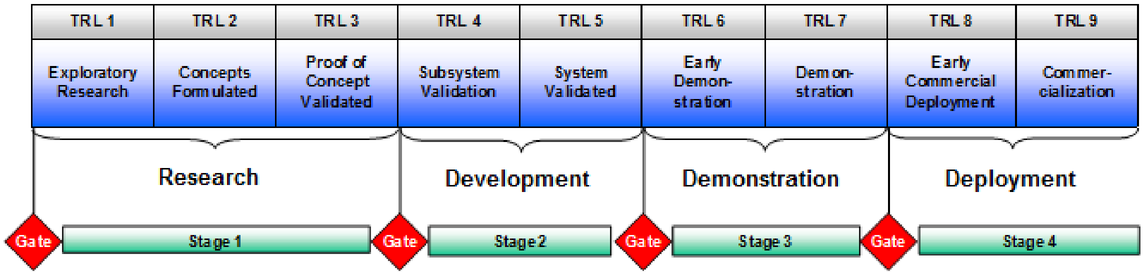

Figure 4
Representation of technology readiness levels and suggested alignment with the research, development, demonstration and deployment paradigm.

The TRL concept was originally developed by the National Aeronautics and Space Administration (NASA) and later adapted by the U.S. Department of Defense for complex technologies or technology concepts that must perform under extreme environments such as space flight and warfare.[10,11] Standard TRL determinations measure technology maturity on a scale from 1 to 9, with TRL 1 corresponding to preliminary descriptions of the scientific and/or engineering principles “on paper” and TRL 9 representing full maturity such as commercial deployment. Figure 4 presents a simplified representation of the TRL scale and correlation with the broader and more commonly used terms: research, development, demonstration and deployment. The TRL metric used for the LFTR evaluation was adapted from one developed by the U.S. DOE.12

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[10] Mankins, J. (1995). Technology Readiness Levels. NASA white paper.

[11] U.S. Department of Defense (2011). Technology Readiness Assessment (TRA) Guidance.

[12] U.S. Department of Energy (2011). Technology Readiness Assessment Guide. DOE G 413.3-4A.

Typically, the first step in TRL determination is to identify components, namely critical technology elements (CTEs). In general, a technology element is considered “critical” if it is 1) essential to the success of the system and 2) being used in a new or novel fashion. However, because many of the important LFTR systems and subsystems have not yet been fully described, traditional CTE identification cannot be consistently applied. Instead, engineering-informed judgment is applied to divide the design components into logical subsystems and groups and determine preliminary TRLs for each component. This determination is informed by the progress made during the MSBR project era (including operation of the MSRE), along with parallel, relevant efforts both for other salt-cooled nuclear energy technologies (for example, the Fluoride-salt-cooled High-temperature Reactor (FHR) as well as pertinent developments in other industries. Definitions and examples of each TRL have been adapted from the DOE and other sources to better “translate” to examples of evidence directly applicable to an MSR technology such as LFTR.

For TRL determination, the LFTR system is divided into these four subsystems (referred to as “systems” hereafter):

- Reactor cell (including not only the reactor vessel but also other primary loop components such as the primary heat exchanger, containment, and supporting pumps)
- Power conversion system
- Chemical processing system
- Off-gas handling system

Of these four, the power conversion system is not unique to molten salt reactor technology and is therefore not evaluated further. The off-gas handling system is not fully described at the component level in the SDD and therefore is not considered here for TRL determination. Consequently, the two remaining systems—the reactor cell and chemical processing system—are the exclusive focus for further evaluation for TRL determination.

As would be expected for any advanced nuclear reactor technology, there are many components and functionalities that require experimentation, testing, and demonstration prior to scale-up or commercial deployment. Because the MSRE, an engineering-scale reactor demonstration, represents the primary source of experimental data and experience for the molten salt reactor technology class, most components do not score above TRL 6 and fall within a TRL band between 3 and 6 (Figure 5 and Figure 6) spanning late development to early demonstration stages. Relative to commercial deployment, the requirements to reach complete maturity can appear overwhelming; a more manageable goal is to focus on near-term activities that support the eventual deployment of a modern, demonstration-scale version of the LFTR. This preliminary TRL determination effort has resulted in the identification of several “challenge areas” that can inform near-term decision-making for LFTR technology development.

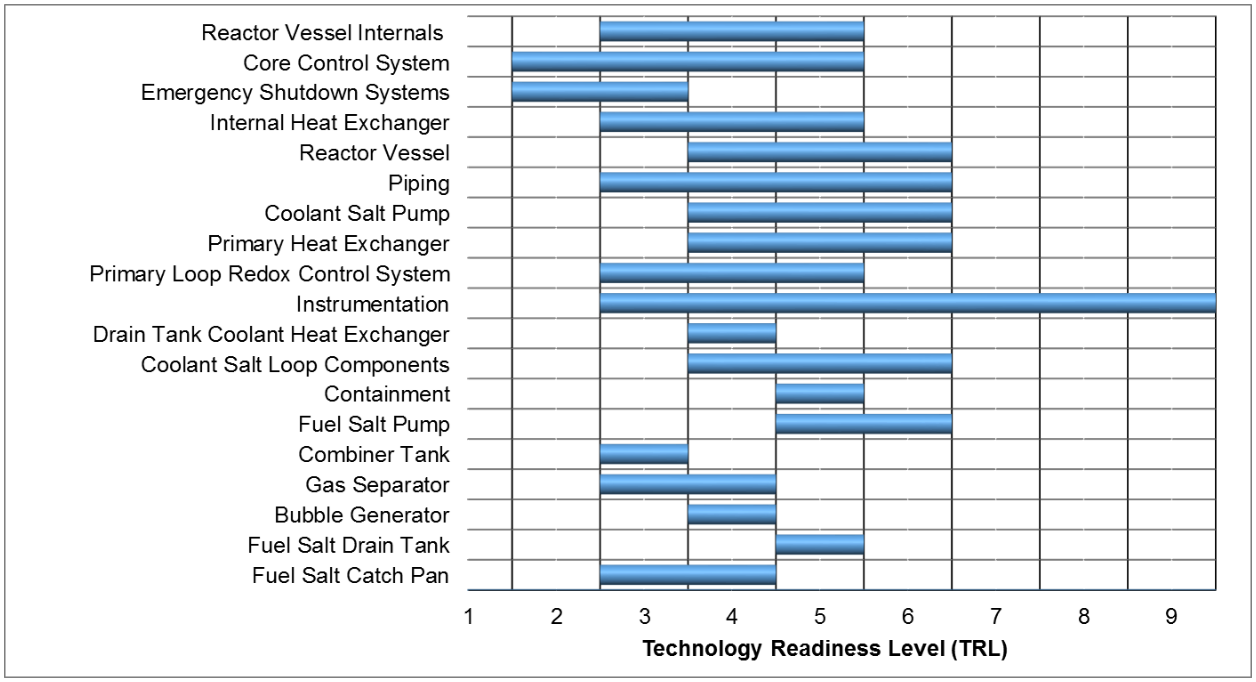

Figure 5
TRL results for LFTR reactor cell and primary loop components.

In terms of the LFTR reactor cell and primary loop, the reactor vessel components generally require significant new work to reach the demonstration phase and beyond for a TRL ≥6. In many instances, it is difficult to define a specific TRL without the final selection of a specific technology for components and systems. Most of these options have not been tested in a radiation environment with molten salts at any scale, establishing a TRL 4 as an upper bound in these instances (Figure 5). In some cases, experience with a component is limited to distantly-related experimental proofs of concept or design reports, and TRLs in the 2–3 range are more appropriate.

Some primary system support components warrant particular attention. The LFTR system relies heavily on its drain tank and supporting components (including the catch pan) for many safety-related, operations, and maintenance functions. While the MSRE also had drain tanks, their key role in LFTR during operations and accident scenarios and in meeting additional performance requirements means that the LFTR drain tank is effectively an untested component. Another area with relatively little associated experience pertains to components with salt-gas interfaces such as the combiner tank, gas separator, and bubble generator.

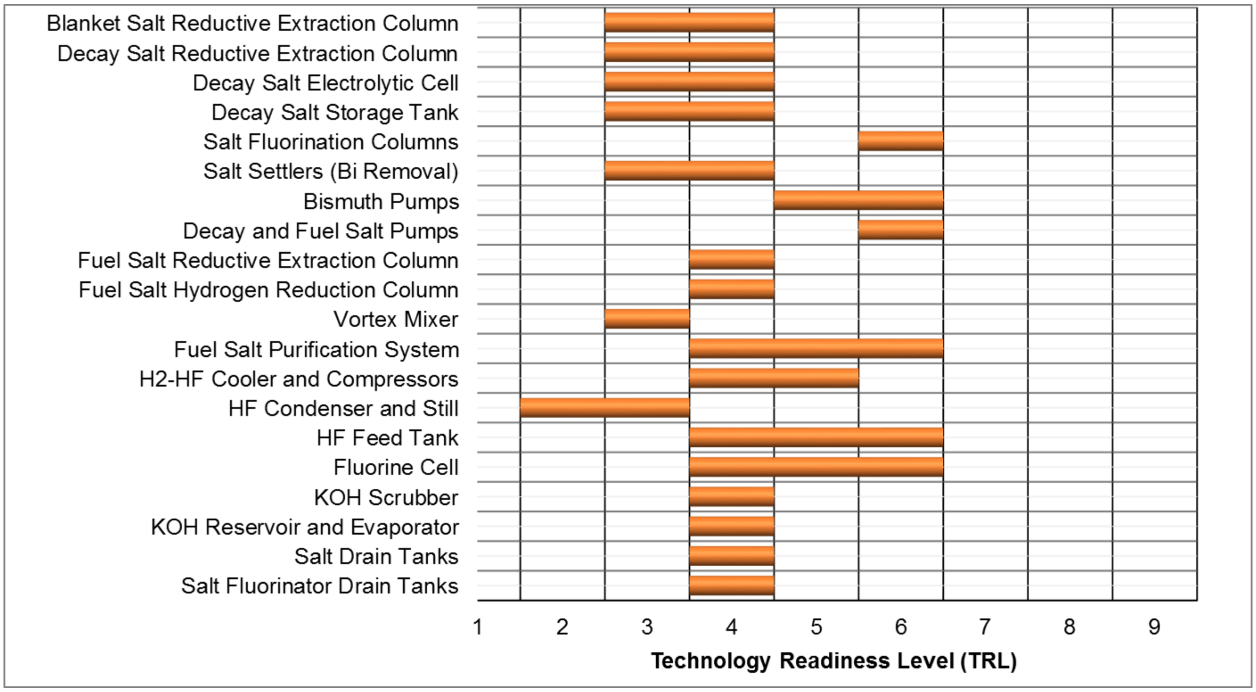

Figure6
TRL results for LFTR chemical processing system components.

Chemical processing system component groups that require significant attention include the following: the decay salt storage tank, components related to the removal of bismuth such as salt settlers, and components related to the salt-gas interfaces and separations such as the vortex mixer (which also presents a challenge for the primary system, as noted above). All of these components were described to a degree in later MSBR design reports but did not undergo substantive development prior to the end of the project in the late 1970s. Significant work was performed on reductive extraction systems with large mass fractions of thorium, which directly supports development and demonstration of the blanket salt processing system. However, the high fissile content of the LFTR fuel salt introduce additional factors that indicate a lower TRL for the fuel salt reduction system is appropriate.

It is important not to overlook the fluorine chemistry processing subsystem, which contains several components that will require additional experimentation and development. Most of the components are similar to those used in commercial chemical facilities involving fluorine or hydrogen fluoride; however, the presence of volatile fission products (iodine, bromine, and possibly tellurium and selenium) may impart additional design requirements that have not yet been anticipated. Uranium conversion facilities—which currently operate primarily in support of the once-through fuel cycle in LWRs— involve operation and maintenance of components in chemical and low-level radiation environments. The applicability of this industrial experience will depend on a preliminary assessment of the quantities of fission products that are expected to pass through the LFTR subsystem and the resulting radiation exposure of the components.

While not addressed as a “component” *per se*, LFTR deployment will be dependent upon the availability of highly depleted lithium (meaning, lithium that contains less than 50 ppm of the isotope lithium-6) for the lithium fluoride component of the FLiBe salt.[13] Lithium isotope separation was historically, but is no longer, performed at industrial scales via a process involving large quantities of mercury. More acceptable and modern methods are under development but require additional effort for industrial scaling (TRL ~4–5).[14] The lithium-6 separation example demonstrates the importance of considering factors outside system components for TRL determinations.

ES.4 Summary

This collaborative effort brought together perspectives of the technology developer and technology customer (an electric utility) to adapt and apply standard evaluation methods and tools in assessing an innovative advanced reactor concept in the early stages of development. An important insight from this effort was recognition that such structured, evidence-based, integrated hazard and technology readiness methods can provide substantial value for multiple stakeholders even at earliest stages of system engineering and design. For the utility or other technology customer, the study offers structured information on the LFTR design status that can directly inform a traditional technology feasibility study in terms of safety and technology maturity. For the developer, the assessment focuses and drives further design development and documentation and establishes a baseline for the technological maturity of key MSR systems and components. For EPRI and Vanderbilt University, the study offers an opportunity to exercise and further develop technology assessment tools and expertise through application to a specific and novel reactor design.

The application of technology assessment tools early in advanced reactor system design, such as the LFTR, provides real value and facilitates advancement by identifying important knowledge and design performance gaps at a stage when changes can be incorporated with the least impact to cost, schedule, and licensing. The resulting technology readiness determination reflects the early design stage for the LFTR concept and indicates the need for significant investment in further development and demonstration of novel systems and components.

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[13] Lithium-6 is a strong neutron absorber at thermal energies; therefore, its isotopic abundance must be reduced for use of FLiBe in a thermal reactor system such as the LFTR to reduce parasitic neutron absorption and related negative effects.

[14] For example: X. Jingjing, L. Zaijun, G. Zhiguo, W. Guangli, and L. Junkang. (2013). “Green and efficient extraction strategy to lithium isotope separation with double ionic liquids as the medium and ionic associated agent.” *Journal of Radioanalytical and Nuclear Chemistry* 295.3: 2103-2110.

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INTRODUCTION

The electric power industry is experiencing fundamental changes in the way that electricity is generated, transmitted, delivered, and consumed. Developed energy markets must adapt large, aging infrastructures to provide adequate energy and capacity for reliability. Developing energy markets are faced with the challenges and opportunities that come with a “clean slate” and many technology options and deployment paths. Within the broader global context of energy production, nuclear generation is but one of many options available for energy generation. Likewise, nuclear must exist and operate in a larger market, policy, and regulatory context and must adapt appropriately to changes in that environment to remain commercially viable and relevant.

Planning for new or replacement power generation capacity can require a decade or more of lead time due to the large capital investment at stake, long queues for fabrication of large components, and licensing requirements. Given the large uncertainty associated with projections of future demand and capacity requirements, utilities are interested in identifying technology options that can mitigate the large uncertainties and business risks associated with future economic, policy, and regulatory constraints. It is in this context that Southern Company and other utilities are taking notice of advanced nuclear generation technologies as options for capital investment in the 2035 time horizon. This is a period in the U.S. during which existing nuclear plants will reach 60 years of operation; concurrently, there will also be a need to replace coal generation.

While current and new build light-water reactors (LWRs) will continue to provide the technology backbone for global nuclear generation throughout the 21st Century, changing and challenging market, regulatory and policy environments are placing the role of new nuclear at risk in many countries and regions. Advanced Generation IV[15] reactor technologies may offer compelling new opportunities and missions beyond traditional power generation derived from their unique attributes and capabilities, e.g.:

- Increased asset flexibility in terms of deployment, operations and products;
- Enhanced passive safety from inherent physical properties of the design; and
- Extension of fuel resources with high conversion or breeding.

EPRI is collaborating with Southern Company Services on a technology assessment of a liquid-fueled molten salt reactor, Flibe Energy’s liquid-fluoride Thorium Reactor (LFTR), which has

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[15] Generation IV reactors are generally understood to be fission reactor designs that offer significant improvements with respect to current nuclear technologies in terms of potential for enhanced resource utilization, inherent safety, economics and proliferation resistance and security. The term Generation IV more narrowly refers to six advanced reactor design classes designated under the Generation IV International Forum (GIF). Reference: *A Technology Roadmap for Generation IV Nuclear Energy Systems*. GIF-002-00. 2002.

been proposed and optimized to utilize natural thorium resources as a fertile support for a uranium-233 based fuel cycle. The LFTR is a liquid-fueled, graphite-moderated thermal spectrum breeder reactor. LFTR's dual fluid design features separate fuel and blanket salt loops. The LFTR is an innovative MSR design that draws heavily from the Molten Salt Reactor Experiment (MSRE), an Oak Ridge National Laboratory (ORNL) engineering-scale demonstration, and subsequent work on a two-fluid molten salt breeder reactor (MSBR) design. The LFTR represents a dramatic departure from the current dominant commercial technology, i.e., solid-fueled light-water reactors operating on the uranium-plutonium fuel cycle. Accordingly, commercialization of an MSR on a relevant timeframe and scale represents a significant challenge in terms of licensing, operations and maintenance while offering a truly transformational energy generation option to electric utilities and other owner/operators.

This report is the result of a collaborative study jointly sponsored by EPRI and Southern Company Services to conduct an independent technical evaluation of the LFTR design in its current state of technological maturity. The performance of this study and the results contained in this report do not constitute and should not be construed as an endorsement of any commercial concept or entity.

1.1 Roles and Responsibilities

EPRI is an independent, nonprofit center for collaborative public interest energy and environmental research. EPRI participation in this collaborative technology assessment represents an extension of recent work with Vanderbilt University and ABS Consulting, Inc., developing and applying decision-analysis methods and tools to support planning and investment in advanced nuclear technology with respect to deployment driven research, development and demonstration (RD&D). This work also complements EPRI's expanding strategic focus on advanced nuclear generation technologies to support flexible, resilient and connected power systems of the future. This research focus leverages decades of EPRI experience supporting the safe, affordable, reliable and environmentally responsible nuclear power generation through:

- Continuous improvement of current fleet performance via enhanced inspection, maintenance and aging management;
- Enabling the construction of a new generation of reactors through articulation of owner/operator requirements, simplification and standardization of designs, and stabilization of licensing; and
- Proactive RDD to support flexible operations and potential extended operations of reactors beyond 60 years.

Vanderbilt University and EPRI have a long-standing contractual and collaborative relationship that has resulted in development and application of a number of decision-analysis and risk assessment tools. Vanderbilt's Nuclear Environmental Engineering Research Group supported EPRI's technology assessment as an independent consultant, providing extensive technical review and conducting the preliminary process hazard analysis (PPHA) and technology readiness assessment (TRA) contained in Sections 3 and 4 of the report and documented in detail in the Appendices.

Southern Company Services (SCS) co-sponsored the study and participated in the role of a prospective owner/operator, i.e., the ultimate technology customer. SCS parent Southern

Company is a large, vertically integrated electric utility serving over 4.4 million customers with 46 GWe of generation in regulated and competitive markets spanning six states in the southeastern United States.[16] Southern Company maintains an active research and development presence to track and promote innovation to fulfill its mission to provide its customers with clean, safe, reliable and affordable electricity. Southern's collaboration with EPRI on this study is consistent with its mission and long-term vision.

Flibe Energy is a private technology developer that has resurrected and updated the ORNL MSBR design effort with the liquid-fluoride thorium reactor (LFTR).[17] Renewed and growing interest in molten salt reactor concepts and thorium use for breeding in the thermal spectrum is widely credited to Flibe Energy's efforts to collect, archive and make publicly available original work and experience of long-retired ORNL staff. Flibe Energy agreed to make the design information presented in this work publicly available to promote public understanding and advancement of MSR technology.

Teledyne Brown Engineering (TBE) provided systems design and engineering support under contract with Southern Company Services, drawing on its experience and expertise as an architect/engineer for advanced nuclear power systems for civilian, defense and space applications.[18] Flibe Energy and TBE worked together to develop a preliminary set of basic engineering documents and to prepare a technology, infrastructure and data gap analysis that led to the LFTR System Design Description presented in this report in Section 3 of this report.

1.2 Technology Assessment Methods

The long timeframes and large investments required for transformational nuclear energy innovation call for a structured, transparent, and evidence-based decision-support approach that supports revision and re-evaluation as information, assumptions, conditions, policies and drivers change. When approaching technology assessment, it is important to identify and distinguish between strategic objectives for deployment of a technology, i.e., the "what" and "why", and the tactical aspects of that deployment, i.e., the "how" and "how difficult". Structured assessments can help provide this clarity.

This study focuses on the tactical aspects of advanced reactor RD&D that are tied to implementation and commercialization and are therefore highly dependent on many internal and external factors such as technological maturity, resources, market interest. These questions typically take the form of "Can the technology be brought to market?" and "If so, how will this be done, how long will it take and how difficult will the process be?" Addressing tactical questions can be particularly challenging for earlier stage, less mature technologies.

EPRI and Vanderbilt have developed and are exercising improved methods for assessing nuclear energy generation technology in its early development through the use of recognized and established approaches and tools such as probabilistic hazard analysis (PHA) methods and TRL determination as useful measures of safety and technology maturity for early-phase concepts. These efforts are documented in a number of EPRI reports, peer-reviewed publications, and

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[16] http://www.southerncompany.com/about-us/our-business/home.cshtml

[17] http://flibe-energy.com/

[18] https://www.tbe.com/

technical papers and presentations [EPRI 2013; Dykes 2013; Sowder 2013; Johnson 2014; Krahn 2014a,b].

1.3 Molten Salt Reactor Technology History and Overview

The technical foundation for MSR designs lies in the successful demonstration of the technology with construction and operation of two experimental reactors at Oak Ridge National Laboratory during the 1950s and 60s [Rosenthal 1969; Greene 2001] . The potential for utilizing fertile Th-232 to breed fissile uranium-233 was identified early in the nuclear era. And the higher average number of neutrons produced per neutron absorbed in uranium-233 in the thermal neutron energy range compared to other fissile nuclides such as uranium-235 and plutonium-239 opens the possibility of a sustainable breeding cycle using a thermal neutron spectrum. The technology was initially developed targeting propulsion systems capable of powering aircraft for extended strategic operations without refueling. [Note: The Aircraft Nuclear Propulsion program ended without actual demonstration of in-flight nuclear propulsion, but an operating reactor was flown on a test aircraft to evaluate shielding requirements and feasibility (Figure 1-1, Left Image).][19]

Figure 1-1
LEFT – Convair NB-36H nuclear test aircraft flew with an operating reactor in preparation for X-6 nuclear bomber program [image courtesy of US Air Force, US DOD]; RIGHT – BeO moderator for 1954 Aircraft Reactor Experiment (ARE) [image courtesy of ORNL, US DOE].

As a result of military interest in this unique application, the first MSR demonstration was the Aircraft Reactor Experiment (ARE), a short duration proof-of-concept test [Bettis 1957; Serp 2014]. The ARE used Inconel as the primary structural material, BeO as the moderator (Figure 1-1; Right Image), and NaF-ZrF$_4$-UF$_4$ as the fuel salt. ARE testing in 1954 included operation for 100 hours up to 2.5 MW$_{th}$ with steady state outlet temperatures up to 860 °C, demonstrating

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[19] The Aircraft Shield Test Reactor (ASTR) was an air-cooled light water reactor that was operational during flights but was not used to power the plane. Reference: *Atomic Energy Commission and Department of Defense (February 1963). Report to the Congress of the United States – Review of manned aircraft nuclear propulsion program. The Comptroller General of the United States*: B-146759. Available at: http://fas.org/nuke/space/anp-gao1963.pdf.

stable, self-regulating MSR operation at very high temperatures. Figure 1-2 depicts the ARE system primary and secondary coolant flows.

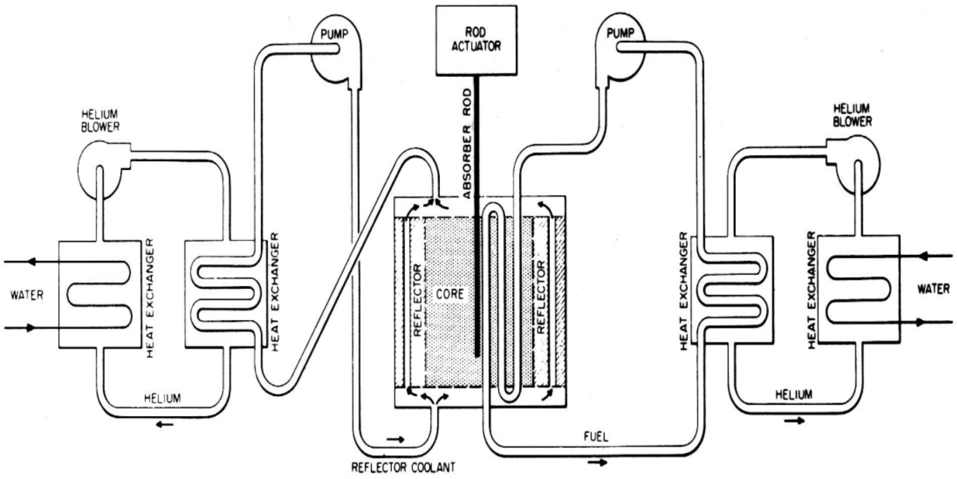

Figure 1-2
Schematic of Aircraft Reactor Experiment [Image courtesy of ORNL, US DOE].

The Molten-Salt Reactor Experiment (MSRE) followed the ARE and was designed to operate at larger scale for a longer period of time to evaluate the technology for use in power reactors (Figure 1-3) [Rosenthal 1969; Greene 2001]. Table 1-1 provides some basic design and operating detail for the MSRE. A primary objective of the MSRE was to evaluate the chemical compatibility of the three materials that made up the reactor: fuel salt, unclad graphite moderator, and a high-nickel alloy. A secondary objective was to demonstrate operation with uranium-233 fuel. The MSRE started in June 1965 with enriched uranium fuel. Examination of reactor components and materials during the test indicated compatibility of the salt-moderator-metal alloy system for the limited duration of the test. After the enriched uranium was removed from the fuel salt and replaced by uranium-233 recovered from commercial nuclear fuel, the MSRE was restarted in 1968 and became the first reactor to operate on uranium-233. MSRE operated for 20,000 hours.

Table 1-1
Molten Salt Reactor Experiment design and operating characteristics [Rosenthal 1969].

Fuel/coolant salt	$^7LiBeF_4$ (Flibe)
Moderator	unclad graphite
Primary system construction	Hastelloy N
Power	7 MWth
Outlet temperature	660 °C

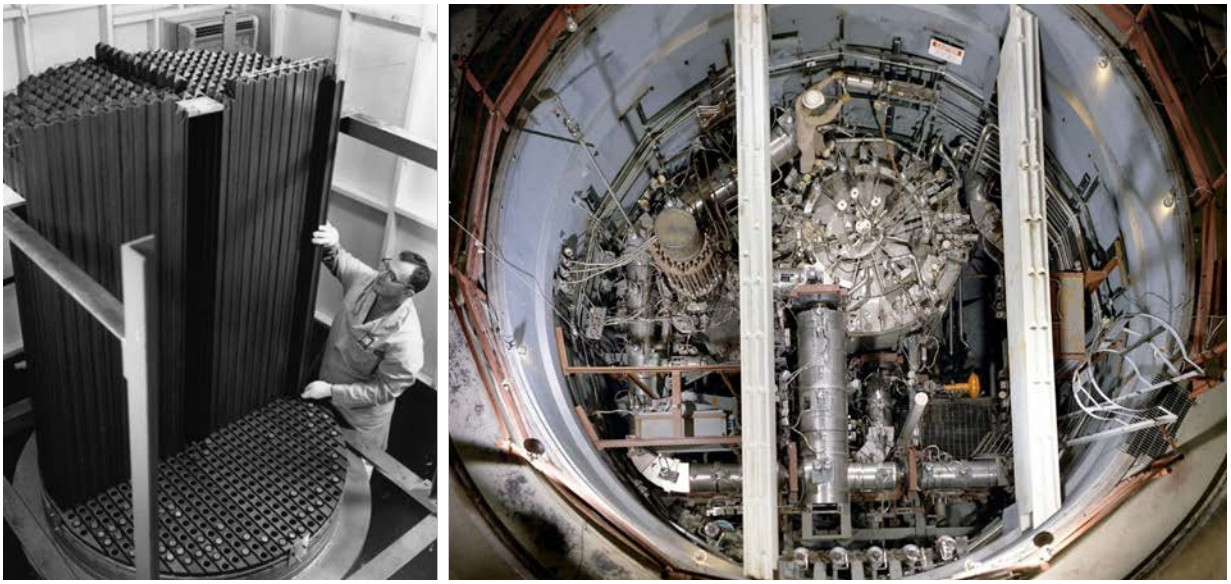

Figure 1-3
LEFT - Assembly of the core of the Molten-Salt Reactor Experiment, illustrating scale and configuration of core internals. RIGHT – View of assembled MSRE from above; top of reactor vessel in upper right quadrant [Images courtesy of ORNL, US DOE].

The next planned phase in MSR development was the construction of a larger molten-salt reactor demonstrating thorium breeding to uranium-233 and associated chemical processing required [Rosenthal 1969]. However, budget constraints led the Atomic Energy Commission, predecessor to the U.S. Department of Energy, to prioritize and select a single breeder reactor concept for further development in the United States, i.e., the sodium-cooled fast breeder reactor. Consequently, all major MSR developmental efforts ended in 1972, although some work continued through the 1970s.

1.4 Report Structure

The report is divided into the following sections:

1. LFTR System Design Overview and Objectives
2. LFTR System Design Description (SDD) Format
3. Process Hazards Analysis (PHA) Results
4. Technology Readiness Assessment (TRA) Results
5. Appendices (to provide supporting and supplemental information)

1.5 References

[Bettis 1957] Bettis, E.S., Cottrell, W.B., Mann, E.R., Meem, J.L. and Whitman, G.D. (1957) The Aircraft Reactor Experiment – Operation. Nuclear Science and Engineering. 2, 841-853.

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[EPRI 2013] EPRI (2013) EPRI Framework for Assessment of Nuclear Fuel Cycle Options, Palo Alto, CA: 1025208.

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[Krahn 2014a] Krahn, S., Ault, T., Gardiner, A., Croff, A., Clarke, J., Machiels, A. and Sowder, A. (2014) A Decision Analysis Tool to Support Planning and Decision-Making for Sustainable, Deployment-Oriented Research, Development and Demonstration (RD&D) of Advanced Nuclear Energy Technologies. ICAPP 2014, April 6-9, 2014, Charlotte, NC.

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[Rosenthal 1969] Rosenthal, M.W., Kasten, P.R. and Briggs, R.B. (1969) Molten-Salt Reactors – History, Status, and Potential. Oak Ridge National Laboratory, Oak Ridge, TN.

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[Sowder 2013] Sowder, A., Machiels, A., Dykes, A. and Johnson, D. (2013) A Decision Analysis Framework to Support Long-term Planning for Nuclear Fuel Cycle Technology Research, Development, Demonstration, and Deployment", Global 2013 International Fuel Cycle Conference, Sept 29 – Oct 3, 2013, Salt Lake City, UT.

2

LFTR REFERENCE DESIGN: OVERVIEW AND OBJECTIVES

Flibe Energy's LFTR concept is a direct descendent of the ORNL MSBR design. Flibe has focused on more contemporary regulatory and economic environments where safety and economic performance are paramount. For example, the LFTR design under consideration here incorporates a closed Brayton-cycle supercritical CO_2 gas turbine power conversion system as opposed to a conventional Rankine steam cycle for greater thermal efficiency for power generation. Modular construction and deployment are also of interest in keeping with government and industry trends; however scaling of the reactor for modular considerations may drive down heat and power output and can further constrain selection and manufacture of reactor components and structures.

Flibe Energy's reference LFTR system described and evaluated in this report is a 600-MWth reactor paired with an advanced power conversion system for a 250-MWe net electricity output. Figure 2-1 provides a high-level schematic of LFTR primary and secondary systems.

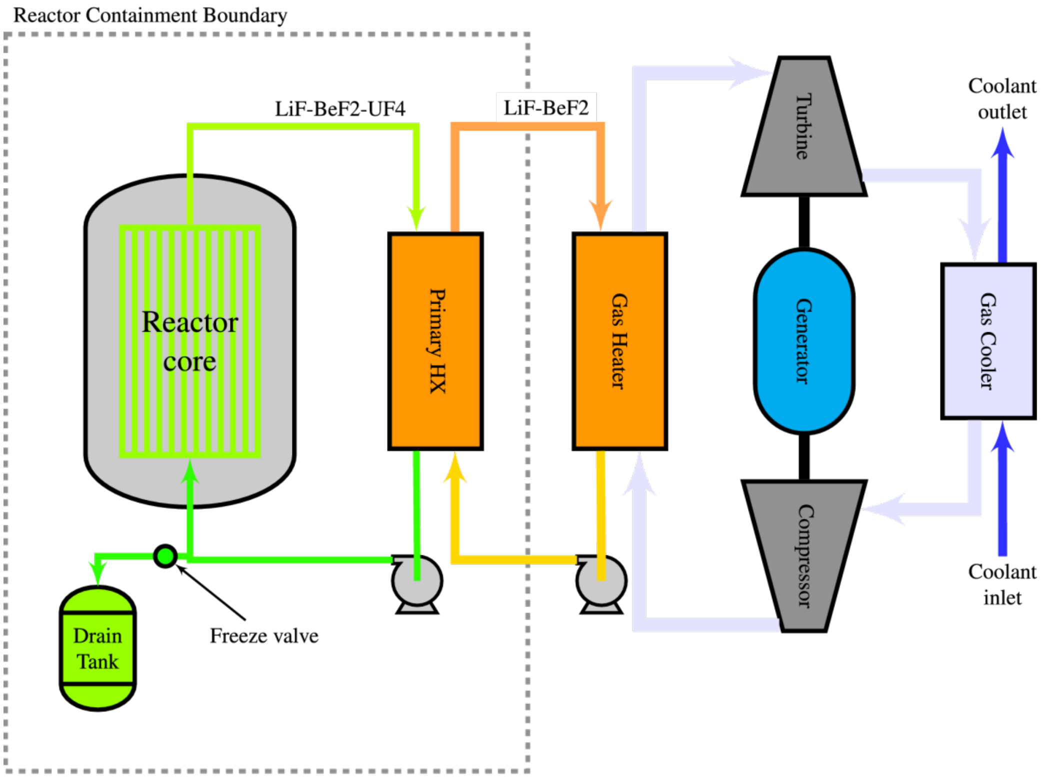

Figure 2-1
Reference LFTR design schematic [Flibe Energy, 2015].

The overall goal of the conceptual design from the developer's perspective is to define a reactor that can produce economic electrical power through a combination of reduced capital cost, enhanced safety, operational reliability and responsiveness, and additional revenue-generating products from the nuclear fission reaction. An economic source of baseload generation capacity is needed as the United States faces the retirement of coal-fired and conventional nuclear electrical generation capacity. Based on current projections of energy demand and regulatory and policy trajectories, development and deployment of advanced nuclear reactor designs to replace existing and provide new generation capacity will be needed in the 2030s to meet electricity demand, provide capacity, and stabilize electricity grids that may need to accommodate increasing distributed and renewable generation.

Interest in LFTR derives largely from intrinsic physical characteristics of liquid-fuel and molten salt as coolant and heat transfer fluid, potential benefits from utilization of alternative natural resources through breeding, high thermal efficiency and product diversification possible by high coolant outlet temperatures. Flibe Energy's LFTR design seeks to exploit the following properties and attributes to the maximum possible extent:

- **Inherent Safety** — Operation at low pressure without stored energy terms coupled with a passive cooling approach offers the potential for a high-margin, more robust safety case. Some important accident scenarios identified and evaluated for LWRs may not be applicable or relevant to MSR licensing.
- **Improved Utilization of an Abundant Fuel Resource, i.e., Thorium** — Use of thorium, an unexploited and relatively abundant natural resource, offers an alternative to exclusive reliance on mined natural uranium and/or use of plutonium for national energy security and commercially reliable fuel supplies. The reasonably assured and inferred recoverable global supply of thorium is conservatively estimated at 6,355,000 tons[20], and substantial inventories of thorium exist as the result of mining for rare earths. Thorium is generally considered a nuisance waste by-product of rare earth mining.
- **Economic Viability** — Improved economic performance and access to new markets beyond baseload electricity generation through product diversification are increasingly considered for successful commercialization. Relative to current LWR technology, the LFTR design targets very high fuel utilization and electrical conversion efficiency (45-50%) when coupled with super-critical CO_2 Brayton cycle power conversion systems. LFTRs also possess the inherent self-controlling characteristics of MSRs, which provides for stable and potentially simplified reactor operation. Compatibility with modular construction and deployment may provide similar capital cost savings to that proposed for current LWR-based small modular reactor concepts.
- **Environmental Sustainability** — Potential for high natural resource utilization and low carbon footprint provide a compelling case in terms of natural resource depletion and long-term climate change mitigation.

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[20] World Nuclear Association. http://www.world-nuclear.org/info/Current-and-Future-Generation/Thorium/, accessed 8/14/2015.

- **Significant and High Value Co-generation** — While electricity generation remains the primary mission, high output temperatures provide access to new markets and business cases through co-generation of high-value products such as hydrogen, potable water and syngas. Radioisotope production represents a potential additional revenue source compatible with power production and other missions. Product switching during periods of low electricity demand and/or low prices also provides de facto energy storage approach through the production of storable, high-value commodities while reducing the need for cycling of plant power.
- **Reduced quantity and optimized characteristics of materials requiring management and permanent disposal as nuclear waste** — Potential for reduced inventories of long-lived waste products and improved radioactive waste characteristics could provide substantial benefits for management and disposal of high-level wastes requiring deep-geologic disposal.

3

LFTR SYSTEM DESCRIPTION

A recommendation provided to the LFTR Design Team at the beginning of this technology assessment (and applies to other entities pursuing advanced reactor technology development) is that the DOE System Design Descriptions (SDDs) could be used as a reference framework to provide a consistent outline for the presentation of engineering information for each system and to ensure safety is integrated early and throughout the design process. When engineering design technical content is presented in the SDD, format as described in DOE-STD-3024-2011 [DOE 2011], PHAs and other safety analysis procedures can be streamlined. Chapter 4 of this standard reviews the objective, purpose, and content of system design descriptions (SDDs), it is summarized below (further details and information on DOE Guidance on SDDs is found in Appendix C):

> "An SDD identifies the requirements associated with system structures and components (SSCs), explains why those requirements exist…and describes the features of the system design provided to meet those requirements. The SDD helps ensure consistency among engineering requirements for systems… [and] often serves as the central coordination link among the engineering documents, facility safety basis, and procurement and construction documents. [The SDD] should identify the components of the system; describe how those components are laid out physically and interconnected; explain the system flow paths; identify the indicators, controls, and alarms provided; define the acceptable ranges for system performance and setpoints; and explain how the system operates."

This section is organized around an outline that originated as the SDD report structure from DOE-STD-3024-2011, but was adapted given the early design and development stage of the LFTR system. What follows below within this section is the LFTR description as organized by the following: (1) introduction, (2) general overview, (2) system classification, (3) requirements and bases, (4) system description, (5) operations, (6) testing and maintenance, (7) source documents, and (8) system drawings.

3.1. LFTR SDD Introduction[21]

The objective of the liquid-fluoride thorium reactor (LFTR) design proposed by Flibe Energy is to develop a power-generating nuclear reactor that will produce electrical energy at low cost by efficiently utilization thorium as a fertile support for breeding of fissile uranium-233 fuel.[22] A graphite-moderated, thermal-spectrum reactor with solutions of liquid fluoride salts containing both fissile and fertile materials appears to be a potential way to realize this objective. This report summarizes the present information on the characteristics of the LFTR design as they are presently understood.

When mixtures of fluoride salts are raised to a sufficient temperature to allow them to liquefy, they form an acceptable medium for nuclear fission reactions to take place. The ionically-bonded nature of the salts mitigates radiation damage to the mixture and allows for operation at high temperature yet at essentially ambient pressure. Most fission products, including those of greatest radiological concern, form stable fluoride salts that are retained in the overall mixture under normal operations and accident conditions. Fission product gases, whose removal is important from a performance and safety basis, are separated from the fluid mixture and allowed to decay to stability in a separate system. New fissile material can be added or removed at rates that allow overall reactivity to be held very close to the minimum amount needed to achieve criticality.[23] The fluoride salt mixtures in question have high volumetric heat capacity, comparable to water, and do not undergo vigorous chemical reactions with air or water in contrast to many liquid metals.

The components of fluoride salt mixtures have both desirable and undesirable aspects, and the two most important are lithium-7 fluoride and beryllium fluoride. The two natural isotopes of lithium must be separated from one another since lithium-6 (7.5% of natural lithium) is far too absorptive of neutrons to be a suitable component of a reactor fluid. Beryllium fluoride is chemically toxic but offers favorable neutronic and physical properties. The chemical processing

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[21] The LFTR SDD has been reproduced here largely in the form it was provided to EPRI by the design team comprising Southern Company, Teledyne Brown Engineering, and Flibe Energy pursuant to the project work scope and objectives.

[22] Nuclear fuel cycles that extract energy from thorium resources using a thermal energy spectrum are proposed as a means to achieve greater resource and energy sustainability relative to traditional LWR fuel cycles as the result of increased fuel utilization of thorium-based fuel and substantial untapped global thorium reserves. Increased fuel utilization is a consequence of the reaction probabilities both of uranium-233 fuel and its daughter products formed by neutron capture. As a result, irradiation of uranium-233 fuel is more likely to lead eventually to fission and less likely to produce transuranics relative to U/Pu-based fuel cycles. Further, the use of liquid-state, real-time fuel processing concentrates uranium-233 in the fuel stream while removing parasitic absorbers thus decreasing competition for neutrons and continuously exposing uranium to the neutron flux. This creates the potential to extract energy via fission from a greater fraction of LFTR fissile fuel than is afforded by solid state systems. In terms of natural resources and security of supply, thorium deposits are abundant in many regions, including those lacking significant reserves of natural uranium.

[23] Most conventional nuclear power plants use solid-state fuel that is sealed in the reactor for the duration of the fuel cycle (18-24 months), which in turn requires that all energy necessary for power production for a given cycle be emplaced at the beginning of the cycle. This excess reactivity must be suppressed in lessening degrees throughout the fuel cycle and drives many safety concerns in conventional, commercial nuclear reactors. The absence of significant excess reactivity in the LFTR means that active reactivity suppression systems are less critical to safety, greatly reducing concerns about reactor accidents.

and purification of fluoride salt mixtures typically involves powerful reactants such as gaseous fluorine and hydrogen fluoride, which are very toxic and chemically reactive. However, incorporation of non-aqueous based separations does provide a safety benefit in terms of criticality control. The absence of water from the chemical processing system reduces the potential for criticality outside of the reactor based on moderator exclusion.[24]

Fluoride salts, due to their chemical stability, have the potential to corrode most structural metal alloys, but some alloys have been developed that are resistant to against corrosive attack, and further improvements in materials may extend economic lifespans of important system components. These alloys are based on nickel with a variety of other metallic constituents. Fluoride salts do moderate neutron energies sufficiently to degrade the energy of neutrons produced by the fissioning of uranium-233, but are not sufficiently effective moderators to generate a thermal neutron spectrum. Thus separate moderator materials are necessary for the reactor and graphite has been proven to be attractive. Graphite is not wetted by the fluoride salts and does not require cladding. If the surface of the graphite is treated so that small pores are closed, most fission product gases can be excluded from the graphite. Graphite does experience issues from dimensional distortion over time; this effect must be accounted for in reactor design and mitigated by operations and maintenance practices.

The high operational temperatures of the fluoride salts (500-700 ^{o}C) make them potential candidates for coupling to a closed-cycle gas turbine power conversion system (PCS). At present, the supercritical carbon dioxide gas turbine employing the recompression cycle appears to be a good candidate for coupling to the reactor. The carbon dioxide working fluid in the cycle provides a final barrier to tritium release into the environment,[25] and tritium generation is an inevitable consequence of using lithium and beryllium in the salt mixture. The gas turbine can generate shaft power at high efficiencies (approximately 45%) yet in a small operational envelope.

Thorium feedstock is introduced as a tetrafluoride into the blanket salt mixture of the reactor. The blanket salt surrounds the active "core" region of the reactor and intentionally absorbs neutrons in the thorium-232, which leads to the transmutation of the thorium via nuclear beta decay, first to protactinium-233 and later to uranium-233[26], as follows:

$$\mathbf{{}^{232}_{90}Th + {}^{1}_{0}n \rightarrow {}^{233}_{90}Th \xrightarrow{\beta} {}^{233}_{91}Pa \xrightarrow{\beta} {}^{233}_{92}U} \qquad \textbf{Eq. 3-1.}$$

Both the protactinium and the uranium are chemically removed from the blanket salt mixture and uranium is introduced into the fuel salt mixture in the reactor. Fission splits uranium-233 into two or more fission products, releasing both energy and neutrons. These fission products are later chemically removed from the fuel salt and in some cases separated and purified before final disposition.

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[24] The salt components are relatively poor neutron moderators.

[25] High-temperature carbon dioxide will chemically react with any tritium present, forming tiny amounts of tritiated steam that can be removed.

[26] Thorium-232 is the “fertile” isotope, and uranium-233 is the “fissile” isotope that LFTR is designed to breed and subsequently fission.

3.1.1 System Identification

The LFTR system described in this document comprises:

- The reactor cores (some of which may be in a state of refurbishment or assembly),
- The primary loop, including the primary pump and heat exchanger,
- The intermediate loop, including the coolant pump and gas heater,
- The power conversion system, including its turbomachinery and recuperators,
- The external cooling system, including the gas cooler and cooling towers,
- The chemical processing system for the reactor fluids,
- The off-gas handling system for reactor gases.

3.1.2 Limitations of this System Design Document

This system design document (SDD) is limited to the LFTR system only. It is assumed that suitable startup materials (fissile, fertile, and salt components) are provided to the facility at startup and throughout plant operation as required. It also assumes that the waste fission products, at a suitable time, can be removed from the facility for further processing or permanent disposal. The facility contains no accommodations for permanent disposal of materials.

The SDD also assumes that the LFTR system is housed within a facility at a site suitable for the generation of substantial amounts of electrical energy, and that an electrical distribution network exists to which the system can be connected. Sufficient coolant (air or water) is also assumed for the PCS, although the quantity has not been presently defined.

This design is of necessity limited by the current immaturity of the LFTR concept. Although a great deal of work was done on thorium-fueled molten-salt reactors by ORNL from 1951 to 1976, only portions of that work are applicable to the present effort. All of the ORNL work has been utilized to the maximum degree possible, but there still remains a great deal of work to do before even a conceptual design effort can be considered complete.

With that in mind, many of the aspects of this document, particularly those that relate to details of operation, transient conditions, maintenance, and decommissioning, are at a very preliminary state of definition.

3.1.3 Ownership of this SDD

The custodian and maintainer of this document shall be the chief engineer of Flibe Energy.

3.1.4 LFTR SDD Definitions/Glossary

Actinides are chemical elements with atomic numbers 89 to 103 (actinium through to lawrencium). Of significance, all actinides are radioactive and undergo radioactive decay. Actinides are important in nuclear engineering because the primary fissile materials used in nuclear fuel are in this group.

Breeding refers to the ability of a nuclear reactor system to generate new fissile material through neutron absorption in fertile material.

A **closed fuel cycle** is described in nuclear engineering as one in which the fuel is or recycled usually after removal of undesirable nuclides (e.g., fission products and possibly some actinides) produced during prior fuel irradiation.

A **closed-cycle gas turbine** refers to a closed thermodynamic system that both heats and cools the working fluid through heat exchange to external fluids. Other working fluids other than air can then be used, such as helium, nitrogen, argon or carbon dioxide.

Coefficient of reactivity in nuclear engineering refers to a numerical method of measuring the effect of particular physical phenomena on the tendency of a nuclear reactor system to either increase or decrease in reactivity or power level. 'Net reactivity' is the sum of all contributions to reactivity (coefficients), both positive and negative. Two of the major coefficients are as follows:

- **Void (coefficient of reactivity)** refers to the effect of removal of coolant from the reactor core, e.g., through loss of coolant events or bubble formation, that changes moderation of neutron energies and therefore overall reactivity.
- **Thermal (coefficient of reactivity)** refers to the effect of temperature shifts on nuclear reactivity, and is primarily affected by Doppler broadening and thermal expansion of materials.

Containment is defined in nuclear engineering as the structure(s) that contains the reactor vessel with the purpose of preventing escape of radiological contaminants from those systems into the external environment under normal and extraordinary circumstances.

Power conversion efficiency refers to the percentage of thermal energy practically converted to electricity.

The **conversion ratio** is a performance metric for a nuclear reactor. It refers to the net number of fissile nuclei created per fissile nuclei consumed. When the conversion ratio is equal to 1, this is known as “breakeven”. When the conversion ratio exceeds 1, it is commonly referred to as the “breeding ratio”.

The **coolant** is the fluid that transports thermal energy from the fuel in the reactor to an external heat exchanger. In most nuclear systems, the coolant enters the reactor core to directly cool the solid-fuel elements; in a fluid-fueled reactor, the coolant is heated outside the core.

Core power density refers to the thermal power generated in a nuclear reactor core per unit volume.

Criticality is defined as a state in which each fission event leads to exactly one more fission event, with this situation continuing indefinitely.

Decay heating is produced by the decay of radioactive elements. Generally the fission products are the source of the majority of the decay heating, and beta and gamma radiation are responsible for nearly all of this energy release.

Fertile material is defined as material that will rapidly decay to a fissile material following the absorption of a neutron. All natural thorium and nearly all natural uranium isotopes are fertile.

Fissile material is defined as material that will undergo nuclear fission after absorbing a thermal neutron. Uranium-233, uranium-235, and plutonium-239 are the most common fissile materials. An important distinction is that fissile material is not the same as fissionable material, such as uranium-238, since many nuclides can be induced to undergo fission when struck by high-energy neutrons, albeit with low probability.

Fission products are the two or more remaining products of the nuclear fission reaction. They inherit the neutron-proton ratio of their parent material, which is too neutron-rich for their mass. They typically undergo several beta decay events before reaching nuclear stability, generating decay heating.

Flibe (also referred to as "FLiBe") is the common name of a molten salt mixture that comprises lithium fluoride and beryllium fluoride.

Fuel assemblies refer to traditional "rod" configuration nuclear reactor fuel elements arranged in "bundles" or "assemblies" that are several meters in length to be loaded into solid fuel reactor cores.

A **fuel carrier**, in the context of fluid or liquid fuels, is the medium in which the fuel material is dissolved in.

The **half-life** is the amount of time required for half of the nuclei of a radioactive material to undergo decay. Half-life is typically converted into a decay constant for nuclear calculations, which is the natural logarithm of two divided by the half-life. If the half-life is infinite, the decay constant is zero and the material is stable.

Hastelloy-N alloy is a nickel-base alloy that was developed at Oak Ridge National Laboratories and tested as a structural material for molten fluoride salts. It exhibits good oxidation resistance to hot fluoride salts at temperatures below 700 C.

The **intermediate heat exchanger** (IHX), also referred to as the **gas heater**, transfers thermal energy from the intermediate system salt to the PCS.

A **Liquid Fluoride Reactor** (LiFR) is the base reactor type that uses molten fluoride salts as the coolant and fuel carrier. LiFRs that breed using thorium as fuel are known as LFTRs, and those that use low-enrichment-uranium are known as LFLEURs (Liquid Fluoride LEU Reactors).

A **Loss-of-Coolant-Accident** (LOCA) refers to a specific mode of failure in a nuclear reactor wherein the capacity of the primary coolant to remove thermal energy from the core and/or fuel elements is partially or totally impaired, either due to physical loss of the coolant medium or stoppage of the coolant flow.

A **neutron moderator** is defined in nuclear engineering as a material that serves to reduce neutron energy through non-absorptive collisions.

Neutron absorption is when a neutron strikes and is absorbed by the nucleus of an atom.

Neutron energy, also called neutron temperature, is the measure of a free neutron's kinetic energy and is usually given in electron volts.

A **power conversion system** (PCS) converts thermal power into electrical power (typically by first converting it to mechanical shaft power) and also waste thermal power (often called "waste heat"). Steam turbines and gas turbines are common PCSs.

The **primary heat exchanger** (PHX) transfers thermal energy from the working fluid of the primary system to the intermediate loop salt.

A **sub-critical** nuclear system describes a configuration in which a fission event leads to less than one additional fission event.

A **super-critical** nuclear system describes a configuration in which a fission event leads to more than one additional fission events.

A **super-critical fluid** is the state of a substance at a temperature and pressure above its critical point and distinct liquid and gas phases do not exist, possessing properties of both but also gaining often substantially different properties.

Thermal expansion is the physical phenomenon where materials expand as temperature increases. In a nuclear reactor core, thermal expansion tends to displace the fuel from optimal conditions for the nuclear chain reaction resulting in a tendency of the core power level to decrease as temperature increases. This effect is significantly more pronounced in liquids than in solids.

Transuranic elements refer to chemical elements with atomic numbers greater than 92 (uranium). In the context of nuclear waste, transuranics are viewed as problematic elements to some if present in waste because they are long-lived and retain significant radiotoxicity.

The **working fluid** in a nuclear system refers to the medium of transport of thermal energy in a PCS (see power conversion system) and is normally separate and distinct from the primary (or secondary, if present) coolant unless the system is a direct cycle PCS.

3.1.5 LFTR SDD Acronyms

IHX	Intermediate Heat Exchanger
LFLEUR	Liquid Fluoride Low Enriched Uranium Reactor
LFTR	Liquid Fluoride Thorium Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
MW	Megawatt
ORNL	Oak Ridge National Laboratory
PCS	Power Conversion System
LiFR	Liquid Fluoride Reactor
PHX	Primary Heat Exchanger
SDD	System Design Description

3.2 General Overview

3.2.1 System Functions/Safety Significance

The LFTR system must perform several functions in order to accomplish its intended purpose of energy generation.

1. It must generate substantial thermal power by maintaining a critical nuclear configuration at an appropriately high temperature and neutron flux.
2. It must compensate for the consumption of fissile material within the fuel salt by generating the precursors of new fissile material within the blanket salt, and then by chemically removing, decaying, and transferring that fissile material to the fuel salt.
3. It must transfer its thermal power to a molten-salt coolant and then to the gaseous working fluid that will be used in a closed-cycle gas turbine.
4. It must retain radioactive fission product noble gases for a sufficient duration to allow nearly all of them to decay to non-volatile forms.

3.2.1.1 Reactor Vessel System

The reactor vessel functions to hold fuel salt, blanket salt, and moderator material together in such a way so as to maintain a critical configuration at the temperatures and thermal power levels required for effective electrical power generation. In addition, it incorporates reactivity control mechanisms, both active and passive. Because fuel and blanket salts are meant to be kept separate from one another, the reactor vessel incorporates two plenums integrated into a single structure that marshal fuel salts into the appropriate channels and receive fuel salt from these channels after it has been heated.

The reactor vessel implements numerous safety functions. It houses a large amount of graphite moderator material. In many accident events, a freeze valve, which is grouped with the primary loop system, melts and allows fuel salt to drain from the primary loop and the reactor vessel as well. The retention of the solid graphite moderator in the reactor vessel helps to ensure that the separation of fuel salt from moderator results in a subcritical configuration.

The reactor vessel accommodates passive and active control rod systems that also have important safety functions. The blanket salt held within the reactor vessel is a strong neutron absorber, and a blanket salt leak from the reactor vessel could lead to the reduction in the blanket salt inventory contained in the reactor vessel, increasing reactivity by removing a neutron-absorbing medium. To compensate for this introduction of positive reactivity, a series of control rods that float in the blanket salt and are thus held outside of the core could be used. An accidental drain of the blanket salt would remove the buoyancy effect of these rods, allowing them to slide down into the core and add negative reactivity to replace and overcome the negative reactivity lost from by the drain of the blanket fluid, for whatever reason. These rods would be designed to enter the core passively, without any operator action, in the event of blanket loss. But it is anticipated that there would also be an active drive system present that could drive these rods into the core intentionally in order to have a shutdown effect on the reactor. It would not be possible to start the reactor unless these rods were fully withdrawn from the core due to their strong negative reactivity.

An active set of control rods, of a more conventional design, would also be present in the reactor vessel and would serve a safety function, allowing the operator to control the reactivity level of the reactor. These rods, which would comprise a smaller and less potent source of negative reactivity, would be clustered near the center of the core and provide finer control over reactivity levels. Another possibility for these rods would be to replace them with a pneumatic system that hold blanket salt down through gas pressure in a central channel. Through control of gas pressure, the level of blanket salt in these channels might also be controlled. This alternate approach may be able to accomplish the same effect and would have the advantage of being able to "fail open" by releasing gas pressure, allowing blanket salt level to rise in these channels, and thus introducing the desired negative reactivity.

The reactor vessel shall be constructed from a material that is suitable for accomplishing its functions at the anticipated temperatures, stresses, and neutron fluxes that will exist during operation. Current evidence points to a modified form of Hastelloy-N as the suitable construction material.

The internal graphite structures of the reactor vessel also have the important safety function of being able to be replaced on a time scale less than that required for the vessel itself. This is because the internal graphite structures will be subjected to a fast and thermal neutron flux that is greatly in excess of that which will be experienced by the metallic reactor vessel itself, and the replacement of these graphite structures will enable the reactor vessel to continue to operate and serve its function.

At present, it is anticipated that the reactor vessel will incorporate a small heat exchanger exclusively meant for cooling the blanket salt, with the blanket salt flowing throughout the core under the driving force of natural circulation. This heat exchanger has an important safety function in that it cools blanket salt which contains short-lived thorium-233, a significant heating term in the fluid that cannot be chemically removed. If the reactor shut down or if blanket salt chemical processing was terminated for any reason, the reactor vessel would also have to accommodate the heating generated by protactinium decay, but thorium-233 decay would end relatively quickly in this case, since thorium-233 only has a 22-minute half-life.

The integrity of the reactor vessel plays an important role in minimizing radiation hazards by confining radioactive fluids to the flow channels and volumes defined by the vessel and its internal structures.

3.2.1.2 Primary Loop

The function of the primary loop (see Figure 3-1) is to direct fuel salt through the primary heat exchanger (PHX) in normal operation, where the fuel salt heats the coolant salt (and is in turn cooled by it) sufficiently for the coolant salt to accomplish its primary function. The primary pump provides the necessary pressure head in the primary loop in order to overcome the pressure losses in the PHX and in the reactor vessel.

The primary loop system begins and ends with its connection to the reactor vessel and includes the primary pump, the PHX, the bubble injection system, and the fuel salt drain tank and its associated external cooling system.

An important safety function is embedded in the primary loop and is activated when the reactor overheats or loses its coolant flow. A freeze valve is integrated into the primary loop that is maintained frozen by an active coolant system. When this coolant is lost or if the temperature of the system exceeds its cooling capability, the freeze valve fails open and the fuel salt drains out of the primary loop and out of the reactor vessel into the fuel salt drain tank.

The fuel salt drain tank is integrated with a separate cooling system that is passively connected to the outside environment, and provides the necessary cooling for the fuel salt within it.

3.2.1.3 Intermediate Loop

The function of the intermediate loop is to isolate the PCS from the primary loop. This is an important safety function because the PCS operates at high pressure and the potential for a failure exists in the gas heater, which would transmit high pressure back through the coolant salt to the primary loop. The primary loop is not designed to handle high pressures and this would lead to the introduction of energy into the system that could cause component rupture and potentially disperse radioactivity into the containment. The intermediate loop exists to communicate thermal energy from the primary loop to the PCS while isolating the high pressures of the PCS from the primary loop using the pressure relief valves.

The intermediate loop system begins and ends on the PHX and includes the coolant salt pump, the salt side of the gas heater (or intermediate heat exchanger, IHX), the coolant salt drain tanks, and the pressure relief (blowout) valves. Since the coolant salt does not contain any significant amounts of radionuclides, a separate cooling system is not required for the coolant salt drain tanks. The intermediate loop interfaces with the primary loop through the PHX and with the PCS through the gas heater.

In the event of a failure in the gas heater and the pressurization of the intermediate loop, the pressure relief valves allow coolant salt to leave the loop, and the design must accommodate for this event. This deprives the primary loop of cooling capability and will lead the melting of the freeze valve in the primary loop and the drain of the primary loop fluid contents into the fuel salt drain tank.

Pumping pressure to overcome pressure losses in the primary and intermediate heat exchangers is provided by the coolant salt pump.

The intermediate loop also serves another practical purpose. Since cooling fuel salt with a coolant salt is more compact and effective than cooling fuel salt directly with a gas, the PHX is much smaller and operates at low pressures. It also reduces the fuel salt inventory of the primary loop which reduces the amount of fissile material needed for a given power rating.

3.2.1.4 Power Conversion System

The function of the PCS is to convert the maximum amount of enthalpy contained in the heated working fluid into shaft work and to reject the remaining enthalpy to the environment in an acceptable manner. The PCS includes four heat exchangers: the gas side of the gas heater, the gas cooler, and the high-temperature and low-temperature recuperators. It also includes rotating machinery: the main turbine, the main compressor, the recompressor, and the electrical generator. The PCS interfaces with the intermediate loop through the gas heater, and interfaces with the external cooling system through the gas cooler. It also includes a tritium removal system, likely consisting of a bed of copper oxide, to capture any tritium in the working fluid.

The PCS has several safety-related functions, but its most important function is to act as a barrier for the release of radioactive tritium to the environment. This function strongly guides the choice of working fluids and the architecture of the system itself. Because of the importance of capturing tritium, working fluids that contain hydrogen are undesirable, and this leads to the choice of carbon dioxide as the working fluid and a closed-cycle gas turbine as the overall system architecture.

Another safety-related function of the PCS is to transmit the electrical loads of the external grid back to the power production capability of the reactor. It is desirable for this communication to be smooth and straightforward and amenable to control and response. Neither too much nor too little time lag is desirable. This is another aspect where the proposed architecture could have advantages over current approaches.

3.2.1.5 External Cooling System

The function of the external cooling system is to reject the enthalpy that was not converted to shaft power in the PCS to the environment in an acceptable manner.

The external cooling system shall be designed so as to prevent the transmission of radionuclides to the outside environment, since the external cooling system is the most direct interface with that environment and the only system intentionally designed for dispersal of an altered fluid (heated air or water). The external cooling system will comprise one of the largest and most physically obvious components of the entire system to an outside observer, since its success relies on a large interface area with external air or water.

Although not strictly an engineering or safety-related function, consideration of the aesthetic appearance of the external cooling system is recommended to support integration into the local environment and community in keeping with a “good neighbor” philosophy.

3.2.1.6 Chemical Processing System

The main function of the chemical processing system is to remove uranium and protactinium from the blanket salt and to return uranium to the fuel salt. Its secondary function is to remove fission products from the fuel salt and to further process them into acceptable forms.

The safety-related functions of the chemical processing system mainly involve the safe handling of highly radioactive materials as they move from one fluid stream to another. Drain tanks and cooling systems must be provided for each reaction vessel at each stage of processing through the system. Gaseous fluorine and hydrogen are also produced and utilized in the chemical processing system. Since they are highly chemically reactive, considering the limited inventories of either reactant reduce the safety risk in the chemical processing. Ideally, gaseous fluorine and hydrogen are created just as they are needed from an electrolytic cell using anhydrous hydrogen fluoride as the feed.

Various fission products disperse into the fluid streams of the chemical processing system and some must be handled differently than others. A class of fission products including selenium and tellurium will migrate with gaseous hydrogen and hydrogen fluoride and are handled in a potassium hydroxide neutralization system. Other fission products are removed from the fuel salt in a reductive extraction column and will exist in a metallic state in bismuth. The high chemical potential of a metal form means that these fission products will need to be oxidized and placed in a disposal form before shipment from the site. The small amounts of material produced means that these disposal plans will not constitute a major issue with reactor operations.

It is envisioned that the chemical processing system will operate with human supervision but not with human actuation, but there will be times when operators will need to interface with the system using remote manipulators. Maintenance of reaction vessels and piping will also be an issue that will have safety-related implications since the system will be highly radioactive and have high operating temperatures. Substantial development work will be needed to prepare for long-term operation of the chemical processing system.

3.2.1.7 Off-gas Handling System

The function of the off-gas handling system is to provide a sufficient holdup volume for xenon and krypton generated in the fission reaction, allowing all of their radionuclides to decay to other forms with the exception of krypton-85, which has a 10-year half-life.

Xenon and krypton (and to some degree tritium) are the most mobile radioactive elements in the reactor system. Tritium is subject to chemical reactions but xenon and krypton are not. Fortunately, with the exception of krypton-85, all Kr and Xe radionuclides are short-lived and a holdup of roughly thirty days is sufficient to allow them to decay to more manageable non-gaseous daughters, i.e., cesium, rubidium, strontium, and barium.

The off-gas handling system utilizes the fuel salt decay tank as a primary storage volume, allowing the initial and most intense stages of decay to take place there. The passive cooling system of the fuel salt decay tank is utilized to cool the noble gases, providing a continuous test of the efficacy of this crucial subsystem. After initial cooling in the decay tank, gaseous xenon and krypton in a stream of helium pass into a long piping arrangement filled with charcoal (that adsorbs these gases) and cooled by water that provides sufficient holdup volume over time.

After all radioisotopes of xenon have decayed away, the remaining gas stream is cryogenically cooled to separate stable xenon from helium and krypton. Xenon is bottled and could be sold at this stage. Krypton is also bottled and stored because of the continuing slow decay of krypton-85. Helium is recycled and returned to the gas handling system.

3.3 System Classification

The LFTR system described in this document is classified as a safety-significant system.

3.3.1 Basic Operational Overview

Within the reactor vessel, a critical configuration of fuel salt, graphite moderator, and blanket salt is maintained so as to permit fission reactions to take place in sufficient numbers to generate the thermal power desired. Each fission reaction causes a fissile nuclide (usually uranium-233) to split into two or more fission products, each of which has significant kinetic energy, as well as two to three neutrons. The fission of the uranium also releases four fluoride ions into the fuel salt. The two fission products slow down rapidly and pick up the fluoride ions to the appropriate valence. This slowing-down of fission products deposits thermal energy in the fuel salt, heating it incrementally. The neutrons are born with a great deal of kinetic energy and lose most of it in the graphite moderator in non-absorptive collisions with the carbon nuclei. One of the neutrons continues the chain reaction by causing another fission event while the remainder are available for absorption[27] by fertile thorium-232 nuclei in the blanket salt, producing protactinium-233. Once formed, protactinium-233 decays with a 27 day half-life into fissile uranium-233.

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[27] I.e., the neutrons that are not otherwise lost due absorption in the fuel salt and other reactor components and leakage from the reactor.

As shown in the numbered flow streams in Figure 3-1, the heated fuel salt (1) passes outside of the reactor vessel, where the critical configuration is no longer maintained, and fission activity very rapidly drops to zero. The fuel salt is hot but no longer being heated by fission (although there is some heating from the decay of fission products). Xenon and krypton fission product gases are sparingly soluble in the salt, and helium bubbles are injected into the fuel salt in order to provide surface area and volume into which these gases can be collected. The fuel salt enters the primary pump where its pressure is increased through mechanical pumping action. After leaving the primary pump, some of the fuel salt (2) is diverted for removal of the gaseous bubbles but most flows into the PHX, where the fuel salt is cooled counter-currently by the coolant salt. The cooled fuel salt (3) leaves the PHX and returns to the reactor vessel, where the critical geometry of fuel, graphite, and blanket allows the fission reactions to begin again and the fuel to be heated once more. Each passage through the reactor vessel homogenizes the composition of the fuel salt, achieving through design the long-sought-after goal of solid-fueled reactor designers: a uniform consumption rate of fissile material.

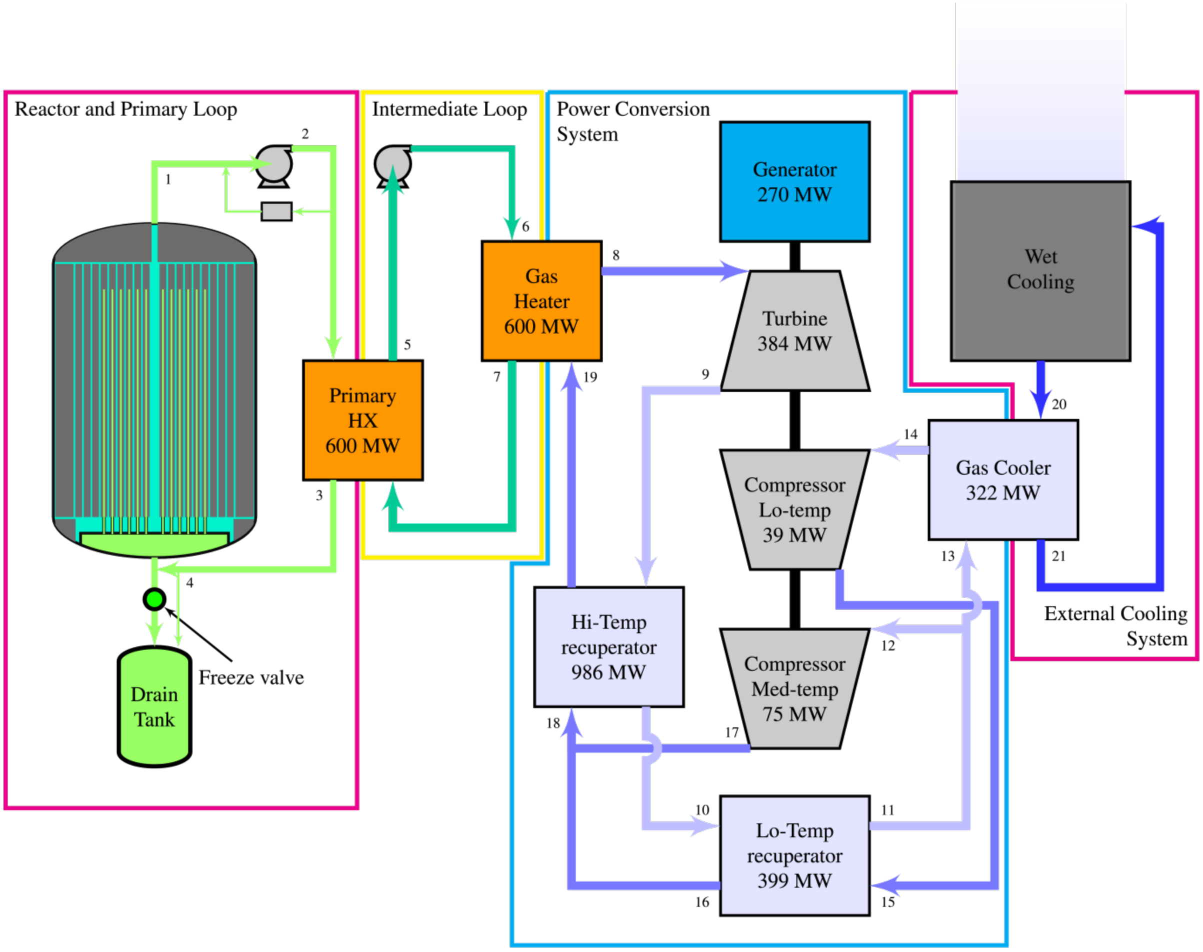

Figure 3-1
Reactor and primary loop, intermediate loop, power conversion system, and external cooling system simplified flow diagram [Flibe Energy 2015].

The coolant salt (5), having been heated by the fuel salt in the PHX, passes outside of the containment boundary and enters the coolant salt pump, where a rotating impeller increases its pressure sufficiently to overcome pressure drops in the intermediate loop. Leaving the pump, the cooling salt (6) enters the gas heater (IHX) where the coolant heats the gaseous working fluid of the PCS. Outside of the gas heater, it (7) flows past blowout valves in the intermediate loop, which exist to relieve a pressure transient that would develop if the gas piping in the gas heater were to fail, and returns into the containment structure. Inside the containment, the coolant salt flows into the PHX to cool the fuel salt.

The gaseous working fluid (supercritical carbon dioxide) of the PCS leaves the gas heater (8) at its maximum temperature and enters the main turbine, where it drives the turbine in a nearly isentropic manner, losing enthalpy and generating shaft work from the turbine. Most of that shaft work is used to drive the electrical generator, producing three-phase alternating current electricity for distribution to the electrical grid. The remaining shaft work drives the main compressor and the recompressor. The carbon dioxide leaving the main turbine (9) enters the low-pressure side of the high-temperature recuperator and is cooled by counter-current flow with the high-pressure carbon dioxide (18) on the other side of the recuperator. The entire stream (10) of gas leaving the low-pressure side of the high-temperature recuperator enters the low-pressure side of the low-temperature recuperator, and is further cooled by counter-current flow with the high-pressure carbon dioxide (15) on the other side of the recuperator.

At the exit of the low-temperature recuperator, the working fluid flow (11) splits into two streams (12) and (13). Flow (12) is directed into the recompressor. Shaft work from the turbine drives the recompressor and pressurizes the carbon dioxide in a nearly isentropic manner (17) back to the pressures typical of the high-pressure side (200 bar). The other split stream (13), at the exit of the low-temperature recuperator, passes into the gas cooler, where it is cooled by counter-current flow with cooling water (20) on the other side of the gas cooler. The cooled working fluid flow (14), now at the lowest temperature of the entire cycle, enters the main compressor. Shaft work from the turbine drives the main compressor and pressurizes the carbon dioxide in a nearly isentropic manner back to the pressures typical of the high-pressure side (200 bar).

The gas leaving the main compressor (15) is only a portion of the total flow, but it enters the high-pressure side of the low-temperature recuperator and is heated by counter-current flow with the low-pressure carbon dioxide (10) on the other side of the recuperator. At the exit of the low-temperature recuperator, the gas stream (16) is joined by the gas stream leaving the recompressor (17) and the full gas flow (18) enters the high-pressure side of the high-temperature recuperator. The full flow is heated by counter-current flow with the low-pressure carbon dioxide (9) on the other side of the recuperator. At the exit of the high-temperature recuperator, the entire flow (19) enters the gas heater and is heated to its maximum temperature by counter-current flow with the coolant salt on the other side of the gas heater, and the cycle continues.

In the external cooling system, cooling water enters the gas cooler and is heated by the lower-pressure carbon dioxide stream, exiting (21) at an elevated temperature. It passes through a set of evaporative cooling towers and is cooled (20) back to the conditions needed for the inlet of the gas cooler.

Table 3-1
LFTR power conversion system mass balance [Flibe Energy, 2015].

Description	Fluid	Temp (°C)	Press (bar)	Density (kg/m^3)	Flow Rates Mass (kg/s)	Flow Rates Volume (m^3/s)
1. Reactor outlet / fuel pump inlet	FLiBeU	653.3	1.62	1952.1	1699.9	0.871
2. Fuel pump outlet / PHX fuel inlet	FLiBeU	653.3	11.07	1952.1	1699.9	0.871
3. PHX fuel outlet / reactor inlet	FLiBeU	500.0	4.45	2005.1	1699.9	0.848
4. Bleed flow to drain tank	FLiBeU	500.0	tbd	2005.1	tbd	tbd
5. PHX coolant outlet / coolant pump inlet	LiF-BeF2	633.3	8.60	1933.7	1629.1	0.842
6. Coolant pump outlet / IHX coolant inlet	LiF-BeF2	633.3	19.00	1933.7	1629.1	0.842
7. IHX coolant outlet / PHX coolant inlet	LiF-BeF2	479.9	15.00	1984.5	1629.1	0.821
8. IHX outlet / turbine inlet	CO_2	550.0	198.28	123.4	3176.3	25.746
9. Turbine outlet / HTR lo-press inlet	CO_2	440.3	79.01	58.5	3176.3	54.296
10. HTR lo-press outlet / LTR lo-press inlet	CO_2	168.3	78.14	103.3	3176.3	30.758
11. LTR lo-press outlet	CO_2	69.6	77.05	164.9	3176.3	19.264
12. Recompressor inlet	CO_2	69.6	77.05	164.9	1302.3	7.898
13. Gas cooler inlet	CO_2	69.6	77.05	164.9	1874.0	11.366
14. Gas cooler outlet / main compressor inlet	CO_2	32.0	76.92	599.5	1874.0	3.126
15. Main compressor outlet / LTR hi-press inlet	CO_2	61.1	200.00	716.7	1874.0	2.615
16. LTR hi-press outlet	CO_2	158.0	199.89	312.7	1874.0	5.993
17. Recompressor outlet	CO_2	158.0	199.89	312.7	1302.3	4.164
18. HTR hi-press inlet	CO_2	158.0	199.89	312.7	3176.3	10.157
19. HTR hi-press outlet / IHX inlet	CO_2	396.5	199.58	157.0	3176.3	20.232
20. External coolant inlet	H2O	27.0	1.00	996.5	2050.2	2.057
21. External coolant outlet	H2O	64.6	1.00	980.8	2050.2	2.090

[a] State points 8-19 based on Dostal, "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors," MIT-ANP-TR-100, March 10, 2004, page 228.

The numbered flow streams in Figure 3-2 illustrate the processing of blanket, decay, and fuel salt mixtures. The process begins in the reactor when thorium in the blanket salt absorbs neutrons and rapidly decays to protactinium. A stream of blanket salt (31) is removed from the reactor vessel and routed to a reaction column employing the reductive extraction technique. In this vessel, the blanket salt is contacted with a metallic stream of bismuth (35) containing dissolved lithium and thorium metal. The concentration of lithium is chosen so that there is no net transfer of material between the blanket and the bismuth, but the metallic thorium reduces any protactinium or uranium present in the blanket from a tetrafluoride salt to a metal. The metallic thorium in turn is oxidized to a tetrafluoride state. In effect, thorium metal trades places with protactinium and uranium in the blanket salt and thus protactinium and uranium are removed from the blanket and enter the bismuth stream. With protactinium and uranium removed, the "clean" blanket fluid (32) returns to the reactor.

The bismuth stream (33) enters another reductive extraction column where it contacts decay salt (39), and then into an electrolytic cell (34) where the metallic constituents in the blanket (lithium, thorium, protactinium, and uranium) are all oxidized to their fluoride states and enter into the decay salt stream (36). In another section of the electrolytic cell, decay salt free of protactinium or uranium (40) is electrolytically reduced to generate metallic reductants for the bismuth (35) that is used in the reductive extraction columns.

The decay salt stream is held up in a decay tank, giving protactinium more time to decay to uranium. After sufficient decay time, decay salt (37) is fluorinated with fluorine gas (42), which removes any uranium present as gaseous uranium hexafluoride (43). The remaining decay salt circulates throughout the loop (38, 39). The uranium hexafluoride produced from the decay salt (43) is routed to a hydrogen reduction column and will be combined with another stream (47) of uranium hexafluoride to "refuel" the fuel salt.

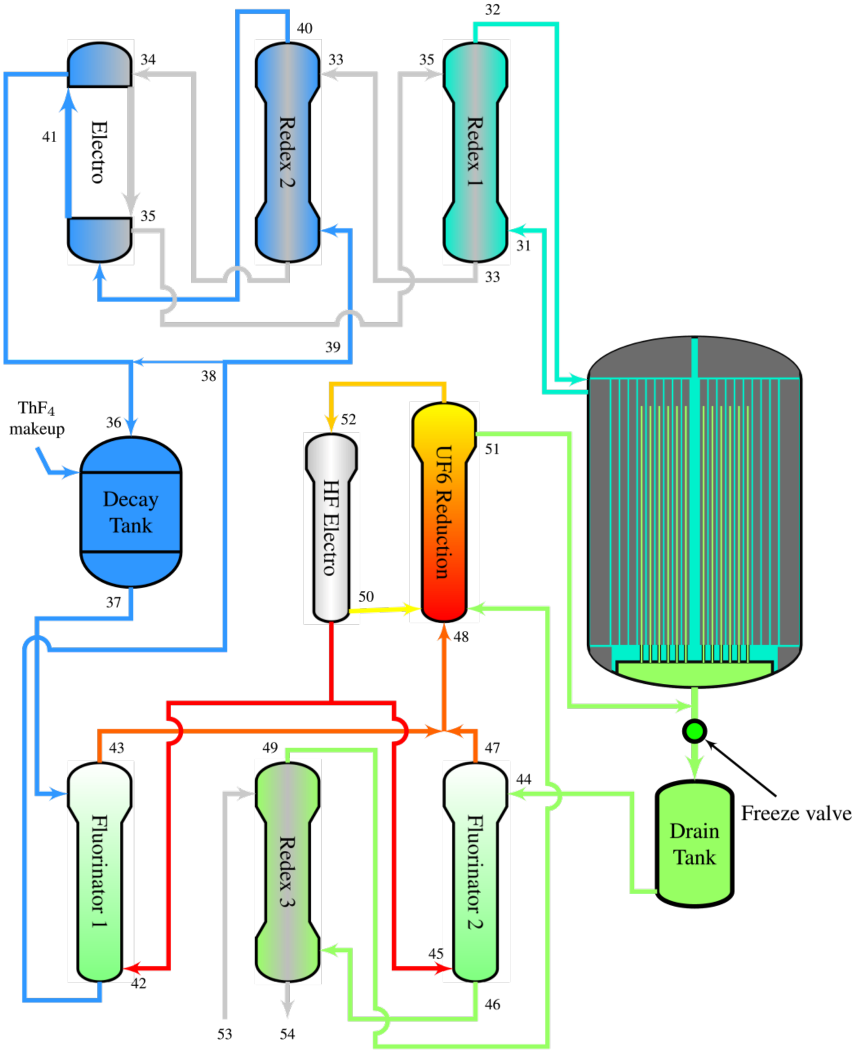

Figure 3-2
Reactor and chemical processing system simplified flow diagram [Flibe Energy 2015].

The fuel salt is processed in a simpler manner. A stream of fuel salt is removed from the reactor and held up for a time in the fuel salt decay tank to allow the most intense stages of fission product decay to take place. The stream of fuel salt (44) is then fluorinated to remove uranium as gaseous uranium hexafluoride (47). The fuel salt (46) then flows through a reductive extraction column using metallic lithium dissolved in bismuth (53) as a reductant. Fission products are reduced to metal and enter the bismuth (54) and are replaced in the fuel salt by lithium fluoride. The fuel salt (49) is then routed to the hydrogen reduction column, where it is contacted by gaseous hydrogen (50) and the two combined streams (48) of gaseous uranium hexafluoride (one from the decay salt, the other from the fuel salt). In the hydrogen reduction column, hydrogen reacts with uranium hexafluoride in the presence of fuel salt, causing it to reduce to uranium tetrafluoride, which is soluble. Gaseous hydrogen fluoride and unreacted hydrogen (52) leave the hydrogen reduction column, as well as "refueled" fuel salt (51), which returns to the reactor.

Table 3-2
LFTR chemical processing system mass balance [Flibe Energy, 2015].

					Flow Rates			Concentrations			
idx	Fluid	Temp (°C)	Press (bar)	Density (kg/m^3)	mass (g/s)	molar (mol/s)	volume (cc/s)	Li (ppm)	Th (ppm)	Pa (ppm)	U (ppm)
31.	HDLiF-BeF2-ThF4	600.0	1.0	4475.6	378.27	3.6876	84.519	71.0%	27.0%	15.0	1.9
32.	HDLiF-BeF2-ThF4	605.0	1.0	4471.7	378.27	3.6876	84.593	71.0%	27.0%	5.8	0.7
33.	Bismuth	640.0	1.0	9585.7	24.305	0.1163	2.5356	3689.	2670.	293.4	36.7
34.	Bismuth	640.0	1.0	9585.7	24.305	0.1163	2.5356	3689.	2657.	306.2	36.8
35.	Bismuth	640.0	1.0	9585.7	24.305	0.1163	2.5356	3689.	3000.	0.5	-
36.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4680.9	0.4104	0.0040	0.0877	67.9%	29.1%	8901.	1068.
37.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4684.4	0.4104	0.0040	0.0876	67.9%	29.1%	382.3	9587.
38.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4520.2	0.0	0.0	0.0	-	-	-	-
39.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4644.6	0.4064	0.0040	0.0875	68.6%	29.4%	386.0	2.2
40.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4644.6	0.4064	0.0040	0.0875	68.6%	29.4%	14.5	-
41.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4520.2	0.3306	0.0032	0.0731	71.0%	-	0.0	-
42.	F$_2$	550.0	2.0	1.1095	0.0022	0.0001	1.9701	-	-	-	-
43.	UF$_6$-F$_2$	550.0	2.0	7.1289	0.0140	0.0001	0.0140	-	-	-	66.7%
44.	HDLiF-BeF2-UF4	550.0	1.0	1987.8	0.8328	0.0251	0.4189	68.5%	-	-	2000.
45.	F$_2$	550.0	2.0	1.1095	0.0029	0.0001	2.5810	-	-	-	-
46.	LiF-BeF2-(FP)Fx	550.0	1.0	1987.8	0.8327	0.0251	0.4189	68.5%	-	-	2.2
47.	UF$_6$-F$_2$	550.0	2.0	7.1237	0.0184	0.0001	0.0184	-	-	-	66.6%
48.	UF$_6$-F$_2$	550.0	2.0	7.1237	0.0324	0.0001	4.5472	-	-	-	66.6%
49.	LiF-BeF2 (68.5-31.5)	600.0	1.0	1987.8	0.8327	0.0251	0.4189	68.5%	-	-	-
50.	H$_2$	550.0	2.0	0.0589	0.0004	0.0002	6.7703	-	-	-	-
51.	HDLiF-BeF2-UF4	600.0	1.0	1970.5	0.8327	0.0251	0.4226	68.5%	-	-	3518.
52.	HF-H$_2$	550.0	2.0	1.1461	0.0130	0.0003	0.0130	-	-	-	-
53.	Bismuth	640.0	1.0	9585.7	0.0321	0.0002	0.0034	-	-	-	-
54.	Bismuth	640.0	1.0	9585.7	0.0321	0.0002	0.0034	-	-	-	-

[a] Maximum protactinium concentration in blanket is 135.0 ppm (no Pa removal).
[b] Minimum protactinium concentration in blanket is 9.7 ppm (complete removal).
[c] 95.71% of protactinium decays to uranium in decay tank.

The stream of bismuth containing fission products (54) will be further processed before disposal of the fission products, but that additional processing has not yet been defined to preserve the option of removing several valuable fission products such as strontium and promethium. The stream of hydrogen fluoride gas (52) from the hydrogen reduction column is purified and refrigerated before being electrolyzed to regenerate the hydrogen gas (50) needed in the reduction column and the fluorine gas needed in the decay salt fluorinator (42) and the fuel salt fluorinator (45).

Helium containing xenon and krypton, called the "off-gas" stream, is routed from the bubble remover to the fuel salt drain tank, giving it an increment of time to undergo the most intense phase of radioactive decay. The off-gas stream then enters a 47-hour holdup loop which consists of a water-cooled pipe filled with activated charcoal. At the exit of the 47-hour holdup loop, most of the gas is returned to the bubble generator but some is directed to a 90-day holdup loop where all radioactive xenon decays to other elements and all radioactive krypton (except krypton-85) decays to stability. The gas stream is cryogenically cooled, separating xenon, krypton, and helium from one another. Xenon is bottled and can be sold, krypton is stored for additional decay, and helium is returned to the bubble generator.

3.4 Requirements and Bases[28]

3.4.1 Requirements

1. **The power system shall produce large amounts of electrical energy in a reliable and controllable manner, while minimizing environmental effluents, particularly carbon dioxide.**

   Basis: developer discussion with utility customers about future needs in light of current and anticipated federal regulations limiting carbon dioxide and other emissions.

2. **The power system shall be designed to maximize safe operation and retention of radionuclides even under severe accident scenarios.**

   Basis: developer discussion with utility customers about desired enhancements with respect to current nuclear reactor technology.

3. **The inventory of fissile material in the reactor shall be minimized.**

   Basis: developer discussion with utility customers the rate at which new electrical generation capacity will need to be added to the generation grid in the late 2020s. Reducing required fuel cycle fissile inventories will accelerate deployment.

4. **Fuel in the power system shall be utilized at the maximum efficiency attainable, thereby minimizing the amount of actinides entering waste streams.**

   Basis: developer discussion with utility customers indicates a strong desire to reduce the production rate of long-lived waste. Since actinides are considered problematic in terms of heat generation, radiotoxicity, and lifetime, an approach that reduces actinide waste to the maximum degree possible is desirable.

5. **The molten-salt reactor shall use a salt mixture that has the best combination of safe performance from a neutronic, thermal-hydraulic, toxicity, and cost basis.**

   Basis: desire to satisfy objectives and reduce costs.

6. **Tritium shall be captured to the maximum degree practical at each stage in the reactor system, with the summation of these capture techniques minimizing tritium release to a degree that is acceptable from a licensing basis.**

   Basis: recognition of multiple tritium formation pathways in desirable salt mixture components.

7. **The working fluid used in the PCS shall not contain hydrogen.**

   Basis: recognition of the challenge of tritium removal from a working fluid containing hydrogen.

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[28] The Requirements and Bases presented here reflect the views and perspective of the technology developer, Flibe Energy; they do not necessarily reflect the views and perspective of EPRI or its contractors.

8. **Xenon and krypton shall be removed from the fuel salt at the maximum degree practical, and shall be held up until all radionuclides of xenon and krypton decay away, except 10-year krypton-85.**

   Basis: xenon-135 is a strong neutron absorber whose presence in solid-fueled reactors complicates their ability to respond to changing electrical loads. Xenon-135 cannot be isolated individually, nor can xenon, generally, hence a requirement to remove all noble gases and hold them for an appropriate duration.

9. **Noble metal fission products shall be removed from the fuel salt to the maximum degree practical and then separated, purified, and dispositioned appropriately.**

   Basis: noble metals are not strongly chemically bound in molten-salts like many other fission products, and their migration and plating in the reactor could pose challenges. Some noble metals may also constitute a valuable revenue stream if they can be separated and purified effectively.

10. **The reactor fueled by thorium shall employ core design arrangements that maximize the production of uranium-232 and its precursors in order to minimize the appeal of any fissile material for diversion away from power production.**

    Basis: the presence of uranium-232 and its gamma-emitting decay products does not compromise the power-generating performance of the reactor but reduces the attractiveness of the isotopic mixture of uranium for diversion to other activities.

11. **Isotopic dilution of thorium-229 (from the decay of uranium-233) shall be avoided to the greatest degree practical.**

    Basis: thorium-229 has economic value if kept undiluted by common thorium-232.

12. **The chemical processing system shall be simplified to the greatest degree possible.**

    Basis: improved probability for successful operation from simplification.

13. **The primary system shall be simplified to the greatest degree possible.**

    Basis: improved probability for successful operation from simplification.

14. **Systems with a fluid that creates negative reactivity in the reactor must have a passive system to compensate for that negative reactivity in the event of a loss of that fluid.**

    Basis: design prudence.

3.4.2 Bases of Design

1. A system based on nuclear fission is proposed to meet requirement #1, since nuclear fission is controllable, reliable, and does not involve carbon combustion.

2. A nuclear reactor using molten fluoride salt mixtures as both the fuel and the coolant is proposed to address requirement #2. Pressurized water, pressurized gas, and liquid metals are not considered as coolants because they operate at high pressures or with chemically reactive fluids. Molten-salt reactors have chemically stable fluids that can operate at high temperatures yet at low pressures. Molten-salt reactors eliminate stored energy terms in the reactor by operating at ambient pressure and with chemically stable fluids. To further improve safety response, a molten-salt reactor shall employ a passively actuated drain system

in its design that permits drainage of the fuel salt into a separate, non-moderated structure at any time during operation. The physical configuration and arrangement of the primary loop shall be designed to conform to this requirement.

3. To address requirement #3 and minimize fissile inventory, the molten-salt reactor will be designed with sufficient moderation material in the core to generate a thermal neutron spectrum. A thermal neutron spectrum increases the probability of the fission of uranium-233, thus requiring less fissile material to achieve the targeted energy release. Graphite is proposed as the material suitable to meet this requirement since it has low neutron absorption, does not require separate cladding material, and does not interact chemically with the salt mixtures. Through the use of a thermal-neutron spectrum, the effectiveness of fuel drain as a safety response is enhanced, since separation of the fuel salt from the moderating material reduces nuclear reactivity.
4. Requirement #4, in conjunction with the requirement for minimum fissile inventory, leads to the selection of thorium as the nuclear fuel rather than uranium. This is because only thorium can be utilized with high efficiency in a thermal-spectrum reactor via breeding; uranium cannot. Only a small fraction of the energy content of uranium can be accessed in a thermal-spectrum reactor. In a fast-spectrum reactor, a far greater percentage of the energy content of uranium can be released, but a fast spectrum reactor has a fissile inventory ten to twenty times higher than a thermal-spectrum reactor. The need for higher fissile inventories runs counter to requirement #3, potentially restricting the deployment rate for future power systems.
5. Requirement #5 is best satisfied through the use of a base salt consisting of lithium fluoride and beryllium fluoride, where the lithium is highly depleted (less than 50 ppm lithium-6) in order to minimize neutron absorption. Although this salt is expensive and toxic, other less expensive alternatives would conflict unacceptably with the requirement to utilize fuel at maximum efficiency since they would be too absorptive of neutrons to permit breeding thorium-232 to uranium-233 in the reactor.
6. Highly-depleted lithium and beryllium still have tritium generation pathways, and tritium can readily diffuse across metallic barriers in the primary and intermediate heat exchangers. It is anticipated that requirement #6 can be satisfied not only through tritium capture at each step but through the use of a closed-cycle gas turbine as the PCS.
7. Requirement #7, in conjunction with the requirement to maximize the retention of radionuclides (requirement #2), precludes the use of a conventional steam turbine PCS, and can be met through the use of carbon dioxide as the working fluid in a closed-cycle gas turbine PCS.
8. Requirement #8 is most likely to be satisfied by the addition of a helium bubbling system through the fuel salt. Xenon and krypton, being sparingly soluble in the salt, will diffuse into the helium bubble and can be processed and removed.
9. A noble metal extraction system is planned for the reactor to help satisfy requirement #9.
10. Through careful arrangement of fuel, blanket, and moderator structures, fast neutrons from fission can be given greater opportunities to generate uranium-232 and its precursors in both the fuel and blanket fluids, satisfying the objective of requirement #10. Intentional

introduction of thorium-230 into the blanket is another option, but this isotope is rare and may be difficult to procure.

11. In a one-fluid reactor, thorium-229 would be utterly lost in the large amount of natural thorium-232 present, and would not be extractable. A two-fluid reactor that keeps thorium-232 out of the fuel salt can satisfy requirement #11. Requirement #10, maximizing uranium-232 production, leads to thorium-228 formation from uranium-232 decay. But this problem can be mitigated by the removal of the actinium, since actinium-225 forms from the decay of thorium-229 but no actinium forms from the decay of thorium-228.
12. Requirement #12, in conjunction with requirement #4, specifies a reactor system where fluoride salt mixtures containing fertile and fissile material are kept separate. By separating the two salt streams, the chemical processing system is simplified, since thorium behaves chemically very much like the lanthanide fission products.
13. Requirement #13, in conjunction requirement #2, #3, and #12, provides a basis for the choice of a reactor core where fuel salt (containing fissile material) is kept separate from blanket salt (containing fertile material) using graphite structures to effect the separation. The precedence of chemical processing simplicity over primary system simplicity leads to the choice of the two-fluid reactor, whereas if the order were reversed the one-fluid reactor might have been chosen. The two-fluid reactor achieves the simplest chemical processing system at the expense of a more challenging primary system design while the one-fluid reactor has a complicated and challenging chemical processing system but a simpler core design and a higher fissile inventory. Both configurations have different but real safety challenges that are unavoidable.
14. Requirement #14 potentially can be satisfied by designing structures in the reactor core that are kept out of the neutronically active region during the time when an absorptive fluid (such as the thorium blanket) are present but slide into the core in the emergency event of a loss of blanket fluid, such as due to damage to the reactor vessel. Floating absorber rods are conceived as a type of solution for this event.

3.4.3 General Requirements

3.4.3.1 System Functional Requirements

1. The reactor vessel must contain the appropriate volumes of fuel salt, blanket salt, and moderator graphite in order to enable a critical configuration. It must maintain criticality across a range of thermal power generation levels, from 0% to 100% of the rated design. It must retain all fluids in operating conditions and reliably drain these fluids to suitable drain tanks in emergency circumstances and shutdown scenarios. It must be able to be drained completely without outside intervention. It must accommodate thermal expansion of internal and external components. It must minimize thermal loss to the surrounding volume.
2. The primary pump must circulate fuel salt by generating the appropriate pressure differential across its rotating structure. It must operate at the high temperatures required by the system.
3. The PHX must transfer the enthalpy generated in the fuel salt in the reactor to the coolant salt while minimizing thermal loss to the surrounding environment. It must maintain its integrity in operating and extraordinary circumstances. It must be constructed of a material that will

retain sufficient integrity over its operational lifetime even under corrosive attack from the fuel and coolant salts, with particular attention to the internal boundary material between the fuel and coolant salts.

4. The fuel salt drain tank must have sufficient volume to receive the entire inventory of fuel salt from the primary loop. It must incorporate sufficient passive cooling capability to accommodate the thermal load of a fuel salt inventory that contains a fresh, equilibrium inventory of fission products. It must maintain its integrity in operational and extraordinary circumstances. It must be located in a position in the overall system that allows it to completely drain all components in the fuel salt loop without resorting to any active systems. It must be capable of being actively drained in order to restore functionality to the reactor system, as it recovers from a drain situation.
5. The helium gas bubbling system must inject a sufficient volume of helium, at a sufficient pressure and flow rate, in order to provide the appropriate volumes and bubble sizes to allow xenon and krypton to diffuse readily to the injected gas. It must also have a system for the removal of bubbles previously injected and the transfer of that gas to the off-gas handling system.
6. The blanket salt chemical processing system must remove protactinium and uranium from the blanket salt at the desired flow rate in order to accommodate performance objectives. The decay tank must possess sufficient volume to enable the volume of decay salt held therein to accommodate performance objectives. The decay salt tank must possess sufficient passive cooling to accommodate the heating generated by the decay process. The decay salt tank must be of a satisfactory geometry to prevent accidental criticality even if the entire protactinium inventory decays to uranium.
7. The fuel salt chemical processing system must remove uranium at very high efficiency to prevent its loss to bismuth in the reductive extraction section of the system. The fuel salt chemical processing system must remove fission products at a rate sufficient to accommodate performance objectives. The fuel salt chemical processing system must prevent the loss of fissile material to the bismuth removal stream. The system must return uranium, in the form of a gaseous hexafluoride, to the fuel salt via hydrogen reduction.
8. The gas heater must heat carbon dioxide using coolant salt to the temperatures needed for the inlet to the gas turbine. The gas heater must accommodate the substantial pressure differential between the gas and the coolant salt under all operational and extraordinary circumstances. The gas heater must minimize the loss of thermal energy to the surrounding volume. It must be constructed of a material that will retain sufficient integrity over its operational lifetime even under corrosive attack from the coolant salt, with particular attention to the internal boundary material between the coolant salt and the high pressure gas.
9. The coolant salt loop must contain pressure relief ("blowout") valves to prevent the transmission of high pressures to the PHX in the event of a failure of the salt/gas interface in the gas heater. The blowout valves must be located at the appropriate position in the coolant salt loop to achieve this goal.
10. The gas turbine must consist of the appropriate turbomachinery to generate shaft work at a high efficiency, on the order of 45%. The seals, bearings, and purge strategies used by the gas turbine must be suitable to prevent the release of tritium to the environment.

11. The high-temperature and low-temperature recuperators in the PCS must transfer enthalpy between gas streams at a high effectiveness in a compact volume. They must maintain appropriate integrity under operational and extraordinary circumstances. They must prevent the release of any tritium in the gas to the environment.
12. The gas cooler must cool the carbon dioxide using a liquid or gaseous external coolant to the temperatures needed for the inlet to the main compressor. The gas cooler must accommodate the substantial pressure differential between the working-fluid gas and the external coolant under all operational and extraordinary circumstances. The gas heater must be constructed of a material that will retain sufficient integrity over its operational lifetime even under corrosive attack from the external coolant, with particular attention to the internal boundary material between the high-pressure gas and the external coolant.

3.4.3.2 Subsystems and Major Components

The requirements definition, and the design basis intended to meet these requirements, lead to the description of the nuclear fission reactor, whose coolant is based on chemically-stable fluoride salts. The fission reactor would utilize a thermal neutron spectrum and thorium as the fertile material and uranium-233 as the primary fissile material. Denaturing the uranium with uranium-238 would lead to substantial transuranic waste production and reduced fuel efficiency and would not be considered.

The reactor vessel would be constructed from a suitable high-nickel alloy such as Hastelloy-N and would include graphite structures to moderate the neutrons and to separate fuel and blanket streams from one another. Thermal power generated in the fuel salt would heat a coolant salt in the PHX, and the coolant salt would exit the containment structure. Outside the containment, the coolant salt would heat the carbon dioxide working fluid of the PCS, which would be configured to generate shaft power. Part of this shaft power would drive the compressors of the PCS, but the remainder would drive an electrical generator which would be tied to the electrical grid.

The carbon dioxide would be cooled in a gas cooler by either air or water, depending on the geographic constraints, and waste heat would be dissipated to the environment.

Helium bubbled through the fuel salt would strip out xenon and krypton, would then be routed to a holdup system which would provide sufficient time for the radioactive xenon and all the radioactive krypton except krypton-85 to decay to non-gaseous nuclides such as cesium and rubidium. Xenon and krypton would be cryogenically separated; krypton would be stored onsite, and xenon would be sold.

The chemical processing system would remove protactinium and uranium from the blanket salt and hold it for sufficient duration in the decay salt to permit protactinium-233 and protactinium-232 to decay to uranium-233 and uranium-232. The uranium would be fluorinated from the decay salt and added to the fuel salt. Fuel salt would be chemically processed to remove fission products via reductive extraction by lithium into bismuth. Further processing of the bismuth is anticipated but not described at present. Thorium-229 would be present in the bismuth in economically attractive quantities.

3.4.3.3 Boundaries and Interfaces

Boundaries define the furthest extents of a given system, while interfaces define how that system interacts with other systems or the outside world. For added explanation, the sub-systems of the overall system are also indicated and their boundaries and interfaces also described. Inputs and outputs across system boundaries are indicated with arrows; "s/u" and "m/u" indicate "start-up" and "make-up", respectively; C, O, U, Pa, Th, etc., are chemical symbols (carbon, oxygen, etc.); and "FP" refers to "Fission Products". The fuel salt and blanket salt consist of $2LiF_2$-BeF_2-XF_4, where "X" is uranium-233 for the fuel and thorium-232 for the blanket.

Figure 3-3 consists of six sub-systems (which will be referred to simply as "systems"), and most of those contain their own sub-systems which are excluded from the figure for simplicity and clarity of presentation. Radioactivity is present in significant amounts in the reactor, blanket, and chemical processing and decay systems (colored orange), while the remaining systems (colored blue) are relatively uncontaminated. Due to the radioactivity of the fuel salt, the intermediate salt loop will also have some radioactivity, though this will be much less than the reactor and other primary system components.

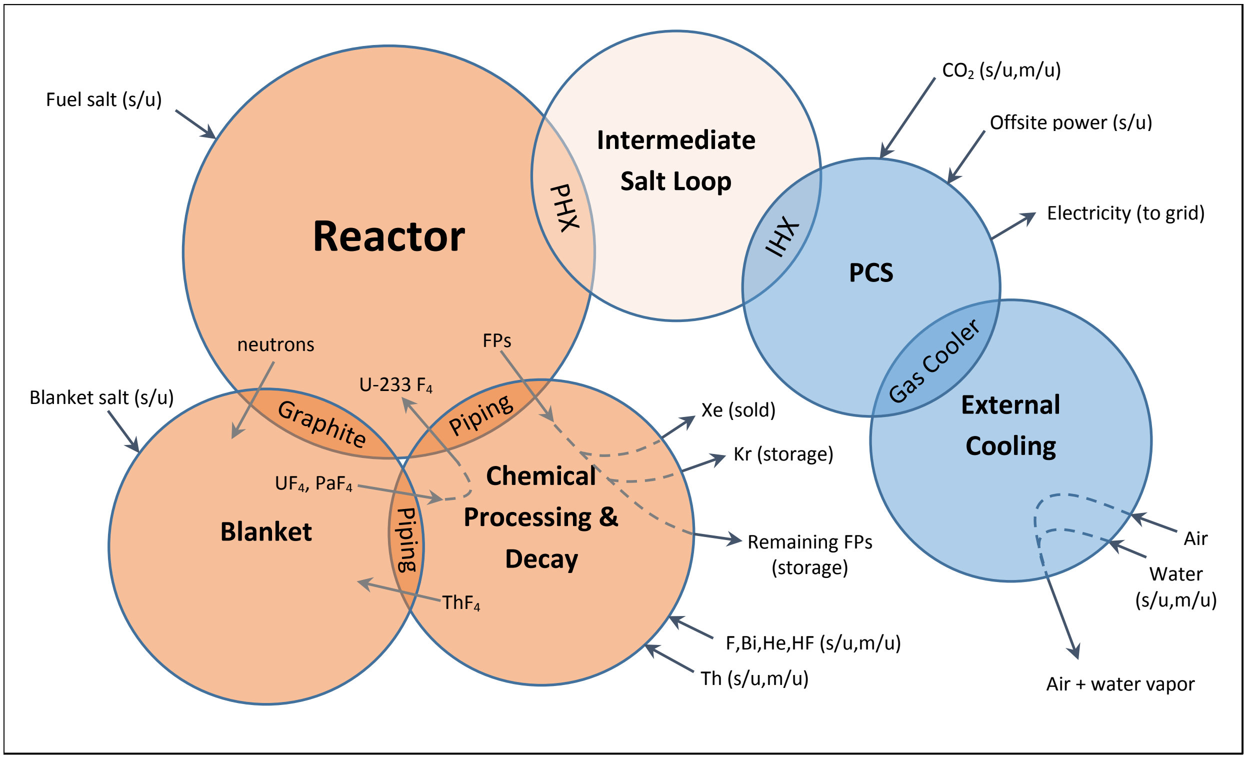

Figure 3-3
LFTR system/sub-system boundaries and interfaces [Flibe Energy, 2015].

Some inputs to the system are only for start-up, such as the initial fuel for the blanket and reactor, CO_2 for the PCS, and start-up power. At steady-state, the main inputs will be thorium make-up for the blanket and air and water as heat sinks for the thermodynamic cycle. The remaining inputs provide make-up for the inevitable losses that characterize real systems (CO_2

loss from the PCS; F, He, Bi, H loss from the chemical processing; etc.). Steady-state outputs are fission products, electricity, and air and water vapor.

3.5 System Description

3.5.1 Description of System, Subsystems, Major Components

3.5.1.1 Reactor Cell

The heart of the overall system is the reactor vessel itself. Inside the reactor vessel, graphite structures separate fuel and blanket salts from one another, and additional graphite structures provide sufficient moderation to slow neutrons so as to maximize their probability of causing additional fission reactions. A plenum structure distributes fuel salt to the various graphite channels and receives heated fuel salt after its passage through the reactor. The entire reactor vessel is constructed of a special nickel alloy called Hastelloy-N. Located under the reactor vessel is a drain tank intended to receive fuel salt in the event of a loss-of-coolant accident and to passively cool the fuel salt by thermal contact with the outside environment. In the event of gross reactor vessel damage a catch pan exists to direct fluids to the drain tank. Located above the reactor vessel is the PHX which cools the fuel salt by counter flow passage with the coolant salt. The primary pump is also located above the reactor vessel, and its shaft exits the reactor cell containment so that it can be driven by a conventional electric motor. The entire reactor cell, containing the reactor vessel, drain tank, PHX, primary pump, and associated piping, is heated by electrical resistance heaters to an elevated temperature in order to keep the fluids liquid. It is also heavily shielded and passively cooled through an air gap between containment linings. This arrangement is depicted in a simplified manner in Figure 3-1 and state points are given in Table 3-1, while the arrangement is shown in greater detail in Figure 3-7 (Section 3.8).

The design thermal power of the reactor is 600 MW. Fuel salt emerges from the reactor at 653 ^{o}C and at low pressure (stream 1) and flows to the primary pump, where its pressure is increased to 11 bar. It then flows (stream 2) into the PHX where it is cooled by a counter-current stream of coolant salt, emerging at 500 ^{o}C. The thermal power in the PHX is 600 MW. Some of the flow is diverted into a gas-separation stage where helium bubbles containing fission product gases are stripped out of the fuel salt. Then new helium bubbles are injected in the diverted stream before returning to the primary pump. The extracted gas mixture, which is mostly helium but contains fission product gases, is sent to a combiner tank where it is merged with a bleed flow of fuel salt (stream 4) that is sent to the drain tank. In the drain tank, some of the short-lived fission product decay and fuel salt is withdrawn to be sent to the chemical processing system while off-gas is withdrawn to be sent to the off-gas handling system. The fuel salt emerging from the PHX (stream 3) returns to the reactor vessel.

3.5.1.2 Power Conversion System

As shown in Figure 3-1(with detail in Table 3-1), the coolant salt emerges from the PHX (stream 5) at a temperature of 633 ^{o}C and flows to the coolant pump, where its pressure is increased to 19 bar. It leaves the reactor containment boundary (stream 6) and passes into the gas heater, where it is cooled by a counter-current stream of supercritical carbon dioxide, emerging at 480 ^{o}C. It then passes back into the reactor containment (stream 7) and enters the PHX where it will be heated back to the initial conditions. The thermal power in the gas heater is 600 MW

Turning now to Figure 3-8 (Section 3.8), the working fluid gas used in the PCS (supercritical carbon dioxide) leaves the gas heater at a temperature of 550 °C and a pressure of approximately 200 bar (stream 8). It enters the turbine (which has an efficiency of 90%) and produces 384 MW of shaft work as it drops in pressure to 79 bar and 440 °C. The shaft work produced by the turbine drives both the electrical generator and the two compressors, all of which are on the same shaft. The turbine exhaust gas (stream 9) then passes into the high-temperature recuperator, where it cools by transferring enthalpy to the full high-pressure gas stream, emerging at a pressure of 78 bar and a temperature of 168 C (stream 10). The thermal power in the high-temperature recuperator is 986 MW.

The low-pressure gas now passes into the low-temperature recuperator, where it cools by transferring enthalpy to a portion of the high-pressure gas-stream, emerging at a pressure of 77 bar and a temperature of 70 °C (stream 11). The thermal power in the low-temperature recuperator is 399 MW. The low-pressure gas then splits into two streams. Stream 12, comprising 41% of the gas flow, is directed to the medium-temperature compressor (often called the "recompressor"), where it is pressurized to 200 bar and emerges at a temperature of 158 °C (stream 17). The remainder of the low-pressure stream (stream 13), comprising 59% of the gas flow, passes through the gas cooler where it is cooled to a temperature of 32 °C and a pressure of 77 bar (stream 14) by a counter-current flow of cooling water. The cooling water enters the gas cooler (stream 20) at a temperature of 27 °C and ambient pressure and leaves the gas cooler (stream 21) at a temperature of 65 °C and still at ambient pressure. The thermal power in the gas cooler is 322 MW, and this constitutes the thermal energy rejected from the system as waste heat.

The cool, low-pressure gas stream enters the low-temperature compressor where it is pressurized to 200 bar and rises in temperature to 61 °C through the application of 39 MW of shaft work (stream 15). It then enters the high-pressure side of the low-temperature recuperator, where this high-pressure stream (which is only 59% of the original flow) is heated by the full flow of the low-pressure stream (stream 10) previously mentioned to generate stream 16, with 399 MW of thermal power exchanged between the two streams.

The partial high-pressure stream (stream 16) emerges from the low-temperature recuperator and is unified with the exhaust of the recompressor (stream 17) which is at the same temperature and pressure. The two streams now form one high-pressure stream (stream 18) which enters the high-temperature recuperator on the high-pressure side. As previously mentioned, 986 MW of thermal power heats the high-pressure stream, and it emerges at 397 °C and nearly 200 bar (stream 19). It then passes into the gas heater where it is heated by counter-current flow with the coolant salt (stream 6), completing a closed circuit of the PCS and emerging as stream 8.

Cooling water passes through a forced draft cooling tower and is cooled to the gas cooler inlet conditions and brought up to the desired pressure by passage through a pump.

3.5.1.3 Chemical Processing System

The overall chemical processing system is depicted in a simplified form in Figure 3-2 with state points given in Table 3-2 above. The detailed chemical processing is shown in Figure 3-9 to Figure 3-12 (Section 3.8). Blanket salt is drawn from the reactor's blanket at a rate which allows the entire blanket to be processed every four days. Figure 3-9 shows the process flows within the blanket salt chemical processing system. The blanket salt (stream 31), containing small amounts of protactinium as a tetrafluoride, and even smaller amounts of uranium as a tetrafluoride, enters a reductive extraction column (W-3101) where the salt is contacted by a stream of metallic bismuth (stream 35) with 3000 ppm of thorium metal dissolved in the bismuth. Reactions between the metallic thorium and the protactinium and uranium salts cause the thorium metal to oxidize to thorium tetrafluoride and to enter the salt, while at the same time protactinium and uranium tetrafluorides in the blanket salt reduce to metal and enter the bismuth stream (stream 33). The blanket salt, with most of its protactinium and uranium removed, leaves the reductive extraction column and returns (stream 32) to the blanket.

The metallic bismuth stream, holding protactinium, uranium, and unreacted thorium metal in solution, then enters another reductive extraction column (W-3102) where it contacts the "decay" salt prior to that salt entering an electrolytic reduction cell. In the second reductive extraction column, the thorium in the metallic bismuth again reacts with any protactinium or uranium held in the decay salt, oxidizing the thorium to its tetrafluoride state and reducing the protactinium and uranium to metals. The reason for this second reductive extraction column is to prevent any protactinium or uranium in the decay salt from being electrolytically reduced to metal in the reducing section of the electrolytic cell. The emerging bismuth stream (stream 34) from W-3102 then flows to the oxidizing section of the electrolytic cell (W-3103). In the oxidizing section, it is contacted with small amounts of bismuth trifluoride in solution in salt, causing any metallic thorium, protactinium, or uranium to oxidize to tetrafluorides and to enter into solution in the decay salt.

The metallic bismuth stream, stripped of all other metals, passes from the oxidizing section of the electrolytic cell to the reducing section, where the electrolytic reduction of decay salt "loads" the bismuth with the proper concentration of metallic lithium and thorium that it needs in order to contact the blanket salt. Thus the source of metallic lithium and thorium used in the bismuth stream (stream 35) is the decay salt.

The decay salt stream (stream 36), loaded with thorium, protactinium, and uranium in the oxidizing section of the electrolytic cell, then flows to the decay tank (T-3104), where the salt is given time for the protactinium to decay to uranium. A stream of salt (stream 37) from the decay tank is directed to the decay fluorinator (R-3105) where it is contacted by a gaseous stream of molecular fluorine gas (stream 42). This causes any uranium in the decay salt to oxidize further to uranium hexafluoride, which is gaseous. The exhaust stream (stream 43) of the decay fluorinator consists of uranium hexafluoride and any gaseous fluorine that did not react in the column and is directed to the vortex mixer (A-3205). Since the column is operated with an excess of fluorine, there is still a considerable amount of fluorine gas leaving the fluorinator.

The decay salt leaving the fluorinator (stream 39) has the option to return to the decay tank, but in normal operation all of it would be directed to the second reductive-extraction column (W-3102). As previously described, the purpose of passing the decay salt through W-3102 is to remove any protactinium in the salt and any uranium that was not fluorinated in passage through the fluorinator. After leaving W-3102, the decay salt (stream 40) passes to the reducing section of the electrolytic cell, where it is electrolytically reduced to provide metallic lithium and thorium for the bismuth stream that will be used to contact the blanket salt in W-3101. During the reducing process, an amount of bismuth trifluoride appears in the decay salt (stream 41) and the salt passes to the oxidizing section, where that bismuth trifluoride is used to oxidize any Li, Th, protactinium, or uranium in the bismuth stream.

Fuel salt is processed on a 300-day cycle. First it is cooled for a time in the decay tank to allow short-lived fission products to decay, and then it passes to the fuel fluorinator (R-3201), where it is contacted by a stream of gaseous molecular fluorine. Uranium hexafluoride is produced from the uranium extracted from the salt and flows from the fluorinator to the vortex mixer (A-3205). The salt, now stripped of its uranium and nearly all actinides, flows to another reductive extractor (W-3202) where it is contacted by a flow of metallic bismuth containing metallic lithium as a reductant. The bismuth leaving the extractor, carrying fission products, is either discarded or processed further. The barren fuel salt leaves the reductive extraction column and flows to a settler (D-3203) where any entrained bismuth can be separated.

Gaseous mixtures of uranium hexafluoride and gaseous fluorine are merged in the vortex mixer (A-3205) in the presence of fuel salt to form uranium pentafluoride, which then proceeds to a hydrogen reduction column (R-3204). Contacted by gaseous molecular hydrogen, the uranium pentafluoride in the salt is reduced to hydrogen fluoride and any gaseous fluorine is also reduced to hydrogen fluoride, which leave the reduction column and are recycled. The fresh fuel salt returns to the reactor. The exhaust gas from the reduction process flows to an electrolysis unit (Q-3307) where the hydrogen fluoride is electrolytically split into gaseous hydrogen and gaseous fluorine, which are used to feed the reduction column (R-3204) and the two fluorinators (R-3105 and R-3201).

Through the operation of this system, actinides are almost entirely contained within the primary containment of the reactor until they are consumed. The only paths for actinide loss come from the inefficiency of the fuel fluorinator coupled with the action of the fuel salt reductive extractor. Losses of actinides can be reduced further by additional fluorination of the extracted bismuth.

Once the system is charged, the input streams consist of a small thorium tetrafluoride feed into the decay tank (T-3104) and the bismuth feed (which may come from recycling). The thorium feed is very small, and even decades of operation will only consume a small amount of the material with which the blanket is originally charged. Material discard takes place at W-3202 as bismuth carrying fission products is either discarded or recycled.

3.5.1.4 Off-gas Handling System

The off-gas handling system is depicted in detail in Figure 3-13 (Section 3.8). The noble gases xenon and krypton are common products of the fission reaction and account for a substantial portion of the fission product mass. One of the radioactive isotopes of xenon, xenon-135, is a strong neutron poison and its rapid removal improves the neutronic performance of the reactor. The off-gas handling system of the reactor enhances the removal of xenon and krypton by using helium bubbles injected into the salt to provide a transfer surface for these gases, which are sparingly soluble in the salt mixture. The helium and noble gas mixture is removed in another part of the loop and allowed to decay for a short period of time in the fuel salt drain tank.

The gas stream then is directed into a long piping system containing charcoal and actively cooled by a coolant fluid such as water. After being held up for about two days, most of the flow is directed back into the reactor system, but a fraction of the flow proceeds to another piping system with sufficient delay to allow all of the radioactive xenon to decay to stable isotopes and all of the radioactive krypton (with the exception of 10-year krypton-85) to decay away as well. The remaining stable xenon and mixed krypton are then cryogenically separated and stored or else vented to a stack to promote its dispersal.

3.5.2 Physical Layout and Location

The physical layout of the LFTR system is in a very early stage of definition, but a notional arrangement is depicted in Figure 3-4. The chemical processing system arrangement is depicted notionally in Figure 3-5, and the 47-hour holdup section of the off-gas handing system is shown in Figure 3-6.

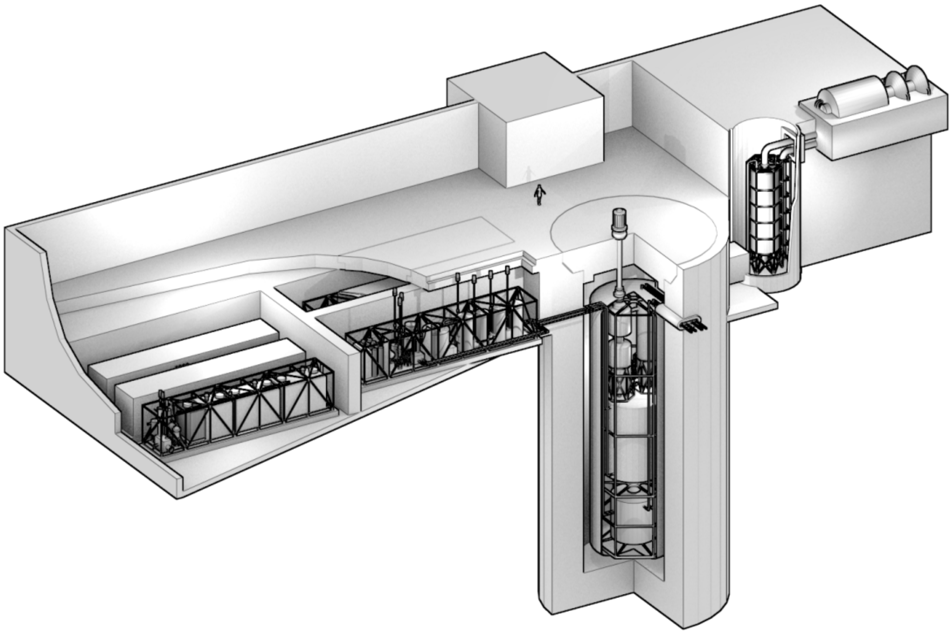

Figure 3-4
Notional arrangement of the modular LFTR system inside of a suitable facility [Flibe Energy, 2015].

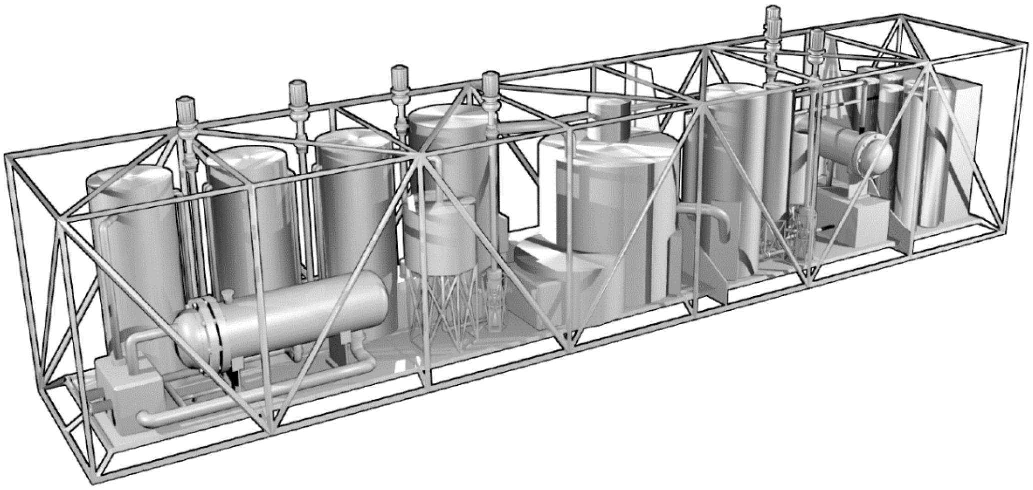

Figure 3-5
Oblique view of chemical processing system component arrangement [Flibe Energy, 2015].

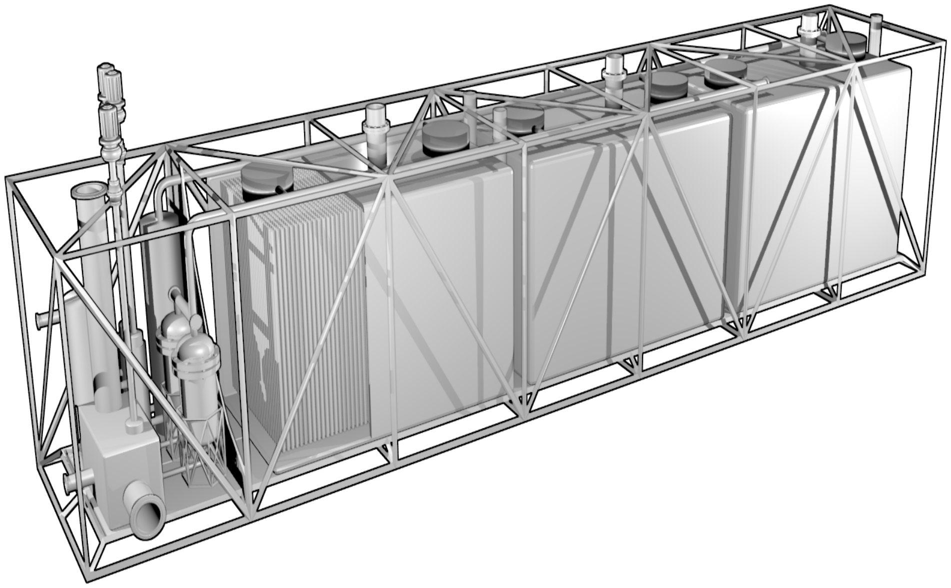

Figure 3-6
Oblique view of the 47-hour off-gas holdup system component arrangement [Flibe Energy, 2015].

3.5.3 System Reliability Features

The operation of the freeze plug is an important system reliability feature that is maintained through active cooling of the freeze plug along with the maintenance of the fuel salt below a design temperature level. There are a number of scenarios that could cause the freeze plug to melt, but in each case the melting of the plug causes the fuel salt to drain out of the reactor vessel (where it is held in a critical configuration with the moderator graphite and the blanket fluid) and to fill the drain tank, a vessel without moderator intended to maximize thermal losses to the outside environment. The freeze plug is a benign failure mode, causing no damage to the system through its activation and is easy to reverse, allowing the cause of the event to be determined and corrected. Then the freeze plug is reinstated, the reactor vessel is refilled from the drain tank, and the reactor is taken to criticality and full power once more.

3.5.4 System Control Features

The aforementioned freeze plug is a gross level of reactor control, essentially turning off the fission reaction and putting fuel salt in a passively-cooled configuration. Finer levels of control are available through the arrangement of control rods in the reactor vessel. As currently envisioned, an array of floating control rods in the blanket salt would slide through channels in the graphite elements in the blanket and would be fully removed from the core during normal operations. In the event of a loss-of-blanket, these floating rods would slide into place through their graphite elements and bring the reaction to a stop through the introduction of large amounts of negative reactivity. In another mode, some or all of these floating rods could be intentionally actuated to be driven into the core for a commanded shutdown. These rods would be used for the insertion of large amounts of negative reactivity.

For finer control, a central series of control rods, or alternatively, a column of blanket salt that is displaced through helium gas, could be used for fine reactivity control. The advantage of using helium gas for displacement of blanket salt in a central channel is that the helium is essentially neutronically invisible, whereas the blanket salt is neutronically absorptive, and varying levels of gas or blanket would serve as a "liquid control rod". Release of gas pressure would cause blanket salt to fill the channel to the normal level of the blanket fluid in the reactor vessel, serving to introduce negative reactivity in an important region.

The details of these control schemes depend on a higher level of neutronic modeling fidelity than currently exists, and will be modeled in the future as resources and modeling tools become available.

3.6 Operations

The operation of the reactor would include all phases of startup from either cold or standby conditions, reliable delivery of electric power at the demanded load level, and procedures for both scheduled and unplanned shutdowns. Safe operation of the plant, protection of its employees, and the protection of the public from any radioactive hazard is the overriding consideration at all times. Operational procedures that protect the economic value of the plant and its equipment are the next level of priority.

The role of the PCS in the operational procedures of the reactor is significant. Since the integration of the supercritical carbon dioxide gas turbine concept with the liquid-fluoride reactor concept is still at an early stage of definition, there will be a degree of uncertainty in operational plans. As the gas turbine concept is defined more fully and integrated more closely with the LFTR concept, there is every reason to believe that these operational procedures will become more resolved.

3.6.1 Initial Configuration (Pre-Startup)

In the initial configuration of the reactor before startup, the fuel salt inventory would reside in the fuel salt drain tank. The blanket salt inventory would reside in the blanket salt drain tanks, and the coolant salt inventory would be in the coolant salt drain tanks.

The gas turbine would not be spinning, and the turbomachinery would be held by brakes. The chemical processing system reaction columns would be empty, and the decay salt would be held in the decay tank. Bismuth inventories would be in storage tanks, and electrolytic cells would be electrically disconnected from their power sources.

3.6.2 System Startup

Two startup procedures should be considered: a cold startup, with all systems cold and empty, and a hot restart from a hot standby condition. If it is practical, it is always desirable to hold the system in hot standby in order to achieve a quick restart of the system and to avoid excessive outage times. Solid-fueled reactors must contend with the ingrowth of xenon-135 during a shutdown (and its effects on reactivity) as a complication to their restart, but this problem is avoided in a fluid-fueled reactor that can remove xenon through the off-gas handling system.

In a cold startup, the primary and secondary cell electric heaters are turned on, and the primary and secondary circulation pumps are started to circulate helium in the salt systems. When the coolant salt system reaches a temperature of 500°C, the loop is filled with coolant salt from the heated drain tank, and coolant salt circulates through the system. When the blanket salt system reaches 550 °C, it is also filled from the blanket-salt drain tank and salt is circulated through the reactor vessel. After positive confirmation that the blanket salt fills the reactor and is at the appropriate level, the fuel salt (also at 550°C) can be introduced into the fuel salt loop from the fuel salt drain tank. All salt systems continue to circulate isothermally at 550 °C until thermal power withdrawal begins via the PCS.

The reactor is made critical at essentially zero-power through the removal of control rods under the surveillance of startup instrumentation and a flux level control system. When the thermal power reaches an appropriate level, which is still below the sensible power-generating range, the automatic neutron flux level controller is used to control the power.

The supercritical carbon dioxide gas turbine is also heated and brought to the appropriate temperature and pressure to begin connection to the reactor system. Thermal power withdrawal in the gas heater to the gas turbine then initiates the increase in reactor power to match withdrawal. When the power level has reached an appropriate level, the electrical generator is synchronized to the electrical grid and the reactor is tied into the overall power distribution system of the electrical grid.

The hot standby startup case is similar to the cold startup but can proceed from the point where the PCS is ready to remove thermal power through the gas heater.

3.6.3 Normal Operations

The normal operation mode of the system is the full-power mode. In this configuration, the reactor produces thermal power at its design rating; that thermal power is transferred to the PCS; and the thermal power is converted to electricity for distribution. The system is connected to and synchronized with the electrical grid. The chemical processing system operates steadily to remove fissile precursors from the blanket, allowing them to decay outside of the core, and then reintroduces the fissile derivatives of that process to the fuel salt. Fission products and off-gas are continuously removed.

Within the core, the floating blanket control rods are fully withdrawn. Fine reactivity control is maintained through helium gas pressure, displacing a column of blanket salt in the center of the core. The fuel salt drain tank serves as a holdup volume for fission product gases as well as a fuel salt hold tank preliminary to chemical processing.

Reactor operation consists of monitoring fuel salt entry and exit temperatures of the reactor vessel as well as the median fuel salt temperature. The key parameters of the reactor vessel, primary loop, intermediate loop, and PCS are automatically recorded.

3.6.4 Off-Normal Operations

There are several possible off-normal operation conditions, of which only a few are described here.

One scenario is a slow but steady increase in median fuel salt temperature in the core. This could be caused by too much uranium hexafluoride being introduced into the fuel salt. The recovery action would be to assess the cause of this temperature rise and to address it; if that proves unfruitful, a system shutdown would be commanded.

Another scenario is a slow but steady decrease in median fuel salt temperature in the core. This would likely be caused by the introduction of negative reactivity in the system, perhaps by inefficiencies in the chemical processing system. The mitigation for this occurrence would be to reduce the blanket salt level in the central control channel to add positive reactivity to the core. This mitigation would reach its limit when the level of the blanket salt in the central channel had reached its lowest level. At this point, a system shutdown would be commanded to assess the situation in greater detail.

3.6.5 System Shutdown

An operator-initiated shutdown would proceed in this manner: load would be reduced on the gas turbine, allowing it to spin down. Circulation of both the fuel and coolant salts would continue for about ten days (depending on the operational history of the reactor) and then the fuel salt would be transferred to the fuel salt drain tank by allowing the freeze valve to thaw. Coolant salt would then be transferred to its drain tank. After confirmation that the fuel salt had been drained from the reactor, blanket salt would be allowed to drain from the reactor into the blanket salt drain tanks.

3.7 Testing and Maintenance

A fluid-fueled reactor differs from today's solid-fueled reactors in that fission products are found throughout the primary loop rather than confined to the fuel pin. This has a number of ramifications for the maintenance strategy. Although most of the fission products are strongly chemically bound to the salt, including all of those of greatest concern, such as cesium, strontium, and iodine, there are other fission products that are expected to disperse, namely, the noble metals are expected to be found in the reactor vessel and its circuits, the drain tanks, the primary pump, and the PHX. Fission product alkali metals and alkaline earths (the decay products of the noble gases xenon and krypton) will be found in the off-gas handling system. Fission products will also be found throughout the chemical processing system.

When one considers whether the maintenance challenges make a fluid-fueled reactor more or less attractive than a solid-fueled reactor, one should also consider the fact that the LFTR, as presently conceived, represents a nearly complete fuel cycle strategy, all embodied in a single system. In fairness, the LFTR should be compared to the entire fuel cycle of a conventional reactor before a judgement is made as to its relative challenges.

The overall philosophy of the maintenance of the reactor is that failed components will be removed from their active location and replaced. The removed component will then be repaired or discarded. Some components are so large, such as the reactor vessel, that a strategy of shifting the operational location of the reactor vessel may be an alternative to the removal of the reactor vessel. In this scenario, multiple reactor vessel locations would be designed into the reactor building but only one vessel would be filled and connected to the PHX. In this way, a reactor vessel could be taken offline but could remain in place for repair or refurbishment at a convenient future time when radioactivity levels had died down considerably.

The radioactivity level for the reactor vessel will depend strongly on the thickness of the blanket fluid and the reprocessing approach used for the blanket, because the blanket fluid will be the material that will be in actual contact with the metallic structures of the reactor vessel. A thinner blanket will mean more neutrons will penetrate to the reactor vessel surface where they will activate some of the metallic elements in the structural alloy. A slower chemical processing schedule will mean more protactinium decays to uranium in the blanket salt, and more uranium in the blanket means more opportunities for fission and the production of fission products in the blanket, which is obviously undesirable but to some degree unavoidable. The actual lifetime of the reactor vessel, and the degree of radioactive contamination it possesses at the time of shutdown, will be dependent on these two factors and cannot be assessed at present.

The PHX, having been in close contact with the fuel salt and its fission products, and having relatively thin interior walls, will likely become so contaminated that it will reach a point where it will need to be discarded. A similar situation will likely exist with the rotary elements of the pump. In some cases, disassembly of a failed component may be desirable to determine the cause of failure without any intention to reassemble the component.

The off-gas holdup system and the chemical processing systems will become strongly contaminated over time, and individual components will have to be removed and replaced with new components. The coolant salt system should not be contaminated beyond the formation of tiny amounts of tritium from the tiny flux of delayed neutrons in the PHX on the small amount of lithium-6 present. Possible tritium contamination will be the main concern for the coolant salt loop as well as for the PCS.

3.7.1 Temporary Configurations

The design of the reactor vessel envisions an internal structure of cylindrical graphite tubes that contain fuel salt arranged between separate graphite moderator elements. The graphite tubes containing fuel salt will be attached in two ways to a plenum structure that provides the incoming fuel salt and receives the outgoing fuel salt. The nature of this connection has not been defined sufficiently to allow a maintenance plan to be created, but all concepts thus far have envisioned remote assembly, maintenance, and disassembly to be prime considerations in the design. The graphite moderator elements do not have to accommodate any fuel salt flow and may be only posted (or "indexed") into the plenum structure, or perhaps held in some other arrangement. An important design consideration is that these moderator elements can be removed in the axial direction relatively easily compared to the cylindrical fuel channel elements, and this facilitates providing a work area for a remote connection or disconnection tool.

Thus one of the temporary configurations that the reactor will encounter will be during the buildup, inspection, maintenance, replacement, or full disassembly of the graphite internals of the reactor core. In these temporary configurations, one, some, or most of the graphite structures will be absent as the reactor graphite internals are built up or taken down.

3.7.2 Safety Required Surveillances

During reactor refurbishment, the reactor would be drained of all fluids and flushed to reduce residual radioactivity. The reactor cell would be cooled to ambient temperatures and sufficient time would be allowed for the most intense radioactivity to die off. The reactor vessel head would be unbolted and lifted by the overhead crane, and via remote manipulators, the individual graphite elements in the core would be removed and inspected. The graphite moderator elements would be the simplest to remove, since they would not have any strong connections in the plenum structure, but could simply be unlocked and removed. These moderator structures would have only been in contact with blanket salt and do not serve any structural purpose but define the blanket volumes and flow paths. They would be remotely scanned for changes in dimensions, both axial and radial, and then sorted as to whether they were suitable for reuse in the reactor and in which location in the core. It is entirely possible that a moderator element is suitable for reuse but not in the same location. Perhaps in parallel and as appropriate, the cylindrical fuel channels would be disconnected from the plenum and lifted out of the reactor vessel for scanning. The connection technique to the plenum and the decoupling procedure has not been defined yet. The fuel channels themselves would need to be disassembled into their three internal components and each component scanned remotely and assessed for possible reassembly and return to the core structure, again, perhaps in a different location.

At the conclusion of this surveillance activity, some fraction of the graphite internals would be returned to the core but in different locations, some fraction will have been designated for discard, and new graphite structures will have been added to the reactor cell to compensate for discarded structures. After removal of graphite (to be disposed through an airlock) and a general cleanup of the reactor cell, the vessel head would be lowered and reattached to the remainder of the reactor vessel. Pressure and fit checks would take place before the reactor vessel could be deemed to be ready to be restored to service.

The PHX presents another surveillance challenge. The design of the PHX proposed in ORNL-4528 is not well suited to repair because of poor accessibility to the tube ends. Any PHX redesign should consider the needs of surveillance of tube integrity into a possible redesign.

The gas heater and the structures in the gas turbine are much more amenable to surveillance and maintenance because radiation fields are much lower. During extended shutdowns it will be possible to assess the integrity of these structures and anticipate potential failures.

3.7.3 Operations, Inspections and Testing

During reactor operations, inspections on the core internals will be very challenging due to the high temperature inside the reactor cell and the high radiation fields. Inspections will have to be limited to indirect sensing of properties inside the core. New techniques for core inspection during operation will need to be developed, with a particular view towards techniques that are suitable for high radiation fields. Various ultrasonic techniques have been imagined that might be suitable for this challenge, particularly since they may make it possible to "image" the core internal structure even during operation. Only further research will show if this is actually possible.

3.8 System Drawings

Figure 3-7. LFTR reactor cell process flow diagram [Flibe Energy, 2015].

Figure 3-8. LFTR power conversion system flow diagram [Flibe Energy, 2015].

Figure 3-9. LFTR chemical processing system section 3100 process flow diagram [Flibe Energy, 2015]. (blanket and decay salts)

Figure 3-10. LFTR chemical processing system section 3200 process flow diagram [Flibe Energy, 2015]. (fuel salt)

Figure 3-11. LFTR chemical processing system section 3300 process flow diagram [Flibe Energy, 2015]. (hydrogen fluoride electrolysis and potassium hydroxide scrub)

Figure 3-12. LFTR chemical processing system section 3400 process flow diagram [Flibe Energy, 2015]. (reactant drain tanks)

Figure 3-13. LFTR off-gas handling system block diagram [Flibe Energy, 2015].

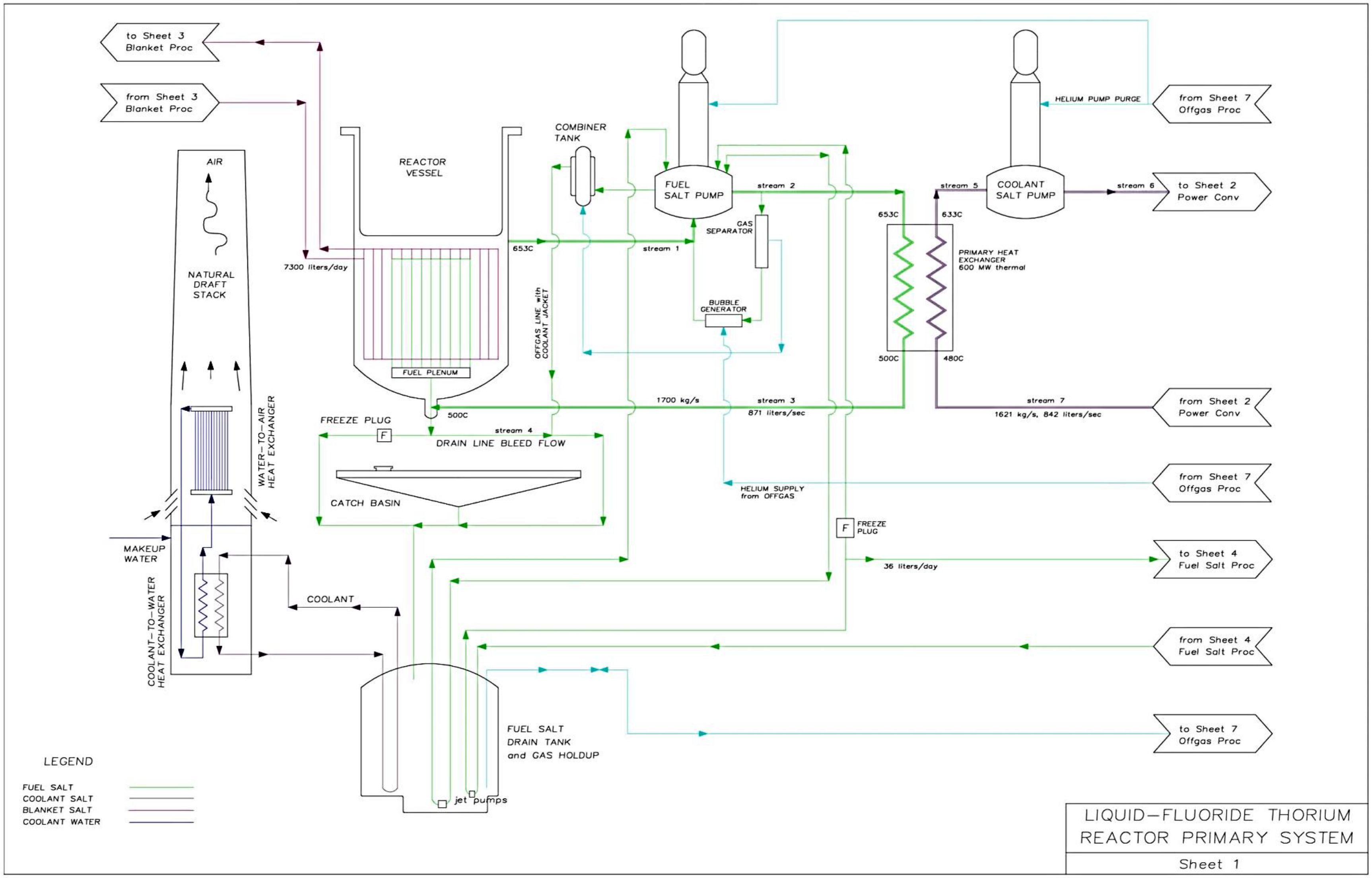

Figure 3-7
LFTR reactor cell process flow diagram [Flibe Energy, 2015].

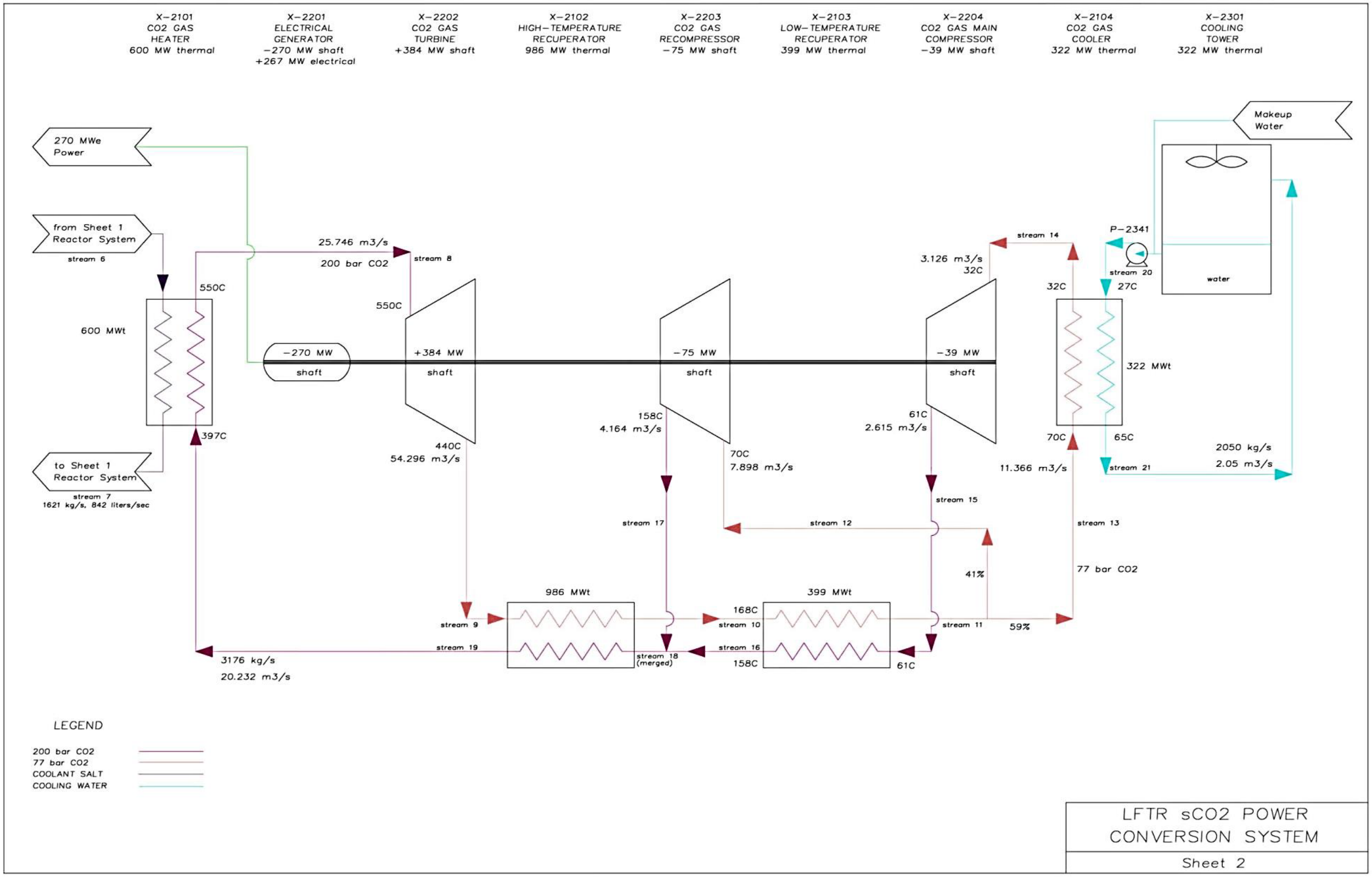

Figure 3-8
LFTR power conversion system flow diagram [Flibe Energy, 2015].

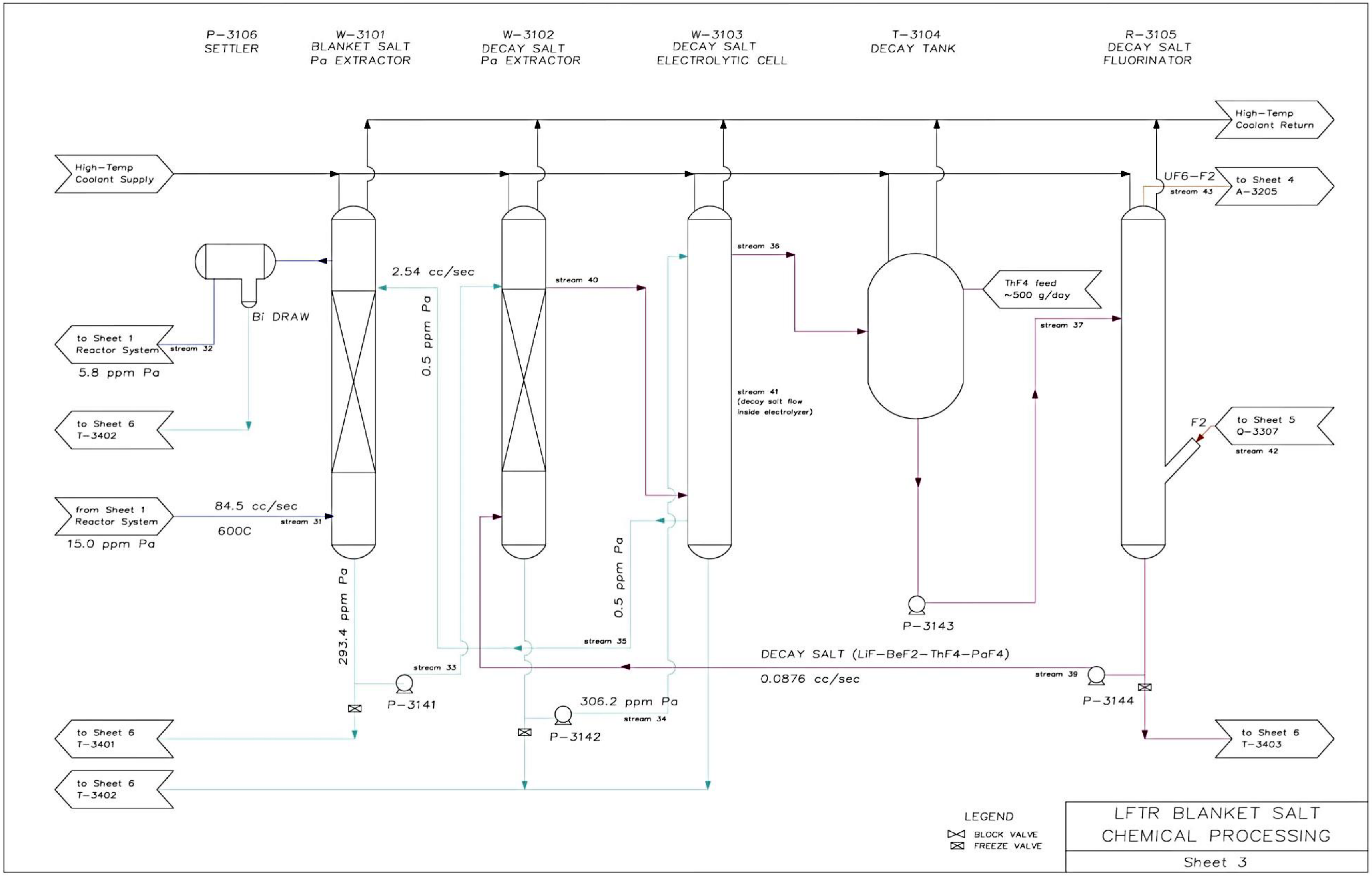

Figure 3-9
LFTR chemical processing system section 3100 process flow diagram [Flibe Energy, 2015].

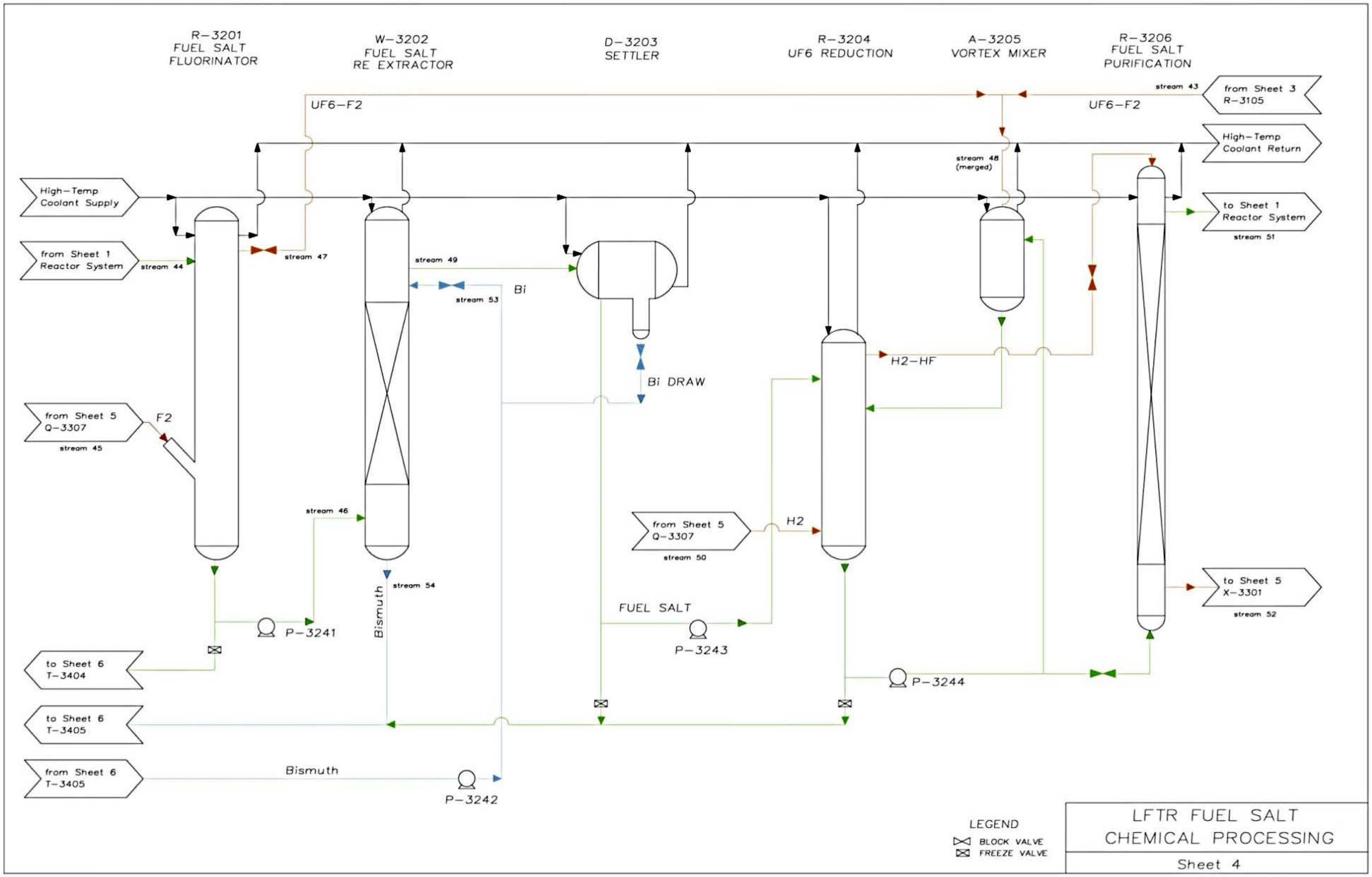

Figure 3-10
LFTR chemical processing system section 3200 process flow diagram [Flibe Energy, 2015].

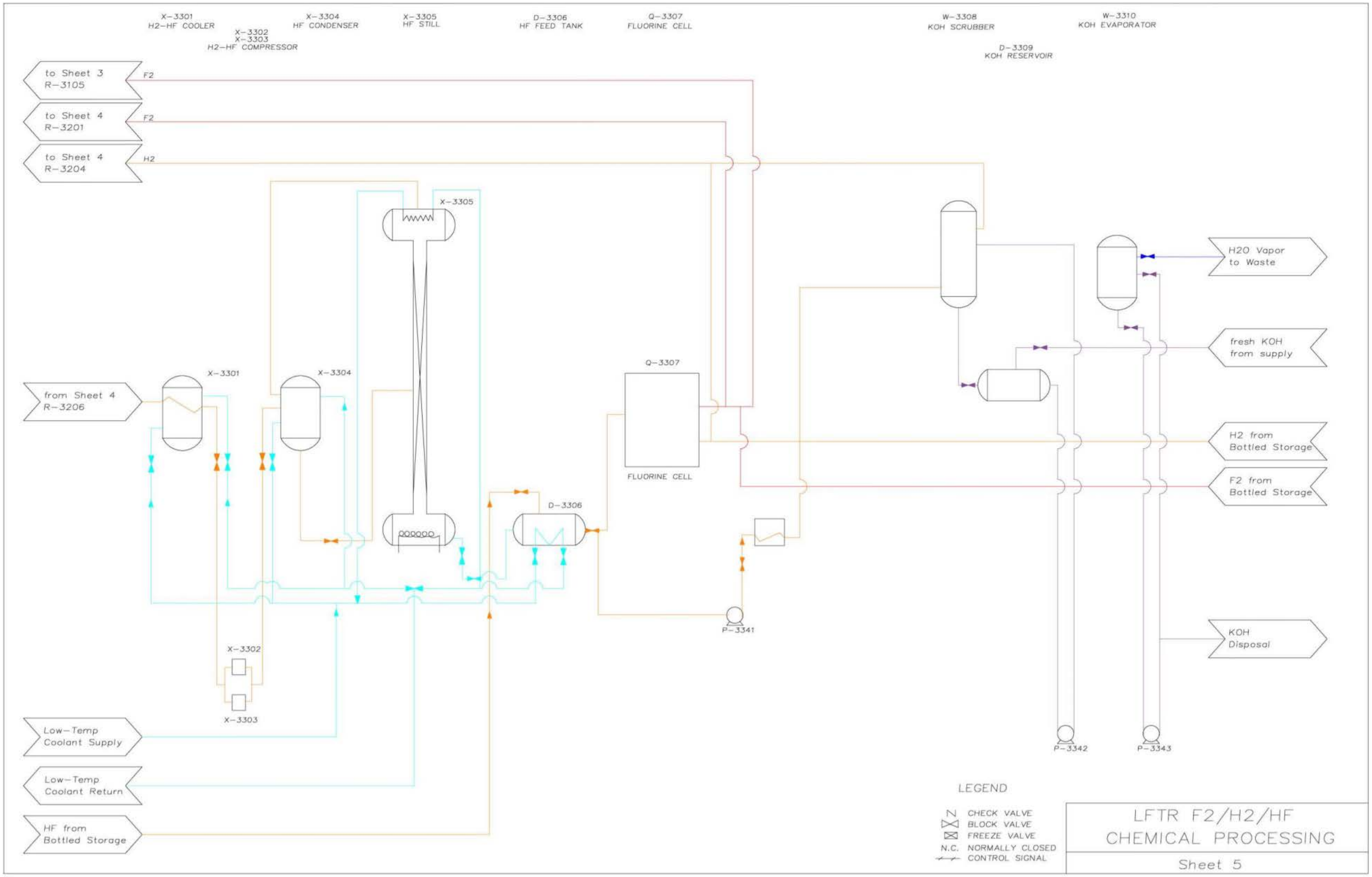

Figure 3-11
LFTR chemical processing system section 3300 process flow diagram [Flibe Energy, 2015].

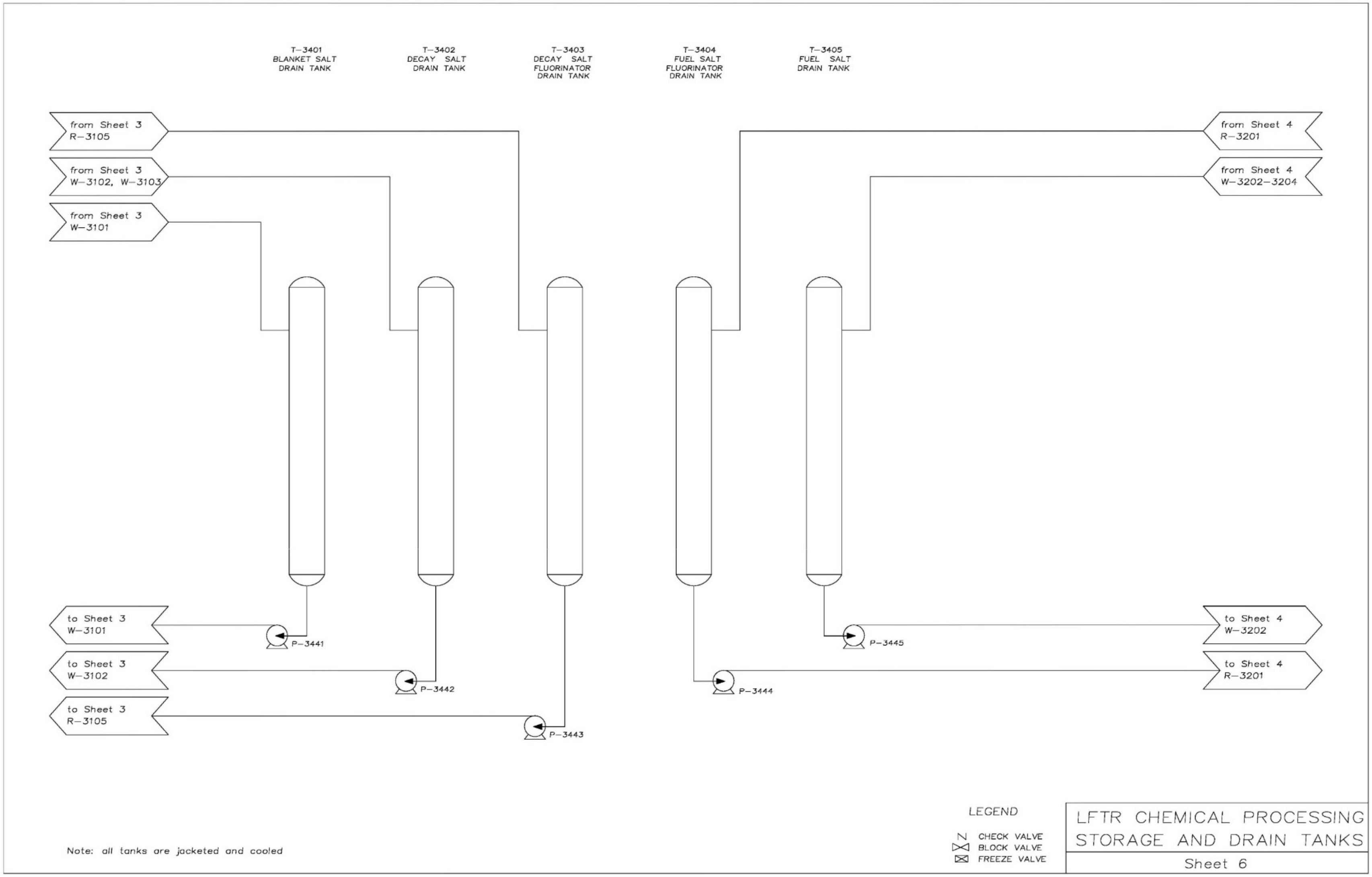

Figure 3-12
LFTR chemical processing system section 3400 process flow diagram [Flibe Energy, 2015].

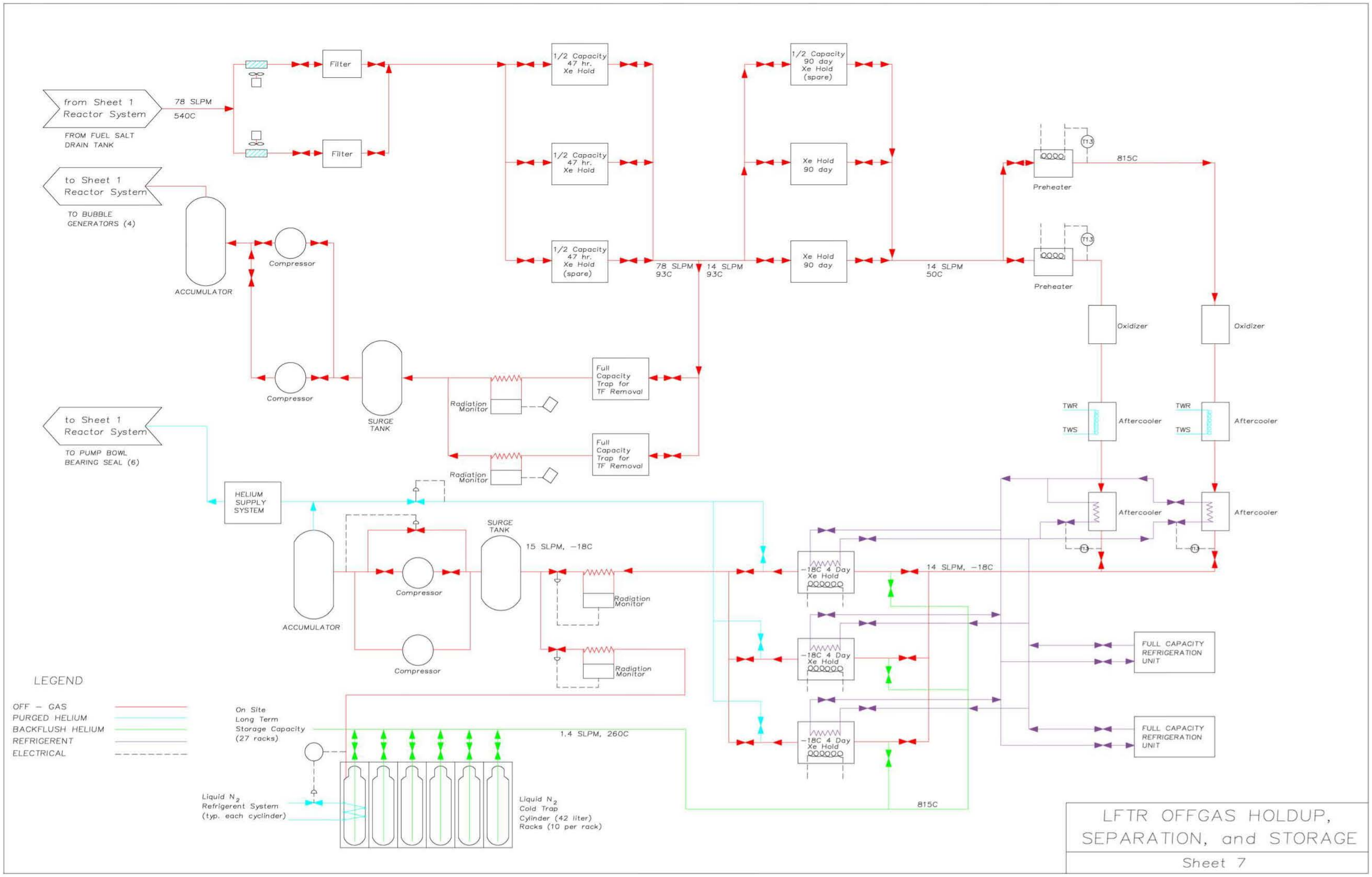

Figure 3-13
LFTR off-gas handling system block diagram [Flibe Energy, 2015].

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4

PRELIMINARY PROCESS HAZARDS ANALYSIS

4.1. Introduction to Process Hazards Analysis and “What-If” Analysis

Technology development and safety analysis expectations have progressed substantially over the intervening decades since the first MSRs were designed, built, and operated. Passive safety built on fundamental properties (e.g., thermal inertia and boiling point of molten salts) and simplified safety systems (e.g., freeze plugs and gravity drainage) are safety features of LFTR. Given LFTR’s pre-conceptual design stage, it is possible to integrate safety elements early into the project lifecycle and any impacts caused by changes to the design are presently limited to paper. And since liquid-fuel MSRs like LFTR essentially co-locate a critical nuclear reactor and a small chemical processing plant for fuel and blanket salt conditioning, it is foreseen that completion of integrated safety analyses and implementation of process safety management practices will be important parts of a balanced approach to plant safety.

Process hazards analysis (PHA) methods have been developed to assess the significance of hazardous situations associated with processes or activities, especially those comprising of complex engineered systems [CCPS 1992]. The U.S. Department of Energy (DOE) uses PHA for evaluating its process hazards and has based its identified seven acceptable PHA methodologies[29] within DOE-STD-3009-2014 [DOE 2014] on guidelines published by the Center of Chemical Process Safety (CCPS) and the American Institute of Chemical Engineers (AIChE) [CCPS 1922; AIChE 2015]. Of these, the so-called “What-If” analysis requires the least design and operational information to apply, making it useful for applications where experience and data are limited [DOE 2004].

PHA and the What-If analysis were developed in the mid-1980s by the chemical process industry following several severe accidents, such as the 1984 methylisocyanate gas release from a Union Carbide pesticide plant in Bhopal India. Earlier reactor designs like the MSBR have not benefitted from this safety evaluation approach. An online search yields minimal results for similar and publicly available work on PHAs and advanced reactor concepts at such an early stage in technology development [Lixia 2010; Brovchenko 2012]. Documenting the PHA

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[29] The other six acceptable methodologies are checklist, what-if/checklist (combination), hazard and operability (HAZOP) study, failure modes and effects analysis (FMEA), fault tree analysis, and “an appropriate equivalent methodology”. While not identical, the requirements for a PHA are related to the technical elements that make up a Probabilistic Risk Assessment (PRA). Since NRC requires a PRA for licensing advanced reactor designs, it is important to keep in mind information needs for a PRA when initiating safety analysis efforts; reference has been made to the American Society of Mechanical Engineers (ASME) Standard for Non-LWRs. The technical elements of a PRA according to the ASME standard are [ASME 2013]: (a) Plant Operational States Analysis; (b)Initiating Events Analysis; (c) Event Sequence Analysis; (d) Success Criteria; (e) Systems Analysis; (f) Human Reliability Analysis; (g) Data Analysis; (h) Internal Flooding Analysis; (i) Internal Fire Analysis; (j) External Events Screening; (k) Other External Events Analysis; (l) Seismic Events Analysis; (m) High Winds Analysis; (n) External Flooding Analysis; (o) Event Sequence Quantification; (p) Mechanistic Source Term Analysis; (q) Radiological Consequence Analysis; (r) Risk Integration

process and outcomes will provide an example that could be applied more broadly among the advanced reactor design community to improve the design process as well as the end product.

This first-of-a-kind study applies the "What-If" Analysis methodology to evaluate the LFTR conceptual design. EPRI and Vanderbilt University are collaborating with Southern Company Services, Flibe Energy and architect/engineer Teledyne Brown Engineering (TBE) to perform a technology assessment of the LFTR design as a non-light water reactor option for a highly uncertain regulatory and economic future. Using preliminary system descriptions provided by Flibe Energy and TBE, a preliminary PHA (PPHA) was performed [CCPS 1992]. The PPHA and PHA provide initial information about system hazards and lay the groundwork for more advanced safety analyses. A review is provided in the following sections of the project objectives, methodology, transactions, observations, and conclusions from carrying out the PHA project.

4.2 PHA and PPHA Overview of Methodology

A number of methods to consider the safety of an engineered system exist and fall under the umbrella-term of process hazards analysis (PHA) [CCPS 1992]. PHA is a semi-quantitative methodology used to identify hazards and initiating events that could lead to an accident. There are several PHA methodologies that are applicable for processes in varying stages of design and operations and accepted as valid by the CCPS, DOE, and NRC (as discussed above). Due to the initial design stages of the LFTR, it was most appropriate to select a PHA method that is amenable to design evolutions. This requires a qualitative PHA method that avoids focusing on design-specific details and addresses basic functional characteristics of systems and components, and considers radiological and chemical materials that can pose as a hazard source during off-normal events. The "What-If" Analysis is an accepted PHA method that requires the least amount of design-specific input information to assess potential hazards and was used for this study. The described work herein is considered a preliminary PHA (PPHA) due to the level of detail that is considered based on early conceptual LFTR design information (where "PPHA" and "What-If Analysis" are used interchangeably in this report).

CCPS (1992) describes the What-If analysis to be a "creative, brainstorming examination of a process or operation…and can be used to examine virtually any aspect of the facility design and operation". A What-If analysis is a series of open-ended questions that begin with the words "What If…" (e.g., What if the primary pump fails?). One of the strengths of this method is that it can be applied to a system at any stage of its development. Moreover, it would benefit system designers to apply the PHA exercise incrementally to examine how changes can have a ripple effect and can require modifications in other system areas. It is best practice in industry, and a top priority for the PHA team performing What-If analyses, that a knowledgeable team is assembled that are familiar with design codes, regulatory requirements, and plant operation makeup. The results of the analysis depend upon the experience of the leader, the team, and the completeness of the list of questions.

Certain steps are inherent to all PHA methodologies (including What-If Analysis); DOE (2004) describes a general 10-step process which applies to all PHAs [DOE 2004]:

A. List processes that are covered.

B. Rank the processes by risk and develop a schedule of PHA.

C. Select the appropriate PHA method for each process.

D. Estimate the required personnel and develop a staffing plan.

E. Select a process to be analyzed.

F. Assemble the PHA team and train its members.

G. Schedule the PHA.

H. Conduct the PHA.

I. Report the analysis results

J. Address the Action Items.

The previous list was grouped into three project-specific PPHA process steps for LFTR implemented by Vanderbilt and EPRI (and shown below with reference back to the above list):

Phase 1: Establishing the What-If questions (encompasses Steps A through E)

Phase 2: Conducting the What-If analysis (encompasses Steps F through H)

Phase 3: Documenting the What-If analysis review and issues requiring resolutions and responsible parties (encompasses Steps I and J)

4.3 Specific Guidance and Methodology of the What-If Analysis

This study uses “What-If” Analysis as a tool to further the LFTR conceptual design by considering safety-related questions (at a high-level) and safety-functions that will need to be addressed for safe operations and licensure. The purpose of this section is to provide specific descriptions of PHA steps listed above that are not self-descriptive (i.e., no further detail on Steps D, F, and G).

During Step “A” as part of Phase 1 and consistent with DOE (2004), the first effort is to break the system under review into individual processes. Since there are many systems and components with a design like the LFTR, it is important to pinpoint which portions are being considered for the purposes of a PHA. The most logical option at the beginning stages of this study were to follow the reactor containment boundary outlined in [Sorensen 2014a,b], which excludes power generation systems beyond the primary heat exchanger as well as material feeds and waste treatment systems. This outline will proceed by dividing the in-containment control volume into six sub-systems (as was generally specified in [Sorensen 2014c]): blanket salt processing system, fuel salt processing system, gas chemical processing system (i.e., H_2-HF supporting systems), drain tank system, reactor vessel, and primary heat exchanger. These top-level subsystems each contain nested subsystems which are discussed below in Table 4-1.

Table 4-1
LFTR System and Components Identified for the PPHA[30]

LFTR System or Component	Potential List of System Components/ Subcomponents	
Reactor Vessel	Graphite Moderator Graphite Reflector Control Rods Hastelloy-N Reactor Vessel	Blanket Salt Piping Fuel Salt Piping Interconnected Piping Instrumentation & Controls
Fuel Salt Processing System	Fuel Salt Fluorinator Fuel Salt Rare Earth Elements (REE) Extractor Settler UF6 Reducer Vortex Mixer Fuel Salt Purification Fuel Salt Pumps Interconnected Piping Instrumentation & Controls	H2-HF Cooler H2-HF Compressors HF Condenser HF Still HF Feed Tank Fluorine Cell Gas System Pumps Interconnected Piping Instrumentation & Controls
Primary Heat Exchanger	Fuel Salt Piping Coolant Salt Piping Fuel Salt Pump	Coolant Salt Pump Interconnected Piping Instrumentation & Controls
Blanket Salt Processing System	Settler Blanket Salt Pa Extractor Decay Salt Pa Extractor Decay Salt Electrolytic Cell Decay Tank	Decay Salt Fluorinator Blanket Salt Pumps Refrigeration Units Interconnected Piping Instrumentation & Controls
Off-gas Handling System	Xenon Holdup Tanks Off-gas Preheaters Off-gas Oxidizers Off-gas Aftercoolers Liquid N_2 Refrigerant System Helium Supply System	Off-gas Surge Tanks Off-gas Compressors Radiation Monitors Interconnected Piping Instrumentation & Controls
Drain Tank System	Blanket Salt Drain Tank Decay Salt Drain Tank Decay Salt Fluorinator Drain Tank Fuel Salt Fluorinator Drain Tank	Fuel Salt Drain Tank Drain Tank Pumps Interconnected Piping Instrumentation & Controls

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[30] LFTR System Description (Section 3) comprises: (1) reactor core(s), (2) primary loop (including the primary pump and heat exchanger), (3) intermediate loop (including the coolant pump and gas heater), (4) power conversion system (including turbomachinery and recuperators), (5) external cooling system (including gas cooler and cooling towers), (6) chemical processing system for reactor fluids, and (7) off-gas handling system for reactor gases.

Traditionally, subsystems are ranked in Step "B" by the risk they represent, but there are additional considerations to be accounted for. The systems prioritized for evaluation in this analysis are those judged to present the highest risk <u>and</u> diverge from previous technology applications. For instance, there are numerous and significant hazards presented by the gas chemical (H_2-HF) system, but evaluation of this subsystem represents a lower priority as it can draw on hazard assessments for other processes which use hydrogen fluoride, such as nuclear conversion and enrichment facilities [IAEA 2010; Siman-Tov 1984].

Accounting for experience, hazardous chemical inventories, activity, temperatures, frequency of use, opportunities for initiating events, and the consequences of those events, a preliminary ranking of the subsystems was developed and is provided below (potential risk shown in descending order):

1) Reactor Vessel and Containment Cell
2) Fuel Salt Processing System
3) Primary Heat Exchanger
4) Blanket Salt Processing System
5) Off-gas Handling System
6) Drain Tank

Full development of the set of What-If questions occurred over the course of several steps and iterations. The basis of the What-If questions was drawn from ORNL documents covering safety-related topics regarding to two MSR development efforts: the MSRE and the MSBR conceptual design work [Beall 1964; Beall 1966; Engel 1966; Kasten 1967; Robertson 1970; Boardman 2013]. Attention was given to basic functional requirements, observed off-normal operational events in the MSRE, and postulated accident scenarios in ORNL literature related to system components that were similar to the LFTR design. An example of a What-If question is "What if loss of blanket salt occurs?" Previously provided material on LFTR system descriptions were then used to formulate other What-If questions not covered from the MSRE/MSBR documentation. Finally, the LFTR technical documents were used to provide a preliminary answer the What-If questions developed with postulated consequences, to the extent possible before conducting the PPHA. Known human health and environmental impacts due to chemical and radioactive material inventories and modern day industry experience with handling such potential hazardous materials were also documented [CCPS 1992; Kolene 2004] (included as part of Appendix B). This information was provided to the LFTR design team prior to the meeting to discuss the PPHA.

Conducting the PPHA (Phase 2) was a structured discussion with the LFTR design team and all involved parties in late May of 2015. Vanderbilt conducted the PPHA by using a tabular format (see Table 4-2) to enable a systematic review of each What-If question, the potential consequences, and measures of mitigation, prevention, and control systems required. An empty cell was provided in Table 4-2 for each What-If question in order to capture potential issues (e.g., safety information pending further design iterations, clarifications on the current design) brought about while conducting the What-If Analysis that would require resolution by the LFTR design team (as described in more detail, below). An option is to assign deadlines to each issue and tracking issues to resolution (this was not included due to the early stage of the LFTR design). The PPHA template follows closely to the table taken from CCPS [1992].[31]

Table 4-2
What-If analysis format for the LFTR review.

What-If Question	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	Applicable References (LFTR and ORNL work)
1. What if …	Potential consequences to system component X are …	Applicable safety systems are…	Applicable references are…
	Issues and Recommendations: Remaining issues that need to be resolved and/or clarified regarding potential consequences, incorporation of safety systems, and applicable references are listed here (with naming responsible parties).		
2. What if …			
3. What if …			

Documenting the What-If analysis (Phase 3) is focused on capturing the conversations in the tabular format shown above, while completing the final two PPHA steps, Step "I" (Report the Analysis Results) and Step "J" (Address the Action Items). Such a tabular structure organizes pertinent information related to each postulated scenario and also allows the responsible individuals to find and resolve issues in a timely manner. All What-If questions, responses and recommendations as generated and captured in the May meeting discussions are found in Appendix A.

The final step of the PPHA is to summarize resolutions to issues uncovered through conducting the What-If analysis (Step "J"). Flibe and TBE have addressed many of these issues within the revised System Design Descriptions (SDDs) as documented in Section 3 of this report. To avoid redundancy, references to the SDD sections within this report are provided in the What-If Analysis Tables (Appendix A), when further explanations or clarifications on safety issues were called for in the "Issues and Recommendations" cell (see Table 4-2).

4.4 PPHA/What-If Analysis Results and Discussion

The results of a What-If Analysis are documented by listing all of the What-If questions, responses, and recommendations generated in the meetings. The entirety of the What-If Questions and responses are found in Appendix A. The full list of What-If questions that were developed and then reviewed during the Phase 2 of the PPHA is shown in Table 4-3. PPHA results, described in the main body of this report, are presented as a summary of significant outcomes of the What-If analysis related to safety and/or potential scenarios causing upset to

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[31] Other "What-If" formats will occasionally include a column for a probability value or rating, potentially enabling a semi-quantitative analysis. Such an approach was not considered for the LFTR PPHA due to data limitations associated with an initial conceptual design.

LTFR system operations. Not all questions from the What-If Analysis are discussed in the Results and Discussion section (Section 4.4).

Table 4-3
What-If questions associated with each LFTR system or component.

LFTR System or Component	What If Question (* denotes questions and responses summarized in this section)
Reactor Vessel/ Containment Cell	What if unintentional control rod withdrawal occurs?*
	What if loss of blanket salt occurs?*
	What if premature criticality occurs during filling?*
	What if the exit temperature of fuel salt from the reactor is much higher than anticipated?
	What if the inflow temperature of fuel salt is relatively cooler than anticipated? / What if inflow of fuel salt contains a “cold slug” or partially frozen salt?
	What if inflow of contaminants or unexpected isotopic ratio in the fuel salt enters the reactor core?*
	What if reactor containment cell pressure is greater than designed operational range?
	What if reactor vessel pressure is greater than designed operational range?
	What if breakage of one or more graphite tubes occurs? *
	What if inadvertent release of fission gas from reactor pressure vessel and/or reactor containment cell occurs?*
	What if accidental loss of fuel/coolant salt occurs?
	What if electrical resistance heaters fail to operate within reactor containment cell?
	What if NaK coolant comes into contact with salt solutions and incompatibility issues arise?
	What if dislodging or jam occurs during replacement of a graphite channel?
	What if flushing of remaining fuel salt after draining reactor core is inadequate and excess residual working salt remains?
	What if a fire outbreaks in the reactor building?
	What if a heavy load drop occurs during maintenance where remote handling maintenance is required
Fuel Salt Processing	What if interruptions in fuel salt flow occur?
	What if decay heat removal rates are lower than expected design rates?
	What if hydrogen reaches the area where fluorine is stored and/or reactor containment cell?*
	What if fluorine accidentally mixes with hydrogen or organic lubricants?*
	What if excess pressure accumulates in the helium bubbler (sparger) used to remove fission products from the fuel salt?*

Table 4-3 (continued)
What-If questions associated with each LFTR system or component.

LFTR System or Component	What If Question (* denotes questions and responses summarized in this section)
Primary Heat Exchanger	What if high pressures cause a minor failure within the primary heat exchanger?*
	What if a major failure within the primary heat exchanger occurs?*
	What if primary fuel pump stops operating?
	What if the sealed housing for the electric drive motors for pumps fail?*
Blanket Salt Processing	What if inadequate removal of Pa or U in the blanket salt occurs due to a failure of the first and/or second reductive extractive column?*
	What if the electrolytic cell is improperly operated?*
	What if blanket salt chemical processing does not occur at designed flow rate?
Off-gas Handling System	What if helium sparger for off-gas fuel salt treatment fails to add adequate/any helium into the fuel salt mixture before entering back into the reactor core?
	What if potassium hydroxide (KOH) is unintentionally released? *
Drain Tank	What if inadvertent thawing of the freeze valve holding fuel salt in the primary coolant loop occurs?
	What if a piece of graphite enters in the drain tank in the event of an emergency drain tank?
	What if the drain tank leaks fuel salt in the event of an emergency reactor shutdown?
	What if improper or inadequate cooling of the drained fuel salt occurs in the event of an emergency shutdown?*
	What if a partially thawed piece of the salt plug (or any other solid mass) obstructs piping to the drain tank occur during times of emergency shutdown?*

What-If questions brought forth from the Appendices are selected by the significance of potential consequences posed to the LFTR system, human health (workers and nearby public), and/or the local environment should an off-normal incident occur. The base design for LFTR components represents the default configuration whenever alternative designs are presented within the SDDs (Section 3).

The 36 What-If questions evaluated for this technology assessment (documented in Appendix A) relate to events that generally fall into four categories: (1) unintentional removal, addition, or accumulation of material in the LFTR system, (2) equipment failure, (3) human/operational error, and (4) an internally-initiated event (e.g., fire).

4.4.1 Reactor Vessel/Containment Cell

Of the 17 What-If questions related to the reactor vessel and containment cell (Tables A-1 through A-17 in Appendix A), six are selected for discussion in greater detail based on the criteria provided in Section 4.4.

What if unintentional control rod withdrawal occurs?

(Table A-1 in Appendix A)

Loss of control over reactivity poses potential significant consequences to any nuclear reactor. By definition, an increase in reactivity is an elevated rate of the fission reaction, and thus core power and temperature rise. Temperature spikes and lack of available ultimate heat rejection sources could cause damage to core internals with possible damage extending to other systems. If a temperature increase were observed during operations due to unintentional control rod withdrawal, the LFTR Design Team stated that corrective actions would include controlled shutdown with remaining reactivity control mechanisms, draining fuel salt into drain tank, continuous circulation of coolant salt, and maintenance on nonfunctional drive rods.

Initially, mechanical control measures in place for LFTR were not self-evident in the LFTR design documentation [Sorensen 2014a] and were clarified in the What-If Analysis discussion and in Sections 3.2.1.1, 3.4.2, 3.5.4, and 3.6.2. As mentioned in previous LFTR design documentation [Sorensen 2014a] and Section 3.1, reactivity can be passively self-controlled by the negative temperature coefficient effect that is an innate characteristic of the salt selected. Three methods of controlling reactivity are now documented in the LFTR system design documentation, for varying levels of control rates.

What if loss of blanket salt occurs?

(Table A-2 in Appendix A)

An interesting outcome of the discussion on the previous question was that the unexpected loss of the blanket salt from the reactor core during operations could present reactivity control challenges. This question was created and then discussed during the May meeting; such improvisation demonstrates the flexibility and creativity of the brain-storming process that occurs during a What-If analysis.

If an unanticipated loss of blanket salt were to occur, reactivity increase within the fuel salt would follow due to the absence of neutron absorbing material in the outer layer of the reactor core. However, it was stated by the LFTR Design Team that it is foreseeable that the fuel salt will expand in volume from higher core power. Negative reactivity feedback could then occur in the fuel salt contained in the outer channels of the reactor, but positive reactivity feedback in the interstitial spacing of the individual salt channels is expected. Methods for control of this reactivity insertion would be similar to those described above and in Table A-1. Specific safety controls have been considered and described in Sections 3.2.1.1 and 3.4.2 to address the issue if the blanket salt lowers in the reactor vessel to an unacceptable level. Section 3.6.5 addresses LFTR system shutdown procedures including blanket salt draining as one of the last steps to provide a source of negative reactivity throughout the shutdown process.

What if premature criticality occurs during filling?

(Table A-3 in Appendix A)

The previous two What-If questions, related to unanticipated loss of control over reactivity increases in any mode (start-up, steady-state, shutdown), but this What-If question addresses the issues of reactivity control specific to start-up conditions. Emphasis was placed by the LFTR design team on administrative controls and operational procedures when safety controls were discussed (see Sections 3.6.2 and 3.6.5) for this particular off-normal incident. However, it should be noted that these types of safety measures are dependent on the final (or near-final) design of the reactor and facility. In Section 3.6.2, the idea of operational philosophy and start-up procedures are addressed by requiring blanket salt presence before loading fuel salt. Once the fuel salt is loaded, then control rods can be slowly and deliberately withdrawn from the reactor.

What if inflow of contaminants or unexpected isotopic ratio in the fuel salt enters the reactor core?

(Table A-6 in Appendix A)

If neutron poisons are present (for example, fission products [FPs]) at higher concentrations than anticipated within a reactor, then reactivity is decreased. A potential sequence of events that was discussed and has the potential for adverse impact is the following: What if the accumulation of FPs cause operators to increase the rate of fissile material addition to counteract neutron absorption of excess FPs, and the accumulation of FPs ceases. This sequence produces another potential reactivity insertion. The LFTR Design Team discussed that operational procedures and administrative controls should be in place in order to implement changes to the rate of fissile material additions. Safety systems in place for controlling significant positive reactivity gains are reliant on the traditional method using controls rods (graphite-tipped boron carbide control rods, as mentioned in Sections 3.2.1.1, 3.4.2, and 3.6.2). Preventive measures that are part of normal operations are to plate out noble metal FPs and remove gaseous FPs through helium bubbling (Sections 3.2.1.6, 3.4.1, 3.4.2, and 3.5.1.4). Additional FP removal occurs within the fuel salt reduction column and is described in Sections 3.4.3.2, 3.4.1, and 3.5.1.3.

What if breakage of one or more graphite tubes occurs?

(Table A-9 in Appendix A)

It was postulated that a piece of graphite moderator could be carried with the fuel salt into the drain tank in the event of an emergency reactor shutdown. The emergency drain tank is designed to eliminate a source of moderation for the fuel salt in the absence of the reflection provided by the blanket salt acting to reduce reactivity. However, with the remnant of graphite now within the entering stream of fuel salt, a localized area could now have potential to reach criticality outside of the reactor vessel. Attention to prevention was given by the LFTR Design Team during discussions and in Sections 3.2.1.1, 3.7, 3.7.1, and 3.7.2 which describes methods of implementing a strong surveillance and testing procedure for the graphite channels in the SDD section.

What if inadvertent release of fission gas from reactor pressure vessel and/or reactor containment cell occurs?

(Table A-10 in Appendix A)

An accident event that could lead to potential overexposure of facility personnel is the release of volatile/gaseous fission products (FPs) from the reactor vessel and/or containment cell. When this particular What-If question was analyzed at the May meeting, there was only one barrier present to prevent FP release into the general area of the reactor building. A more comprehensive safety system was discussed by the LFTR Design Team that could include a variety of sensors and alert systems to fission gas release:

- Radiation sensors for the argon (inert) atmosphere used for containment cell cover gas,
- Operate the off-gas handling system at a lower pressure than the containment cell, and
- A double walled pipe system with radiation sensors monitoring radiation levels in gas flow within the annular space could be installed.

It was also noted that redundant systems should be in place to prevent backflow of volatile/gaseous FPs from off-gas line into the drain tank and then reactor cell. Appropriate sizing of connecting pipelines and negative operating pressures of systems could also potentially mitigate impacts to facility workers (as discussed at a high-level in Sections 3.4.1, 3.4.3.1, and 3.5.1.4).

4.4.2 Fuel Salt Processing

Of the five What-If questions related to fuel salt processing (Tables A-18 through A-22 in Appendix A), three are selected for discussion in greater detail based on the criteria provided in Section 4.4. ***Note: two similar questions have been combined into and addressed in the same subsection.***

What if hydrogen reaches the area where fluorine is stored and/or reactor containment cell?

(Table A-20 in Appendix A)

Both hydrogen and fluoride will be used within LFTR as part of the fuel salt processing system. The potential for consequences exist if the two gases come into contact with one another and it will be important as safety systems are further developed to prevent and/or mitigate accident consequences. It was discussed with the current design that the most likely place to occur is where H_2 and F_2 are separated and one is coming out of the anode and other cathode. LFTR's high operating temperatures (~600°C) will bring the hazard potential closer to realization, but the existence of H_2 and F_2 will not definitively ignite without an ignition source itself. Potential ignition sources are rotating equipment, pumps, and switches.

It was discussed by the LFTR Design Team that careful separation of processes must be designed when H_2 and F_2 are involved. Safety systems including engineering in the containment to mitigate potential consequences were discussed (e.g., keeping lines of H_2 separate and operate at a lower pressure with respect to containment system pressure) and addressed at a high-level as part of Section 3.2.1.6. Future design iterations may look to industry experience for best practices on management of hydrogen storage and intra-movement of hydrogen between segments of the LFTR facility, such as [ISO 2004].

A similar what-if question postulates that contact of fluorine with organic lubricants that could have potential for energetic reactions (Table A-21 in Appendix A). An estimate of the available material vulnerable to combustion could be on the order of $1\text{x}10^0$ (single order of magnitude) of gallons per minute regarding the flow rate used within the fuel salt processing system during normal operations; but the total inventory stored at the facility could be large enough to warrant further actions and redundant safety systems. Accurate accounting for the lubricant inventory required and its location for the LFTR system will need to be performed with a combination of engineering controls and administrative controls. The LFTR Design Team also discussed the idea to investigate solid lubricant options as an alternative.

What if excess pressure accumulates in the helium bubbler (sparger) used to remove fission products from the fuel salt?

(Table A-22 in Appendix A)

It is anticipated that there will be an open interface with the bubble generator and overpressurization could be caused by a closed discharge valve. The safety margin for pressure increase was unknown at the time of the conducting the What-If analysis. Potential overpressurization and limiting components has yet to be developed, but further designs will likely consider margins of operating safety for the helium bubbler system. General system descriptions and requirements are found in Sections 3.2.1.2, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.4.

4.4.3 Primary Heat Exchanger

Of the four What-If questions related to the primary heat exchanger (Tables A-23 through A-26 in Appendix A), three are selected for discussion in greater detail based on the criteria provided in Section 4.4.

What if high pressures cause a minor failure within the primary heat exchanger?

(Table A-23 in Appendix A)

Because the coolant loop pressure (in the range of 10-15 bar) is higher than the fuel salt (near atmospheric pressure, approximately 1-2 bar), a small leak within the primary heat exchanger would cause an injection of coolant salt into fuel salt and reduction of reactivity would occur. The median temperature of fuel salt would then trend downward. The multiple potential root causes that were discussed that can result with a decrease in reactivity led the LFTR Design Team to emphasize the need for a variety of sensors and instrumentation that can differentiate the actual problem so appropriate corrective actions can be taken (see Table A-23). They also noted that a “saw tooth” trend in reactivity would be occurring during normal operations due to batch processing and additions of fuel salt material, which will present challenges when attempting to detect small failures that manifest as slight changes in reactivity. Consistent with the current design, a change in the level of coolant salt material in the pump bowl would become evident first and sensors could be designed using this knowledge. A monitoring system with built-in redundancies is needed.

It was acknowledged in the LFTR system design description that radiation effects to the primary heat exchanger could be the most damaging due to conflicting engineering objectives: optimizing heat exchange by using the thinnest wall possible while providing sufficient structural integrity (Sections 3.2.1.3, 3.4.3.1, 3.7, and 3.7.2).

What if a major failure within the primary heat exchanger occurs?

(Table A-24 in Appendix A)

This What-If scenario differentiates itself from the previous What-If question because the magnitude of the consequences could be larger and the timescale of when the failure occurs to observed consequences is shorter. A major tube failure within the primary heat exchanger causes a large and sudden increase of material in the fuel salt loop because of the pressure differential between the coolant and fuel salt. The contamination of fuel salt with a large portion of coolant salt can cause a rapid and significant decrease in reactivity and median temperature.

The LFTR Design Team stated that reactor shutdown and draining of contaminated fuel salt and leaked coolant salt into drain tank would be necessary. The emergency drain tank needs to be appropriately sized to hold any/all coolant salt loop plus other working fluids in LFTR within proximity of fuel salt loop. The remaining uncontaminated coolant salt would be recovered by treatment involving sending coolant salt through uranium removal chemical processing system. As above, it is acknowledged that the primary heat exchanger may be the most vulnerable to failures because the walls are thin to maximize heat transfer and where radiation fields will be intense (see Sections 3.2.1.3, 3.4.3.1, 3.7, and 3.7.2).

What if the sealed housing for the electric drive motors for pumps fail?

(Table A-26 in Appendix A)

A failure of the sealed housing of the electric drive motors for pumps represents a potential leak of contaminated argon gas into reactor building, because the pump housing is outside of secondary reactor containment and would lead to potential exposure of facility personnel. A redundant set of radiation alarms is required (including any dry well area above the structure containment) and evacuation procedures in place for facility personnel.

The LFTR Design Team stated that a thorough investigation would need to be performed of other containment methods, use of other barriers for leakages and breakthroughs of integral equipment that sits outside of the containment cells. Engineering controls have not been designed as this early of a stage within the system design descriptions, but the general need for protection of workers from radiation hazards with remote operations discussed in Sections 3.2.1.6 and 3.7.2.

4.4.4 Blanket Salt Processing

Of the three What-If questions related to blanket salt processing (Tables A-27 through A-29 in Appendix A), two are selected for discussion in greater detail based on the criteria provided in Section 4.4.

What if inadequate removal of Pa or U in the blanket salt occurs due to a failure of the first and/or second reductive extractive column?

(Table A-27 in Appendix A)

In the event that inadequate removal of protactinium (Pa) or uranium (U) the blanket salt occurs, the batch filling process will be considered insufficient and shut down of blanket salt processing and reactor system will occur. The LFTR Design Team described that fission events in the blanket from accumulated Pa and/or U could result with unintended levels of fission product accumulation that would prompt using the designated drain tanks for the electrolytic cell and/or reductive extraction columns (as discussed in Section 3.3.1). Post-draining, condensation of UF6 in reduction vessels could form hardened UF6 heels in configurations that could pose criticality concerns. Preventive measures were discussed by the LFTR Design Team that could keep UF6 from solidifying and safety features could include appropriately sizing drain tanks to processing vessels. Volume requirements are addressed in Section 3.4.3.1 while the solidification of material within holding tanks is not directly addressed, but the topic of bringing working fluids to operating temperatures is discussed in Sections 3.5.1.1, 3.6.1, and 3.6.2. General system descriptions and requirements are found in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.4.

What if the electrolytic cell is improperly operated?

(Table A-28 in Appendix A)

Improper loading concentrations of metallic lithium and thorium into the metallic bismuth stream could prevent contact with the blanket salt as intended. If excess loading arises, higher concentrations of lithium and thorium will result but effectively will not change the reactivity significantly if the lithium and thorium are placed back into the blanket fuel and enters the reactor vessel. However, too little loading of lithium and thorium onto the anode and cathode of the electrolytic cell will shut down the electrolytic reaction.

The LFTR Design team noted that if bismuth travels to the reactor, potential damage to the core could occur due to Hastelloy-N degradation when in contact with the bismuth contaminant. As MSRE experience unfolded, it was identified that the chemistry of system must be maintained to keep bismuth to ppm levels; however, it was explained by the LFTR Design Team that further research is needed to understand the extent of bismuth concentrations can be tolerated within LFTR. This knowledge will dictate how closely monitored and degree of quality control should be employed during batch processing. Chemistry control requirements described at a high-level in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.3 and characteristics of functional and general system requirements are listed in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.3.

4.4.5 Off-gas Handling System

Of the two What-If questions related to the off-gas handling system (Tables A-30 through A-31 in Appendix A), only one was selected for discussion in greater detail based on the criteria provided in Section 4.4.

What if potassium hydroxide (KOH) is unintentionally released?

(Table A-31 in Appendix A)

KOH is an industrial safety concern and will result with chemical exposure impacts to workers if released [ASHTA 2014]. KOH will be used within the reactor containment, but the LFTR Design Team described that KOH exists at low operating temperatures (~120-150°F). This may present a potential problem by requiring air conditioning system/ partition to the containment to lower ambient gas temperatures from 600°C to ~30°C. A storage and maintenance philosophy will need to be developed if reactive chemicals are chosen as part of the final LFTR design. This will include separation of chemical stocks and use of complex containment with interfaces/locks/pipes interchanges (e.g., perhaps by locating KOH container in an adjoining leg of the reactor containment cell). Because exact chemical stocks and the plant layout configuration have not been finalized, the storage and maintenance philosophy has not been described in detail but a discussion of H_2 and F_2 inventories safe storage is found within Section 3.2.1.6. In future design iterations, the magnitude of potential suite of problems should be evaluated related to the air conditioner system required to lower ambient gas temperature from 600°C to ~30°C.

4.4.6 Drain Tank

Of the five What-If questions related to the drain tank (Tables A-32 through A-36 in Appendix A), two were selected for discussion in greater detail based on the criteria provided in Section 4.4.

What if improper or inadequate cooling of the drained fuel salt occurs in the event of an emergency shutdown?

(Table A-35 in Appendix A)

Use of the emergency drain tank was further explored by asking a What-If question relating to the potential inadequacy of the external cooling system dedicated to cooling drained fuel salt. The result of such a failure mechanism was posited to be unlikely given the planned natural circulation of the drain tank cooling system, which would still be functional without access to external power. Calculations of the cooling requirements have yet to be completed and discussed within the system design description; however, it is noted that a design similar to the direct reactor auxiliary cooling system (DRACS) loop included in the design of the FHR (fluoride-cooled high-temperature reactor), as described in Forsberg (2014), is being considered by the LFTR Design Team.

What if a partially thawed piece of the salt plug (or any other solid mass) obstructs piping to the drain tank occur during times of emergency shutdown?

(Table A-36 in Appendix A)

A blocked line from the reactor vessel to the drain tank could be in the form of an incompletely melted frozen salt plug or a failed component that has become stuck within the pipe. With such an event, this blockage in the LFTR system could represent a loss of the ability to circulate fuel salt and the ability to drain fuel salt completely to the drain tank. A corrective action was discussed by the LFTR Design Team such that coolant salt should be added the drain tank first to reduce potential criticality in the remaining geometry, preceding any fuel salt additions. Safety systems that could be included are a fill sensor for the pump bowl heading combined with subsequent operational procedures/administrative controls before addition of fuel salt material is permitted. Future design considerations would aim to keep the following operations independent (with corresponding safety systems, sensors, etc.): (1) maintaining criticality control/configuration, (2) partial draining, and (3) loss of fuel salt circulation. Design requirements of properly sizing pipelines and drain tank capacities were discussed in Section 3.4.3.1.

4.5 PPHA Summary

What-If analysis/PPHA is a tool used to further the conceptual design by considering safety-related questions (at a high-level) and safety functions that will eventually need to be addressed. Particular to this project, it was useful in the early development stage for both developers and evaluators to check for significant open questions with respect to required safety functions. Ultimately, the objective of PHA is to identify the hazards associated with the system operation. Because PHA is a structured process, many safety related design aspects can be explored, documented and revisited as the design evolves and matures to help advance the design to more comprehensive state.

One tangible outcome of the PPHA/What-If Analysis process was that associated face to face dialog with the developer team led to an important revision of the system description to include operational and maintenance philosophy that had been lacking. PPHA dialog also drove clearer description of safety systems, engineering controls, and administrative controls that were designated for specific event classes (e.g., loss of blanket salt). The PPHA dialog also led to identification of an additional postulated scenario and iterative resolution thereof; this flexibility demonstrates the value of such an open, brain-storming process offered by PPHA/What-If analysis.

The reviewed What-If questions generally fell within four categories: (1) unintentional removal, addition, or accumulation of material in the LFTR system, (2) equipment failure, (3) human/operational error, and (4) an internally-initiated event (e.g., fire or explosion). A short list of the hazards spanning the evaluated LFTR systems and components that were deemed most significant in terms of consequences (based on expert judgment and technical documentation) is presented in Table 4-4. A number of the reviewed What-If questions largely share the technical challenges identified in the 1960s the MSRE era, in which safety studies focusing on reactivity control and reactor operations [Beall 1964]. Other significant hazards not directly tied to neutronics and reactivity control include those related to stresses on and corrosion of primary loop system components operating at high temperatures and in contact with molten salt fluids.

Table 4-4
Important hazards identified during PPHA process with most significant consequences for safety or integrity of LFTR system (Derived from corresponding What If questions).

LFTR System or Component	Hazard Scenario
Reactor Vessel/ Containment Cell	Unintentional control rod withdrawal
	Loss of blanket salt
	Premature criticality during filling
	Inflow of contaminants or unexpected isotopic ratio in the fuel salt
	Breakage of one or more graphite tubes
	Inadvertent release of fission gas from reactor cell and/or containment
Fuel Salt Processing	Hydrogen reacts with fluorine in chemical processing system
	Excess pressure in the helium bubbler
Primary Heat Exchanger	Minor failure in the primary heat exchanger
	Major failure within the primary heat exchanger occurs
	Sealed housing for the electric drive motors for pumps fail
Blanket Salt Processing	Inadequate removal of Pa or U in the blanket salt
	Electrolytic cell is improperly operated
Off-Gas Processing and Treatment	Potassium hydroxide (KOH) is released
Drain Tank	Improper or inadequate cooling of the drained fuel salt
	A partially thawed piece of the salt plug or other solid mass obstructs piping to the drain tank

Overall results of the consequences and issues requiring resolution were discussed in a manner to improve the next LFTR design evolution. A significant outcome to the PPHA review was recognition by the technology design team and technology customer that the PPHA/What-If Analysis has value to all entities involved. The review provides fresh perspectives to act as a sounding board to the designer and architect/engineering team, which the designer can then use this as input to refine and add detail to future design evolutions. The evaluation and review team benefits from gaining an intimate familiarization with the proposed design and an opportunity to gauge and understand work scope and path to commercialization. This process clearly illustrated the benefits of PHA as a structured, repeatable technology review process that can benefit even very early design efforts.

4.6 PPHA References

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5

TECHNOLOGY READINESS LEVEL DETERMINATION

5.1 Introduction to Technology Readiness Levels

A primary motivation for evaluation of the LFTR design is to characterize the maturity of the technology with respect to deployment as a future commercial generation option based on existing documentation, preliminary design detail provided by the developer, and new information developed over the course of the assessment. The technical basis for LFTR and other MSR variants remains heavily rooted in the design and experimental work conducted at ORNL over a two-decade period spanning from the late 1950s to early 1970s.

Liquid-fueled MSRs like LFTR represent a dramatic departure from traditional solid-fueled designs that have operated and are operating at demonstration and commercial scales, incorporating novel systems and components for specialized functions like online fuel cleanup and processing. And similar to other advanced Generation IV concepts under development, operation with new coolants (heat transfer fluids) at higher temperatures (> 500 °C) opens a new set of reliability, performance, inspection and maintenance challenges to be addressed for successful commercialization. Consequently, a measure of technological maturity is required that can accommodate this complexity, novelty, and corresponding variation in the quality and nature of supporting evidence.

The technology readiness level (TRL) represents a common measure of maturity for complex technologies or technology concepts that must perform under extreme environments, e.g., space flight and warfare. Standard TRL determinations measure technology maturity on a scale from 1 to 9, with TRL 1 representing a preliminary description of the scientific and/or engineering principles "on paper" and TRL 9 representing full maturity such as commercial deployment. Figure 5-1 presents a simplified representation of the TRL scale and correlation with broader and more commonly used terms: research, development, demonstration and deployment.

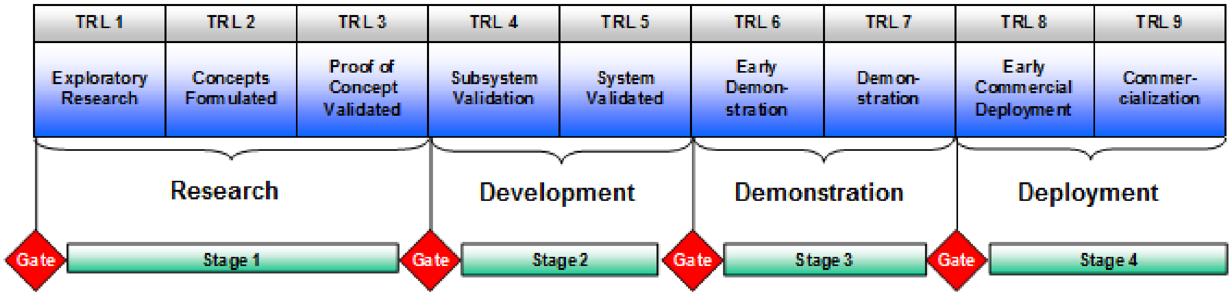

Figure 5-1
Representation of technology readiness levels and suggested alignment with the Research, Development, Demonstration and Deployment paradigm.

TRLs were first developed by the National Aeronautics and Space Administration (NASA) in the mid-1970s to facilitate development of complex engineered systems to meet the challenging conditions of space flight [Mankins 1995]. The U.S. Department of Defense (DoD) developed its own TRL determination process to support development of combat-ready military hardware [DoD 2011]. The U.S. Department of Energy (DOE) developed and implemented a technology readiness standard for waste treatment technologies [DOE-EM 2010; DOE-EM 2013] and is expanding application to other missions [DOE 2011; Krahn 2014]. The International Organization for Standardization has now established an ISO standard for the definition of technology readiness levels [ISO 2013].

5.2 Identification of Critical Technology Elements

Frequently, the first step of TRL determination is to identify components which are called "critical technology elements" (CTEs). In general, a technology element is considered "critical" if it is (1) essential to the success of the system and (2) being used in a new or novel fashion. To determine if this is the case, a series of yes-no questions are answered concerning the component or subsystem in question. A CTE is identified if there is at least one positive response for each set of criteria. The following questions are taken from the Office of Environmental Management's guide to technology readiness assessment [DOE-EM 2013].

Set 1 - Criteria (Yes/No)

- Does the technology directly impact a functional requirement of the process or facility?
- Do limitations in the understanding of the technology result in a potential schedule risk, i.e., the technology may not be ready for insertion when required?
- Do limitations in the understanding of the technology result in a potential cost risk, i.e., the technology may cause significant cost overruns?
- Are there uncertainties in the definition of the end state requirements for this technology?

Set 2 - Criteria (Yes/No)

- Is the technology new or novel?
- Is the technology modified?
- Has the technology been repackaged so a new relevant environment is realized?
- Is the technology expected to operate in an environment and/or achieve performance beyond its original design intention or demonstrated capability?

In addition to the use of these questions, engineering judgment is required to determine the level of detail captured within a technology element. If the system is not adequately characterized or too coarsely defined, valuable information on engineering and development challenges of a design can be obscured. On the other hand, if the system is characterized or defined with too much detail, e.g., at the individual mechanical component level, the TRL determination process will likely prove cumbersome and impractical and will lose much of its value as a decision support tool.

The CTE Identification Process works best for technologies whose system functions have been defined and whose design to implement those system functions has been characterized. The challenge for the LFTR at this stage of design is that some of its important systems and sub-systems have not been fully characterized, and in some cases several design options have been proposed without a final selection having been made (e.g., the coolant material for the drain tank). Thus, at this stage, traditional CTE identification cannot be consistently applied. Instead, engineering-informed judgment is applied to group the design components into logical sub-systems and groups and determine preliminary TRLs for each component. This determination is informed by the progress made during the Molten Salt Breeder Reactor (MSBR) project era (including the deployment of the Molten Salt Reactor Experiment [MSRE]), along with parallel, relevant efforts both for other salt-cooled nuclear energy technologies (e.g., the Fluoride High-Temperature Reactor [Holcomb 2013]) as well as pertinent developments in other industries. Further effort will be needed at a later stage of design development to assess whether each group of components serves a functional requirement of the system; however, this method will be effective in identifying whether a sub-system/component group is new/novel and whether it has been demonstrated in a relevant or partially relevant environment.

5.3 Technology Readiness for Relevant System Components

In a detailed technology readiness assessment (TRA, e.g., per [DOE-EM 2013]), each TRL has a series of associated questions which are answered in a “yes/no” format for each component or subsystem being evaluated. In order to achieve the TRL in question, each of these questions must be answered with a “yes” response and justified by appropriate evidence. The exact wording and nature of these questions can vary by the technology under review, but at a high level, the definitions of the TRLs are similar to those defined by ISO and DOE-EM (see Table 5-1 below) [DOE-EM 2013]. The application of these definitions is guided in part by extended descriptions in the US Department of Energy Technology Readiness Assessment Guide [DOE 2011]. These definitions have been “translated” to examples of evidence directly applicable to an MSR technology such as LFTR.

TRLs are determined for each component group. Each question under the heading for a given TRL must be answered with a “yes” for the CTE to achieve that TRL. In the case where designs are not yet fully specified, as is the case with the LFTR, it can be difficult to clearly answer “yes” or “no” to every question, since the answer may be dependent on a design decision that has not yet been made. Thus, at this preliminary stage, it is more practical to estimate a sub-system or component’s TRL using personnel experienced with the TRL determination process, who have a sound knowledge of the definitions of the TRLs and the nature of the questions associated with each TRL. This is similar to the original TRL determination approach developed by NASA [Mankins 1995] and has been used by other organizations since this time [Mobilia 2013; Liu 2014]. Accordingly, this is the approach currently taken for the sections that follow below.

In some cases it can be challenging to accurately judge the relationship between the intended component and experimental work that was performed for a similar component as part of a different system. Thus, some of the LFTR components have been assigned a “range” of potential TRL values on the 1-9 scale rather than a single value. A single-value determination is still preferred when possible, and most of the estimated TRL ranges only encompass two values for cases where the TRL estimate is “on the fence” between two bins. A few larger TRL ranges are given in cases where key design decisions are yet to be made, and the final TRL would depend on whether the design ultimately selects a more or less technologically mature option.

Table 5-1
General definition of TRLs and corresponding examples of evidence for MSRs.

TRL	Relative Level of Technology Development	TRL Definition from [DOE-EM 2013]	Description of Objective Evidence Requirements, Specific to MSR Technology
9	System Operations	Actual system operated over the full range of expected mission conditions.	The only time this TRL would be applicable is if the component is not intended for contact with molten salts and/or radiation fields, and the component's function and design precisely matches that of a non-MSR application.
8	System Commissioning	Actual system completed and qualified through test and demonstration	See TRL 9 example.
7		Full-scale, similar (prototypical) system demonstrated in relevant environment	See TRL 9 example.
6	Technology Demonstration	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	The component has been used in its intended integration with other components as part of an engineering-scale demonstration system in a near-actual environment. For MSRs, this effectively means that the component had the same intended use during the operation of the Molten Salt Reactor Experiment.
5	Technology Development	Laboratory scale, similar system validation in relevant environment	The component, if intended to operate in contact with molten salts and/or in a radiation environment, would have been exposed to those environments. Even if at reduced scale, the system (or subsystem) should closely resemble that of the fully-scaled operational system.
4		Component and/or system validation in laboratory environment	The component was subject to actual laboratory experimentation. Compared to TRL 3, a greater emphasis is placed on engineering and science, and the component tested should at least be similar to that which is intended for use in the fully-scaled version. The experimentation should indicate that the component at least appears to be capable of interacting successfully with other components.
3	Research to Prove Feasibility	Analytical and experimental critical function and/or characteristic proof of concept	Development of the component has moved from beyond paper studies to preliminary experimentation. These experimental efforts may be complemented by modeling and/or simulation for well-characterized phenomena. Examples include materials testing outside of molten salts, or tests with similar components for other systems with notably different applications.
2	Research to Prove Feasibility/Basic Technology Research	Technology concept and/or application formulated	Practical applications have been proposed to implement basic principles. Development is still limited to analytical studies. Examples include preliminary design reports and system descriptions.
1	Basic Technology Research	Basic principles observed and reported	The underlying scientific principles related to a component function have been described, even if the component has not been fully conceptualized. Examples include publications related to basic scientific principles relevant to a function that may eventually be defined as a specific component.

For TRL determination, the LFTR system is divided into these four subsystems (referred to as "systems" hereafter):

- Reactor Cell (including not only the reactor vessel but other primary-loop components such as the primary heat exchanger, containment, and supporting pumps);
- Power Conversion System;
- Chemical Processing System; and
- Off-gas Handling System.

Of these four, the Power Conversion System is not unique to a molten salt reactor technology and is therefore not considered here for TRL determination. The Off-gas Handling System has is not fully described at the component level in the SDD and therefore is not considered here for TRL determination. **The remaining two systems, the Reactor Cell and Chemical Processing System, are the exclusive focus for further evaluation for TRL determination.**

5.3.1 Reactor Cell (Primary System Components)

The "Reactor Cell" subsystem includes the reactor vessel and its associated internal components, along with other components including and supporting the primary (fuel salt) loop. This includes the primary heat exchanger, the drain tank and its supporting equipment, salt pumps (there are also additional pumps associated with the chemical processing system), primary loop instrumentation, and affiliated piping.

Some LFTR reactor cell components can draw insights from related components of another recently-evaluated molten salt reactor technology. In 2013, Oak Ridge National Laboratory created a Fluoride Salt-Cooled High-Temperature Reactor Technology Development and Demonstration Roadmap to identify research, development, and demonstration (RD&D) needs for a solid-fueled molten-salt-cooled reactor design called the fluoride salt-cooled high-temperature reactor (FHR) [Holcomb 2013]. Part of the report entailed an estimation of TRLs for FHR system components.

In spite of the use of solid fuel, as opposed to the LFTR's liquid fuel, there are a number of system components which are shared by both reactor technologies, and many of the technology readiness conclusions for the FHR are informative for the LFTR. Table 5-2 estimates TRLs for reactor and primary loop components which may have relevant ties to the FHR design. The table also includes how the conclusions of the FHR roadmap may be relevant to the LFTR design and whether design differences exist that would warrant a different estimate for the LFTR relative to that for the FHR.

In some cases, the TRL range for the LFTR component group has been adjusted not due to design differences between the FHR and LFTR, but rather due to a determination that the FHR roadmap estimate required an adjustment. For instance, for even the most mature components, the MSRE or advanced MSBR technology demonstrations represent the extent of component testing, and optimistically these demonstrations would be classified as TRL 6 proofs-of-concept. Also, in many cases the TRL range provided by the FHR Roadmap is too broad to be of much use, and subsequent review of the literature and application of expert judgment has been applied to refine these ranges.

Admittedly, there are some challenges with using the TRL values or ranges described in Table 5-2. In most cases, components were assigned a range of possible TRL values, some of which are rather wide (e.g., TRL 3-8 for the reactor vessel), making it difficult to draw precise conclusions for those components; however, in each case the portion of the system causing the uncertainty is described--given the information availability, this is probably the best approach that can be taken.

There are a few FHR design components which are currently not discussed as part of the LFTR design but could later prove to be relevant. These components, the corresponding TRL estimates, and relevant discussion, are presented in Table 5-3. The FHR, however, is not a perfect surrogate technology for the LFTR. Apart from the chemical processing system (which will be discussed separately in the next section), there are also a handful of components of the LFTR's primary reactor system for which insights from the FHR design are not applicable. These components are presented separately in Table 5-4.

Table 5-2
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][32]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Reactor Vessel Internals	Sub-component of R-1000 (Reactor Vessel)	Reactor Core Structure	3-5	Core materials (C-C composites, compatibility with fluoride salts, heat transfer performance) have basic performance demonstrations. Integration evaluations have not been performed.	Similar to the FHR, Section 3.2.1.1 indicates that the reactor vessel will primarily include graphite structures. LFTR has yet to identify specific composites, but the materials would likely be similar to those in the FHR and the TRL should be similar as well.	3-5
		Reactor Vessel Internals	4-5	Mechanical and radiation performance of materials have been demonstrated in general for ceramic materials, but specific material specification remains to be completed.		
Core Control System	Sub-component of R-1000 (Reactor Vessel)	Control Blades	5	Fabrication and performance of molybdenum with fluoride salts has been demonstrated. Alloying with hafnium remains to be demonstrated.	Section 3.2.1.1 indicates that, most likely, a set of control rods will operate to finely control reactivity. An alternative design of a pneumatic system to hold the blanket salt down is also presented. Because this component has not yet been fully determined, there are a range of possible TRLs corresponding to the diverse experience levels associated with different implementation options.	2-5

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[32] These summaries were developed from descriptions provided in Section 16.2 “FHR Systems, Structures, and Components TRL Assessment” of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][33]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Emergency Shutdown Systems	Sub-component of R-1000 (Reactor Vessel)	Thermal Release Mechanism (Melt-Point Alloys to Trigger Emergency Heat Removal)	3-4	Melt-point alloys are a commercial technology, but use in near-core environment with molten salt environment is unproven. Testing methods will need to be developed. The MSRE moved salt to its drain tanks by use of freeze valves [Guymon 1973, p. 129], but this technology probably not offer the same accident response behavior afforded by melt-point alloys.	Melt-point alloys are mentioned as a form of accident reactivity control for LFTR in Section3.2.1.1, but this is not described as the primary shutdown mechanism. Section 3.5.4 describes how floating control rods will be present in the blanket salt which would be fully removed from the core during routine operation. In a loss-of-blanket accident, these control rods would slide into place in the core and shut down the reaction. The development of this concept is limited to a few paper design studies (e.g., [Germer 1970]).	2-3
Internal Heat Exchanger	Sub-component of R-1000	DRACS In-Vessel Heat Exchanger	3-8	The FHR in-vessel HX will likely be a tube bundle type, which is the most widely used commercial HX type. However, a specific design for the FHR must be developed. *(Note: High end of TRL band seems unlikely, would require testing in molten-salt, radiation environment.)*	Section 3.2.1.1 indicates LFTR will use an internal heat exchanger for blanket cooling, although the design is not specified. Probably similar maturity to FHR in-vessel heat exchanger, although contending with greater FP concentrations than in FHR could be challenging.	3-5

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[33] These summaries were developed from descriptions provided in Section 16.2 “FHR Systems, Structures, and Components TRL Assessment” of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][34]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Reactor Vessel	R-1000 (Internals Addressed Separately)	Reactor Vessel	3-8	Fabrication technologies are commercialized, and MSRE was a demonstration of the technology. However, long-term high-temperature degradation in the presence of molten salts has yet to be studied (the TRL will vary depending on intended component lifetime). *(Note: High end of TRL band seems unlikely, would require testing in molten-salt, radiation environment.)*	Section 3.2.1.1 indicates that, like the MSRE and MSBR, the LFTR will use Hastelloy N as a material of construction. MSR-vessel-grade Hastelloy N has not been fabricated in many years and may require materials development to bring it to ASME standards (potentially requiring a revisit of the applicable ASME pressure vessel code case).	4-6

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[34] These summaries were developed from descriptions provided in Section 16.2 “FHR Systems, Structures, and Components TRL Assessment” of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][35]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Piping	Not Applicable (Piping does not normally routinely receive a separate component number in technology diagrams)	Primary Piping	3-8	Like the reactor vessel, fabrication is commercialized, but long-term high-temperature degradation in the presence of molten salts has yet to be studied and the TRL will vary depending on intended component lifetime. *(Note: High end of TRL band seems unlikely, would require testing in molten-salt, radiation environment.)*	This report does not dwell on the design requirements of LFTR's piping; however, the requirements can largely be inferred from the overall design. The estimated TRL range for FHR piping represents a ceiling for the maturity of LFTR's counterparts; LFTR salts (especially the fuel salt) will also expose the primary piping to significant radiation fields, so the TRL could be somewhat lower than for the FHR. External radiation damage from radiation originating from the reactor vessel could also be significant; a preliminary analysis would need to be conducted to compare whether the impacts from the "internal" or "external" radiation field is more significant.	3-6

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[35] These summaries were developed from descriptions provided in Section 16.2 "FHR Systems, Structures, and Components TRL Assessment" of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][36]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
		DRACS Piping	3-8	Like the reactor vessel, fabrication is commercialized, but long-term high-temperature degradation in the presence of molten salts has yet to be studied and the TRL will vary depending on intended component lifetime *(Note: High end of TRL band seems unlikely, would require testing in molten-salt, radiation environment.)*	Not specified in Section3, but the design and corresponding TRL estimate for the FHR and LFTR are probably comparable. The FHR Roadmap's uppermost TRL range seems unreasonably high.	
		Intermediate Loop Piping	5-8	Piping for molten salts is relatively mature but long-term effects at high temperatures in molten salts are unknown. The intermediate loop may experience more frequent transients than the primary loop during maintenance shutdowns. *(Note: High end of TRL band seems unlikely, would require testing in molten-salt, radiation environment.)*	Not specified in Section3, but the design and corresponding TRL estimate for the FHR and LFTR are probably comparable. The FHR Roadmap's uppermost TRL range seems unreasonably high.	

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[36] These summaries were developed from descriptions provided in Section 16.2 “FHR Systems, Structures, and Components TRL Assessment” of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][37]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Coolant Salt Pump	No Component Number, But Shown in Diagrams	Primary Coolant Pump	4-7	An overhung cantilever pump would be similar to that of the MSRE, but modern seals and bearings to extend maintenance-free performance would need to be demonstrated *(Note: High end of TRL band seems unlikely, would require testing in molten-salt, radiation environment.)*	While not addressed in this report, the LFTR primary pump design will be staying fairly faithful to MSR-era work, so the TRL estimates for the FHR and LFTR are probably comparable. The FHR Roadmap's uppermost TRL range seems unreasonable.	4-6
Primary Heat Exchanger	R-1002	Primary Intermediate Heat Exchanger	3-7	The FHR uses a double-walled HX and yttrium-based tritium trapping in a "liquid salt shell-and-tube" format. The MSRE demonstrated this format and other industries have demonstrated double-walled HXs. However, the tritium-trapping layer is not yet designed.	While not addressed in this report, the LFTR will also employ a shell-and-tube heat exchanger, so the system is comparable to what is described for the FHR. Because tritium trapping will occur in the off-gas handling system for LFTR, the primary HX TRL could be slightly higher for LFTR. However, the FHR Roadmap's upper range of TRL 7 seems unjustified for a technology which at best has been tested at an engineering scale demonstration.	4-6

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[37] These summaries were developed from descriptions provided in Section 16.2 "FHR Systems, Structures, and Components TRL Assessment" of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][38]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Primary Loop Redox Control System	No Component Number, but known to exist from review discussions	Redox Control Systems	3-5	The use of sacrificial carbon electrodes in fluoride salts is the basis for aluminum electrowinning from molten cryolite. Beryllium contacting to make Flibe more reducing was demonstrated in the MSR program, but a specific design of the overall system has yet to be created.	While not addressed in this report, discussion with the LFTR Design Team during internal review noted that redox control via beryllium control contacting will be a part of the LFTR design. Requirements are expected to be similar for FHR and LFTR.	3-5
Instrumentation	No Component Number, but known to exist from LFTR Discussions	Instrumentation	4-9	Some instrumentation is identical to that of other reactor types and is thus commercial. However, in-vessel optical measurements have unresolved integration issues, and demonstration of neutron flux instruments at high temperatures is at an early phase.	While instrumentation and monitoring equipment are not addressed in detail in this report, they are expected to be similar to those used in the FHR with regards to design, function, and maturity. Instrumentation components at the high end of the spectrum (TRL > 7) are limited those which do not come in contact with molten salts and can be essentially the same as those used in commercial LWRs (e.g., a remote radiation detector on the exterior of a piping system). For most primary system components, TRLs 3-5 should be anticipated (it is unlikely that the instrumentation installed on the MSRE would be directly available).	3-9

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[38] These summaries were developed from descriptions provided in Section 16.2 “FHR Systems, Structures, and Components TRL Assessment” of [Holcomb 2013].

Table 5-2 (continued)
TRL estimates for LFTR Reactor Cell components, based on applicability of FHR component TRLs.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Relevant FHR System Component(s) [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][39]	Applicability to the LFTR and Implications for TRLs (and whether conclusions primarily draw from MSRE/MSBR experience)	Modified TRL Range for LFTR Component Group
Drain Tank Coolant Heat Exchanger	R-1103	DRACS NDHX	5-7	NDHXs are commercialized, but a specific design for the FHR that accounts for integration needs to be developed, and tritium may pose challenges	This is most closely analogous to LFTR's drain tank coolant heat exchanger, which in turn is derived from the MSBR design [Robertson 1971]. This component was not fully demonstrated. As noted by the FHR Roadmap, similar heat exchangers are used in commercial applications, but TRLs higher than 4 require testing in relevant environments (i.e., molten salt + coolant + radiation).	4
Coolant Salt Loop Components	No Component Number, but known to exist from review discussions	Intermediate Loop Components	4-7	This includes bellows, rupture disks, a pump, a redox control system, and a salt impurity removal system. The basic technology has been demonstrated in related but non-identical systems.	These components are not specified in this report, but the design and corresponding TRL estimate for the FHR and LFTR are probably comparable.	4-6
Containment	No Component Number, but known to exist	Containment	8	The containment is traditional and low-pressure, although the ability to remove the roof for long-term maintenance is not yet proven. *(Note: This TRL seems too high for a component with a previously undemonstrated feature…TRL 5 seems more appropriate)*	The containment design for LFTR will likely take a similar form to that of the FHR, but TRL seems too high for a component that has not yet been proven	5

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[39] These summaries were developed from descriptions provided in Section 16.2 "FHR Systems, Structures, and Components TRL Assessment" of [Holcomb 2013].

Table 5-3
TRL estimates for FHR Reactor Cell and Primary System components which are not presently described as part of LFTR design but may prove to be relevant.

Corresponding FHR System Component [Holcomb 2013]	Roadmap TRL Range for FHR [Holcomb 2013]	Summary from Holcomb [2013][40]	Potential Applicability to the LFTR and Implications for TRLs
Fluidic Diodes	3-7	Fluidic diodes are an optional FHR component that can be used to minimize bypass flow in the DRACS cooling loop during loss-of-forced-flow-accidents; a similar setup could possibly be incorporated into LFTR's blanket cooling system. Fluidic diodes are a commercial technology, and the proposed scale or operating conditions should not be exceptional. However, a specific design has yet to emerge and component integration is complex.	Fluidic diodes are not mentioned in this report, but they may ultimately be incorporated in future iterations of the LFTR design.
Safety Assessment Tools	3-6	Accident initiators and DBAs have not yet been developed, so modeling requirements have not been developed either. Single-phase heat transfer and coolant flow scan be modeled.	Not a "component" per se, but the insights from [Holcomb 2013] are useful. Different modeling approaches would be required for a liquid-fueled system, but the difference in maturity for safety analysis capabilities between FHRs and LFTRs is probably negligible. Safety assessment tool expectations are significantly different than those of the MSBR era given modern computing capabilities and software quality assurance requirements.
Lithium Isotope Separation (not a reactor component *per se*, but relevant to many LFTR subsystems)	4-6	Displacement band chromatography and electrophoresis methods have been demonstrated at a laboratory scale for fusion energy research. Specific requirements for FHR purities need to be addressed.	The same evidence applies for LFTR, which has similar requirements for Li-6 depletion (<50 ppm).

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[40] These summaries were developed from descriptions provided in Section 8.2.9 "Fluidic Diodes" and Section 16.2 "FHR Systems, Structures, and Components TRL Assessment" of [Holcomb 2013].

Table 5-4
TRL estimates for Reactor and Primary System components which are unique to LFTR.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Preliminary Estimated TRL Range	Summary Justification
Fuel Salt Pump	R-1001	This component was based on the preliminary design for the MSBR in the early 1970s [Robertson 1970]. The fuel salt pump has similar requirements to the coolant salt pump, but exposure to radiation fields from fission products would be considerably higher. The MSRE operated a fuel pump at about 1000 gpm with “satisfactory” performance throughout operation [Smith 1970], and probably represents a similar exposure environment to what would be experienced during operation of the LFTR. Designs were laid out for a molten salt breeder experiment with a pump that was capable of flowrates of 7000 gpm (compared to the LFTR’s fuel pump requirement of 14000 gpm) [Grindell 1969], but this experiment was not realized.	5-6	A very similar fuel salt pump design was demonstrated during MSRE operation albeit at lower flowrates.
Combiner Tank	R-1005	This component was based on the preliminary design for the MSBR in the early 1970s [Robertson 1971]. The combiner tank combines a partial “bleed” flow of the fuel salt with the gases that are removed by the gas separator. Design diagrams show how this component would be integrated with other MSBR components, but the combiner tank receives no further treatment. There is no obvious record of any salt-gas combination technology experimentation occurring at ORNL or elsewhere.	~3	Basic functionality of component described in paper studies.
Gas Separator	R-1006	This component was based on the preliminary design for the MSBR in the early 1970s [Robertson 1971]. Its purpose is to strip helium and fission product gases from the primary fuel salt loop after leaving the core but prior to reaching the primary heat exchanger. [Robertson 1971] affords a few pages (section 3.9, pp. 61-64) to the gas separator and bubble generator concepts. Gas separation efforts performed for homogeneous reactor tests in the 1950s [Hafford 1954] were the basis for this design. However, this system was designed to remove air bubbles from water.	3-4	The underlying principles are known, but experimentation is limited to tests in a completely different environment.

Table 5-4 (continued)
TRL estimates for Reactor and Primary System components which are unique to LFTR.

LFTR Reactor Cell & Primary System Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Preliminary Estimated TRL Range	Summary Justification
Bubble Generator	R-1007	This component was based on the preliminary design for the MSBR in the early 1970s [Robertson 1971]. Its purpose is to add helium from the off-gas handling system to the fuel salt after its helium and fission product content has been removed. [Robertson 1971] affords a few pages (section 3.9, pp. 61-64) to the gas separator and bubble generator concepts. This report specifically notes that almost no previous information was available before the MSBR era on this type of technology. Experiments were performed with specialized Venturi meters, and a conceptual system for the scaled-up design was produced. This work is catalogued in more detail in a separate report [Koger 1972]; this report describes how several candidate materials were tested in approximate bubbler conditions.	4	A related component has been tested in a laboratory environment.
Fuel Salt Drain Tank	R-1101	This component was based on the preliminary design for the MSBR in the early 1970s [Robertson 1971]. Under normal conditions, the drain tank receives helium- and fission-product-loaded fuel salt from the combiner tank and provides passive cooling so the gas can be collected and sent to the off-gas handling system. The drain tank is also intended to provide storage and passive cooling to the fuel salt inventory in the event of a major reactor vessel breach. The MSRE included two fuel salt drain tanks in its design for safe storage of fuel salt during shutdown periods [Guymon 1973, p. 129]. Small molten salt drain tanks have been constructed for molten-salt test corrosion loops, but these were not exposed to radiation fields or integrated with a reactor cell [Huntley 1976].	~5	A related component has been tested in a laboratory environment. The MSRE had drain tanks, but the design may have somewhat different design requirements than LFTR's.
Fuel Salt Catch Pan	R-1102	This component was based on the preliminary design for the MSBR in the early 1970s [Robertson 1971, pp. 143-144], although it was originally conceived for a one-fluid design. This component is only intended to play a role during an event of gross reactor vessel damage and would direct all fluids exiting the vessel into the drain tank. The MSBR design for the catch pan was fairly specific regarding material and supporting valve requirements. However, it does not seem that this was concept was actualized in a laboratory.	3-4	Critical functions described with moderately detailed design and analysis
NOTE: The LFTR design infers that a blanket salt pump will not be required since it is assumed that natural circulation will be sufficient for the blanket due to the heat removal process with the internal heat exchanger; however, the concept remains to be demonstrated.				

5.3.2 Chemical Processing System

While a subsystem of the LFTR design, the chemical processing system itself is a combination of many different functional component groups. Unlike the reactor cell, it is difficult to draw conclusions for large numbers of components from any one source. The FHR, for instance, has been designed for a once-through fuel cycle, and considerations of online chemical processing are limited to the continuous removal of impurities (salt cleanup) using bismuth-lithium reductive extraction. In contrast, the LFTR design requires an integral processing system for fuel and blanket salt inventories. The LFTR chemical processing system is broken down into five foundational functions [TB 2015b]:

- Reductive extraction of metals from a salt into metallic bismuth;
- Fluorination of salt to separate uranium as the gaseous uranium (VI) hexafluoride (UF_6);
- Reduction of gaseous UF_6 to UF_4, using hydrogen gas in presence of salt;
- Reduction of salt compounds to metals and free fluorides (via electrolytic cells), using bismuth as both anode and cathode; and
- Reduction of hydrogen fluoride to hydrogen gas and fluoride gas via electrolytic cells

The LFTR design includes 35 individual components that collectively serve and support these five functions. However, several of these components serve similar or redundant functions, and they have been grouped accordingly to simplify the preliminary TRL determination process. Table 5-5 names these components and also adds a few additional groups which need to be considered for comprehensiveness.

For some of the components related to the conversion of hydrogen fluoride to hydrogen gas and fluorine gas via electrolytic cells, the technologies are very similar to those used in the conversion and/or enrichment of natural uranium, which would already provide experience with a low-level radiation environment. However, many of the more volatile fission products (namely: I, Br, Se, and Te) would be anticipated to pass through this part of the chemical flowsheet, potentially imparting a higher impact from radiation than would be the case during uranium conversion or enrichment. A rough comparison of the anticipated radiation impacts from these fission products versus those from the natural uranium decay chain would be needed to determine the full relevance of the operation of commercial facilities for the uranium fuel cycle as TRL evidence in this application.

Table 5-5
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
Blanket Salt Reductive Extraction Column	W-3101	Derived from MSBR [Carter 1972]. The reference system was a one-fluid design. The fundamental concept was demonstrated in an experimental setup with a salt containing thorium and rare earths [Rosenthal 1969, p. 194].	3-4	Demonstrated at laboratory-scale, but high concentrations of REEs represents somewhat different environment
Decay Salt Reductive Extraction Column	W-3102	Derived from MSBR [Carter 1972]. The MSBR project focused mostly on separating Th from REEs, since its one-fluid design contained a fuel salt with 12% Th and less than 1% U-233. Thus, while the fundamental concept of reductive extraction has been demonstrated in a laboratory, the decay salt's significant Pa and U-233 content in LFTR means that the tested environment is not identical.	3-4	Demonstrated at laboratory scale, but would need to be examined specifically for salt with high Pa, U content
Decay Salt Electrolytic Cell	W-3103	This component's design is based on an MSBR report [Carter 1972] for W-3103, but then Table 7 indicates that such a feature is NOT described in [Carter 1972] so this may be a mis-citation. In any case, [Carter 1972] only describes electrolysis for HF-H_2 systems. The LFTR desires this cell to reduce both Th and Li; an experimental design was demonstrated to reduce 99% of incoming thorium, but lithium reduction was not an objective [Rosenthal 1969, p. 273].	3-4	Demonstrated at laboratory scale for related but not identical system with somewhat different objectives
Decay Salt Storage Tank	T-3104	This component's design is based on an MSBR design [Carter 1972]; this report does mention that Pa-233 will be stored but does not describe the design of such a storage tank [Carter 1972, pp. 3-5]. Another report acknowledges some of the functional requirements of such a tank, including that a Pa decay tank would require its own heat exchanger to remove decay heat, to the extent that the maximum heat generation rates would imply that associated technologies with the Pa isolation system "will require considerable development" [Wheatley 1970]. Discussions of the criticality/safeguards aspects of such a tank have not been identified.	3-4	The general requirements of such a system have been described and past reports have indicated some design parameters, but the concept remains to be demonstrated. It may be possible to draw from reactor vessel designs, which could arguably bring the TRL closer to 4.

Table 5-5 (continued)
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
Salt Fluorination Columns	R-3105, R-3201	In these columns, gaseous molecular fluorine is bubbled through the decay or fuel salt, with the purpose of oxidizing uranium from a tetrafluoride to a hexafluoride. Fuel salt was fluorinated from the MSRE during the U-233 phase of operation in significant quantities (211 kg) [Rosenthal 1969, p. xii]. The decay salt is not expected to require any differences in design regarding fluorination.	6	Technology demonstrated on engineering scale in relevant environment
Salt Settlers (Bi Removal)	P-3106, D-3203	The purpose of these components is to allow any entrained bismuth to leave the blanket or fuel salt before returning to the system. Molybdenum is listed as the material of construction, but the component does not reference a particular design report as a basis. Bismuth removal from fuel salt was a stated objective of the MSBR project; “engineering experiments” were performed with bismuth-laden fuel salt which resulted in bismuth concentrations between 10 to 100 ppm. It was speculated that bismuth concentrations could be removed further by contacting the salt with nickel wool, although that technique did not reach the experimentation phase [Rosenthal 1972, pp. 352-353]. Some developmental needs for this proposed campaign were outlined in a separate report [Carter 1972, pp. 61-62].	3-4	Some bismuth removal strategies have been tested in laboratories. It is unclear how these strategies would integrate with the LFTR system, so the TRL straddles the 3-4 cutoff
Bismuth Pumps	P-3141, P-3142, P-3242	The details of the LFTR bismuth pump design have not been characterized. The MSBR design also called for bismuth pumps [Carter 1972, p. 55], which would use electromagnetic (EM) technology [Rosenthal 1969, p. 194]. Experiments were performed with thorium-laden bismuth, and the EM pump was demonstrated at rates of 50 to 200 cc/min [Rosenthal 1969, p. 195]. EM pump technologies have evolved since time, but it is not believed that a relevant demonstration has been conducted since the MSBR era.	5-6	Demonstrated at laboratory scale in relevant (thorium-laden) environment, on cusp between laboratory and engineering scale

Table 5-5 (continued)
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
Decay and Fuel Salt Pumps	P-3143, P-3144, P-3241, P-3243, P-3244	The requirements for the decay and fuel salt pumps in the processing system are anticipated to be similar to those for the fuel salt pump in the reactor system (see Component R-1001 in Table 5-4). According to LFTR material flow calculations, the flow rates through the chemical processing system are several orders of magnitude smaller than those through the primary system. Thus, the appropriate scale has already been demonstrated for the decay and fuel salt pumps of the chemical processing system.	6	A very similar fuel salt pump design was demonstrated during MSRE operation
Fuel Salt Reductive Extraction Column	W-3202	Derived from MSBR [Carter 1972]. The MSBR salt, which contained much more thorium than fissile uranium-233, was probably more representative of the LFTR's blanket salt than its fuel salt, so the experiments performed for the MSBR [Rosenthal 1969, p. 194] may not be as directly applicable to fuel salt reductive extraction. Still, the concepts are at least similar.	4	Demonstrated at laboratory scale, but would need to be examined specifically for 233U-REE separations
Fuel Salt Hydrogen Reduction Column	R-3204	The hydrogen reduction column contacts UF_5 from the fuel salt with molecular hydrogen to form UF_4 and hydrogen fluoride. The design is adapted from [Carter 1972], which refers to the component as a "purge column" [Carter 1972, p. 18]. It is not evident that experimentation was done with this component, but columns which reduce uranium penta- and hexafluoride with hydrogen have been used in other applications (e.g., the production of uranium metal), although these would have been subject to lower radiation fields [Yemel'Yanov, 2013, p. 174]	4	A similar component has been demonstrated in an environmental with much lower radiation and less complicated chemistry.

Table 5-5 (continued)
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
Vortex Mixer	A-3205	The vortex mixer is used to merge gaseous mixtures of UF_6-F_2 with fuel salt to form UF_5, which in turn feeds the hydrogen reduction column. Prior to the operation of the MSRE, experiments were performed which involved combining uranium- and plutonium-bearing molten salts with hydrogen fluoride gas; the experimental procedure implies that this required a mixing step but does not specify the technique that was used [Cathers 1962, pp. 1-2, 5].	3	It appears that there is some experimental basis for mixing molten salts with fluoride gases, but the applications are only loosely tied to LFTR's functions.
Fuel Salt Purification System	R-3206	The purpose of this component is not fully described; however, an internal review indicated that this system is intended to remove oxide and sulfate impurities. A system for the removal of these impurities was described in [Shaffer 1971, pp. 7-11] and was deployed for the MSRE. This system used hydrogen fluoride to react with oxide anions to produce water (which could be removed as water vapor), while sulfates required reduction to the sulfide ion with hydrogen and volatilization to dihydrogen sulfide via hydrogen fluoride. These systems performed effectively for the MSRE, although it is unclear if it is possible to readily implement this technology into the LFTR design.	4-6	The MSRE included a system which executed these functionalities effectively; the compatibility with LFTR needs to be assessed.
H_2-HF Cooler and Compressors	X-3301, X-3302, X-3303	This component group collectively cools the H_2 and HF gases coming from the salt purification system (R-3206) and then compresses them to feed the condenser. Hydrogen fluoride and hydrogen cooling and compression are commercial technologies for miscellaneous industries [Acton 2013, p. 96]. However, these applications are not exposed to volatile fission products that would be present in LFTR's H_2-HF system. Compressor systems have been used at uranium enrichment facilities which operate in low-level radiation fields [NRC 2008]. Whether this experience is applicable to the radiation fields presented by LFTR volatile fission products is unclear.	4-5	Commercialized technology for non-radiation environments and natural uranium processing, but need to assess impact of fission product presence on design requirements

Table 5-5 (continued)
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
HF Condenser and Still	X-3304, X-3305	The exact functionality of this component group is not immediately clear from preliminary design documents. However, it is implied that this component group receives the compressed H_2-HF, liquefies the HF, and distills the mixture into separated liquid HF and gaseous H_2. While further clarification is needed, discussions with the LFTR Design Team suggest that the fission products (as hydrogen halides) are anticipated to follow the hydrogen gas, whereas it seems more likely that they will behave more like HF. Documentation about separations of gaseous HF from hydrogen are scarce in any context.	2-3	Component does not appear to be rooted in prior reports or designs, will require subsequent attention
HF Feed Tank	D-3306	This is a storage tank that receives the liquid HF from the still for subsequent use in the Fluorine Cell. Essentially any chemical industry which relies on a reaction with hydrogen fluoride will require some sort of feed tank like this one. However, the maturity of this system is dependent on whether or not fission product gases are expected to traverse this portion of the system.	4-6	Commercial technology, but need to assess impact of potential fission product presence on design requirements
Fluorine Cell	Q-3307	The fluorine cell electrolyzes the HF into hydrogen gas (H_2) and fluorine gas (F2). Uranium enrichment uses fluorine gas and relies on electrolysis to accomplish fluorine production. However, the chemical reaction described to explain the function of this component ($HF + 2e^- \rightarrow H_2 + F_2$) is not viable, in part because HF is such a poor conductor of electricity. Instead, HF must be mixed with KF and then melted to enable electrolysis to proceed; it is not possible without KF's catalytic effects [Kirsch 2004]. Whether the radiation environment from uranium enrichment is applicable to the radiation fields presented by LFTR volatile fission products is unclear.	4-6	Assuming design modification, represents commercialized technology for natural uranium processing, but need to assess impact of fission product presence on design requirements

Table 5-5 (continued)
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
KOH Scrubber	W-3308	Some of the more volatile fission product compounds (e.g., iodine, bromine, selenium, and tellurium) follow the hydrogen gas into the H_2-HF processing unit and are removed here. Acidic gases such as HI and HBr are routinely scrubbed using KOH by various chemical industries [Chironna 2011]. No references were identified which documented H_2Se or H_2Te removal via KOH in any industry. Regardless, while halide removal processes are commercialized, they do not have to deal with radioactive isotopes of the halogens.	~4	Approach demonstrated commercially for HI and HBR, but not at all for H_2Se or H_2Te. Also, no experimental work involving radiation.
KOH Reservoir and Evaporator	D-3309, W-3310	This component group stores the residual KOH reactant used in the scrubber for eventual evaporation. While not explicitly stated in design reports, it is implied that the function of the evaporation system is to remove water resulting from reactions of hydroxide and acidic gases from the scrubbing agent so that the remaining potassium hydroxide can then be re-used. Such processes are used commercially to prepare dry potassium hydroxide products [Ashta 2003]; however, it is not evident that such a process has been used in conjunction with the radiation environment posed by the halide fission products.	4	Approach demonstrated commercially in non-radiation environment, would require testing or validation for operation in radiation environment
Salt Drain Tanks	T-3401, T-3402, T-3405	These drain tanks would not be used during routine operation but rather would be employed if an incident required the rapid drain of reactants from one of the reaction columns. These tanks would handle streams that could contain significant concentrations of bismuth, so molybdenum as a construction material is planned. A Hastelloy N drain tank was tested (see component R-1101 in Table 5-4). This difference in structural material places the achievement of TRL 4 in question, as the different chemical, thermal and structural responses of Hastelloy and molybdenum have to be evaluated to determine whether design properties are impacted.	~4	A related component has been tested in a laboratory environment, but with a very different structural material.

Table 5-5 (continued)
TRL estimates for LFTR Chemical Processing components.

LFTR Chemical Processing Component Group	Constituent Component(s)	Notes on Design Derivation or Other Experience	Estimated TRL Range	Basis
Salt Fluorinator Drain Tanks	T-3403, T-3404	These have a similar function to the salt drain tanks, but Hastelloy N is a sufficient construction material for these tanks since no bismuth is present. Given the lack of additional functionality requirements, these components should be at least as mature as the Fuel Salt Tank in the Reactor Cell (see component R-1101 in Table 5-4).	4	A related component has been tested in a laboratory environment.

5.4 Insights from Preliminary TRL Determinations

As would be expected for any advanced nuclear reactor technology, there are many components and functionalities which require experimentation, testing, and demonstration prior to scale-up or commercial deployment. Significant data gaps identified for LFTR are summarized in the tables above. The ONRL Molten Salt Reactor Experiment, characterized here as an engineering-scale reactor demonstration, essentially represents the primary source of experimental data and experience for the molten salt reactor technology class. As a result, most components do not score above TRL 6. Most component groups are assigned TRLs of 3 to 6 (Figures 5-2 and 5-3), which span late Development to early Demonstration stages.

Relative to commercial deployment, the requirements to reach complete maturity can appear daunting, so a more manageable goal is to focus on near-term activities that support the eventual deployment of a modern, demonstration-scale version of the LFTR. This preliminary TRL determination effort has resulted in the identification of several "challenge areas" which can inform near-term decision-making for LFTR technology development.

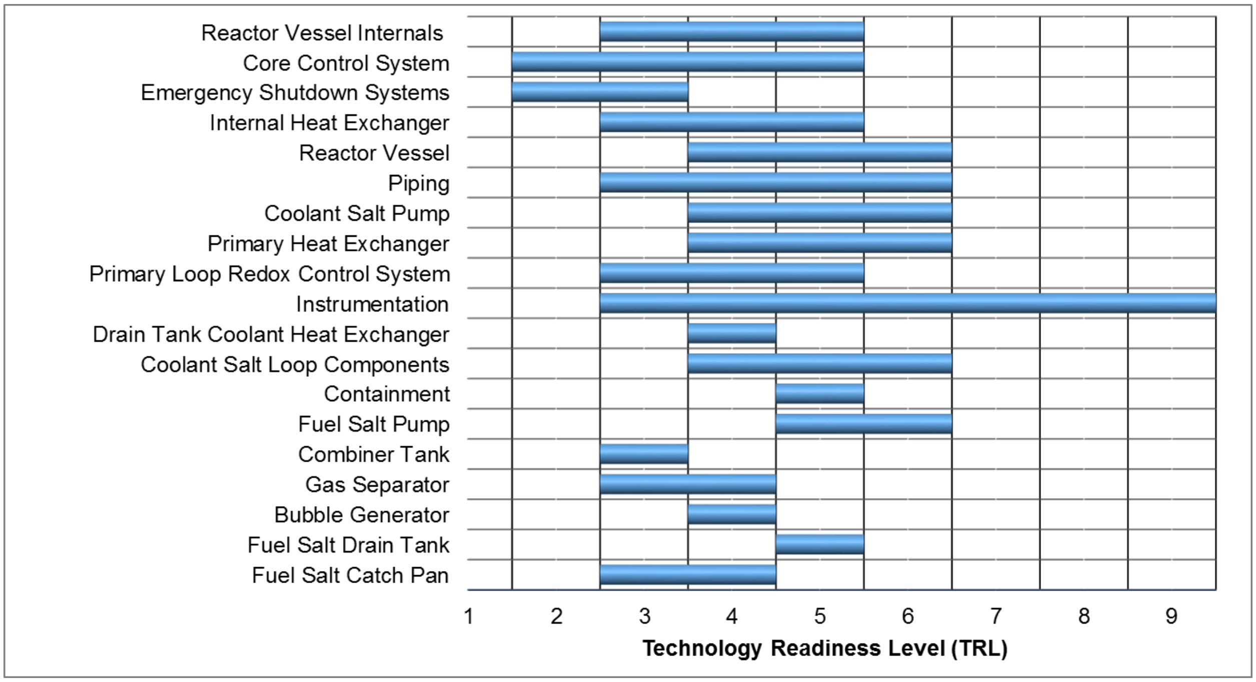

Figure 5-2
TRL results for LFTR Reactor Cell and Primary Loop components.

The reactor vessel components of LFTR generally will require significant new work prior to reaching the demonstration phase. In many instances, it is challenging to define a specific TRL without the final selection of a specific technology option; at this phase of the LFTR design, there are often several candidate technology options presented. Most of these options have not been tested in a radiation environment with molten salts at any scale, setting the highest TRL achievable as 4 in these instances (as shown in Figure 5-3). In some cases, experience with a component is limited to distantly-related experimental proofs of concept or design reports, and TRLs 2-3 are more appropriate.

There are some primary-system support components which warrant particular attention. The LFTR system relies heavily on in its Drain Tank and supporting components (including the catch pan) for many safety-related and operations and maintenance functions. While the MSRE also had drain tanks, their key role in LFTR during operations and accident scenarios and additional performance requirements means that the LFTR drain tank is more nearly a new, untested component. While the drain tank and catch pan are related to components described during MSBR design efforts, these designs were not completed, and the extent of testing varied. Another area with relatively little associated experience pertains to components with salt-gas interfaces, such as the combiner tank, the gas separator, and the bubble generator.

With regards to the LFTR chemical processing system, most of the components are drawn from design and testing performed during the MSBR era. However, the intended components for the MSBR were not developed evenly; some components were thoroughly tested in relevant radiation and salt environments, while others were merely described in a few sentences of a report.

Component groups which will require attention include: the decay salt storage tank, components related to the removal of bismuth (e.g., the salt settlers), and components related to the salt-gas interfaces and separations (e.g., the vortex mixer); the last of which also presents a challenge for the primary system, as noted above. All of these components were described to a degree in later MSBR design reports and did not receive as much attention prior to the end of the project in the late 1970s. Significant work was performed on reductive extraction systems with large mass fractions of thorium which augments the maturity of the blanket salt processing system; however, the high fissile concentrations of LFTR's fuel salt introduce additional considerations that make the fuel salt reduction system somewhat less mature.

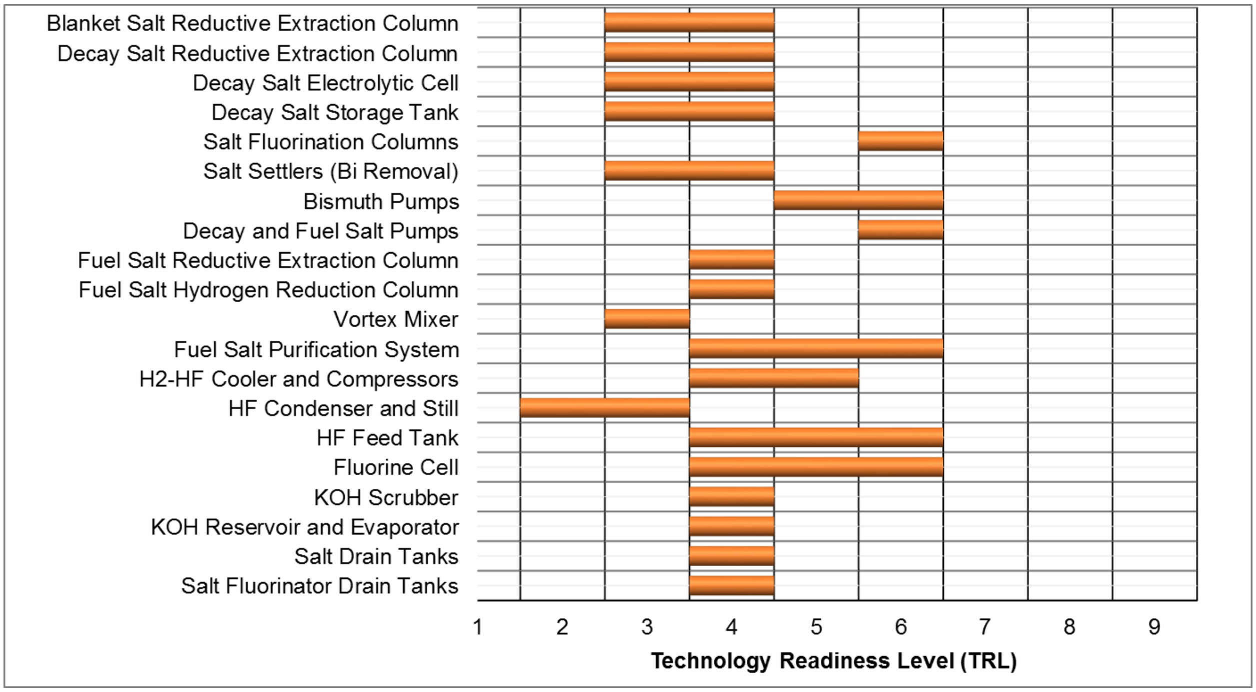

Figure 5-3
TRL results for LFTR Chemical Processing System components.

It is important not to overlook the fluorine chemistry processing subsystem, which contains several components that will require additional experimentation and development. Most of the components are similar to those used in commercial chemical facilities involving fluorine or hydrogen fluoride; however, the presence of volatile fission products (iodine, bromine, and possibly tellurium and selenium) may impart additional design requirements that have not yet been anticipated. Uranium conversion facilities, which currently operate primarily in support of the once-through fuel cycle in light water reactors, entail the combination of chemistry and a low-radiation environment. The applicability of this experience will depend on a preliminary assessment of the quantities of fission products that are expected to pass through this LFTR subsystem and the resulting radiation exposure of the components.

While not addressed as a "component" *per se*, LFTR deployment will be dependent upon the availability of highly-depleted lithium, i.e. lithium which contains less than 50 ppm of the isotope Li-6. Lithium isotope separation was performed in significant quantities at the Oak Ridge Y-12 National Security Complex in the 1950s and 1960s; however, this process relied on large quantities (>10,000 tons) of mercury which involves a number of health and safety issues and later resulted in non-trivial environmental management problems [Brooks 2011]. Since this time, work has been performed in several countries to develop a solution that is safe, environmentally conscious, and commercially effective.

Lithium isotope separations techniques have been developed which rely on liquid-liquid solvent extraction (e.g., [Nishizawa 1984; Kim 1991; Xu 2013]) or on the use of laser-based excitation (e.g., [Arisawa 1982; Olivares 2002]). The results have shown an increasing effectiveness of performance, and with the well-documented experimental procedures and results the TRL for lithium isotope separations probably sits on the cusp of TRLs 4 and 5. However, significant work will be required to scale this process up to the extent required for LFTR operation. Furthermore, while the sequence of development is less important for other projects, the availability of this technology will be required for the overall LFTR system to achieve TRL 6 and will facilitate achieving TRL 5. This example demonstrates the importance of considering factors beyond just system components when preparing a strategic response to a TRL determination.

5.5 TRL Determination Summary and Conclusions

Assigning an "overall" system TRL is difficult at this stage of design since there are still several subsystems or component groups for which final design decisions have not yet been made. Traditionally, the overall system TRL is equivalent to that of the least mature component. Depending on final design decisions, the LFTR could ultimately implement components which could capitalize on physical phenomena with little prior application. However, there are several identified components which are probably at no higher than TRL 3 at the present time, particularly for certain chemical processing components that were still speculative in late-era MSBR work and never reached component-specific laboratory experimentation. The estimates presented in this report should be regarded as "baseline" estimates; additional evidence from other studies could justify slightly higher TRL estimates for certain component groups. In general, TRLs evolve as a function of time, and in addition to new developmental work, sometimes the resurfacing and review of previous work can improve technological maturity.

It is worth keeping in mind that many of the TRL estimates for LFTR are based on evidence provided by the MSRE and MSBR projects which are now several decades past. Most TRL determination methods, including the approach used in this report, do not explicitly account for the fact that the applicability of evidence can decline over time, as the ability to reproduce particular demonstrations can be lost. For instance, a certain required material may no longer be manufactured regularly, validation for a supporting software tool may have lapsed or evolved since the previous demonstrations, or quality assurance expectations may have changed. This notion of "obsolescence" with regards to evidence requirements can result in somewhat overstated TRL estimates for technologies which have not been the subject of recent research, development and demonstration [Valerdi 2004].

Further, it is important to remember the significance of a TRL determination. The levels are not intended to serve as a "grade", but rather they provide a snapshot in time of technological maturity. For an advanced technology concept like LFTR which has many unique components, even compared to its most related predecessor (the engineering-scale setup of the Molten Salt Reactor Experiment), it is not surprising that many of LFTR's components would require extensive modeling and laboratory research and testing, with an eventual transition to scaling-up to larger tests and demonstrations. Nonetheless, there are still several components which were either subject to significant development and testing in the MSBR era or which benefit from work on other projects which have taken place since that time. These insights should facilitate the prioritization of resources for subsequent research and deployment efforts for technologies related to the LFTR design.

5.6 TRL Determination References

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A

WHAT-IF ANALYSIS TABLES

What-if analysis tables are reproduced for reference on the following pages.

A.1 Reactor Vessel/Containment Cell

Table A-1
What if unintentional control rod withdrawal occurs?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Increase in reactivity leading to increasing temperatures. Stopped operations and reactor shutdown	Safety systems for different levels of reactivity control and redundant systems: (1) Shutdown: graphite-tipped boron carbide rods with continued circulation of coolant salt, (2) Slow control: change U-233 concentration by slowing introduction of U-233 into the inflow stream of the reactor, (3) Fast control: graphite-tipped boron carbide rods Corrective actions would include controlled shutdown with remaining reactivity control mechanisms, draining fuel salt into drain tank, continuous circulation of coolant salt, and maintenance on nonfunctional drive rods	May 19-20, 2015 PPHA Discussion [VU 2015] [Sorensen 2014a] Document pg. 2
	Recommendation(s) :	a. Share conceptual design information on redundant safety systems including control rods b. Evaluate potential consequences, safety systems, mitigative measures, and corrective actions associated with loss of blanket fuel What-if question c. Incorporate material discussed above (and previous recommendation) by including revisions into the Conceptual Design document/ System Design Description (SDD) d. Add What-If question for loss of blanket fuel *(resolved)*	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.2.1.1, 3.4.2, 3.5.4, 3.6.2) b. Flibe Energy: Addressed (see Table A-2) c. Flibe Energy: Addressed d. Vanderbilt University: Resolved (see Table A-2)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Excessively high temperatures; first in the fuel salt loop, and ultimately in the coolant salt loop, with resultant damage to equipment and, if unchecked, loss of primary containment	Scram any remaining functional control rods; Open vent valves; relieves filling pressure in fuel drain tanks One or more control rods are provided in the MSBR in order to provide flexibility in reactor operations, and to control reactivity additions such that fuel temperatures and associated temperatures do not become excessive The normal complement of control rods is three, of which two are required to scram for safety action. The maximum scram time (time from initiation of signal until a rod is in the seat) is 1.3 seconds. The rod speed (motor powered) is 0.5 ± 0.05 inches/second. This speed permits maximum reactivity additions in “start” of 0.1% ðk/k per second. The scram time will be checked before each fill with fuel salt. The power level for safety-rod scram trip is 15Mw of less. (The maximum steady-state power level is 10Mw [administrative limit]). A positive period of 1 second or less will cause a safety-rod scram.	[Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row I [Kasten 1967, ORNL-TM 1858] Report pg. 20 [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 4, 5

Table A-2
What if loss of blanket salt occurs?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Increase in reactivity leading to increasing temperatures due to lack of neutron absorbing material in the outer layer of the reactor core. It is expected that expansion of fuel salt will occur. Negative reactivity feedback will occur in the fuel salt within outside channels but positive reactivity feedback in the interstitial spacing is expected. Temperature spike increase expected. Stopped operations and reactor shutdown	Safety systems for different levels of reactivity control and redundant systems: (1) Shutdown: graphite-tipped boron carbide rods with continued circulation of coolant salt, (2) Slow control: change U-233 concentration by slowing introduction of U-233 into the inflow stream of the reactor, (3) Fast control: graphite-tipped boron carbide rods Corrective actions would include controlled shutdown with reactivity control mechanisms and draining fuel salt into drain tank, continuous circulation of coolant salt. Alternatively, in the event of a loss of blanket accident, graphite prisms would slide down into the core due to the drop in fluid level and their own buoyancy, introducing more negative reactivity in the reactor than the positive reactivity that would be introduced by the loss of the blanket. In the event of blanket salt loss (maybe due to a puncture to the reactor vessel), blanket salt would drain to designated catch pan/holding vessel.	May 19-20, 2015 PPHA Discussion [VU 2015] [Sorensen 2014a] Document pg. 2 [Sorensen 2014a] Document pg. 2
	Recommendation(s):	a. Address the issues of where the blanket salt would drain to. b. Incorporate material discussed above (and previous recommendation) by including revisions into the Conceptual Design document/ System Design Description (SDD)	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Section 3.6.5) b. Flibe Energy: Addressed (see Sections 3.2.1.1, 3.4.2, and 3.6.5)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: Could represent a loss of primary containment. Contamination of coolant salt, coolant salt loop, and components therein, with possible contamination of area in the event radiator or other coolant system components fail. Otherwise, no hazard exists.	Potential use of similar safety systems, corrective actions, and mitigative measures of the MSRE: Scram any remaining functional control rods; Open vent valves; relieves filling pressure in fuel drain tanks One or more control rods are provided in the MSBR in order to provide flexibility in reactor operations, and to control reactivity additions such that fuel temperatures and associated temperatures do not become excessive The normal complement of control rods is three, of which two are required to scram for safety action. The maximum scram time (time from initiation of signal until a rod is in the seat) is 1.3 seconds. The rod speed (motor powered) is 0.5 ± 0.05 inches/second. This speed permits maximum reactivity additions in “start” of 0.1% δk/k per second. The scram time will be checked before each fill with fuel salt. The power level for safety-rod scram trip is 15Mw of less. (The maximum steady-state power level is 10Mw (administrative limit)). A positive period of 1 second or less will cause a safety-rod scram.	[Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row I [Kasten 1967, ORNL-TM 1858] Report pg. 20 [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 4, 5

Table A-3
What if premature criticality occurs during filling?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Prompt criticality could occur due to improper reactor configuration of absent blanket salt and sufficient presence of control rods. Posited overheating and system shutdown with use of drain tank	Safety systems for different levels of reactivity control and redundant systems: (1) Shutdown: graphite-tipped boron carbide rods with continued circulation of coolant salt, (2) Slow control: change U-233 concentration by slowing introduction of U-233 into the inflow stream of the reactor, (3) Fast control: graphite-tipped boron carbide rods Procedural requirements for filling the reactor vessel with fuel salt will need to require blanket salt to be present in the system before fuel salt filling begins. Physical/mechanical safety system(s) could be designed to prevent filling without blanket present. Corrective actions would include controlled shutdown with reactivity control mechanisms and draining fuel salt into drain tank, continuous circulation of coolant salt. Alternatively, in the event of a loss of blanket accident, graphite prisms would slide down into the core due to the drop in fluid level and their own buoyancy, introducing more negative reactivity in the reactor than the positive reactivity that would be introduced by the loss of the blanket.	May 19-20, 2015 PPHA Discussion [VU 2015] [Sorensen 2014a] Document pg. 2 [Sorensen 2014a] Document pg. 2
	Recommendation(s):	a. Information on procedural requirements could be added to the operational philosophy section (if incorporated into SDD). b. Share conceptual design information as its being developed on safety systems related to blanket salt loss/absence and incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.6.2 and 3.6.5) b. Flibe Energy: Addressed (see Sections 3.6.2 and 3.6.5)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Excessively high temperatures; first in the fuel salt loop, and ultimately in the coolant salt loop, with resultant damage to equipment and, if unchecked, loss of primary containment	Scram any remaining functional control rods; Open vent valves; relieves filling pressure in fuel drain tanks The maximum amount of U-235 which will be added at one time is 120 grams. During operation fuel will only be added through the sampler-enricher. Physical restrictions on the fill rate and safety actions of control rods and gas control valves limited the calculated power and temperature excursions so that any damage to the reactor would be prevented.	[Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row I [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 5 [Engel 1966, ORNL-TM-0497] Abstract pg. 1 of PDF, Report pg. 27

Table A-4
What if the exit temperature of fuel salt from the reactor is much higher than anticipated?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Raised median temperature (as a combination of raised inlet and exit temperature) will melt the freeze valve and fuel salt will dump to the drain tank with reactor shutdown.	Corrective actions depend on the rate of median temperature gains: If a slow temperature gain is observed (on the order of days), fissile material addition rate is lowered. If the temperature gain is relatively quick, the increased temperatures will volumetrically expand the fuel salt, thereby decreasing reactivity. Lowered reactivity can also occur from the corrective action of lowering power output at the turbine/generator ("Power conversion feedback process"). Reducing power output translates to less heat rejection of the coolant loop (secondary coolant loop) and then fuel salt loop (primary coolant loop). Heat accumulation will result in higher exit temperature and median temperature will rise with accompanying increased fuel salt volume – leading to decreased reactivity. The intended safety system employed during quick median temperature gains is to dump the fuel salt into the drain tank. The freeze valve will melt when the median temperature of the fuel salt exceeds the melting temperature threshold of the frozen plug. Control of the median temperature is done by controlling fissile addition rates. The spread of the outlet temperatures is controlled by the power output level at the power conversion stage.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Information on procedural requirements could be added to the operational philosophy section (if incorporated into SDD). b. Determine where expansion of fuel salt displacement will occur during times of rapid temperature increase – (excess volume goes into off gas lines or integrated design for overflow?) and incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.4.3.1 and 3.6.4) b. Flibe Energy: Addressed (see Sections 3.4.3.1 and 3.5.1.1)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Excessively high temperatures (> 1300°F) of the fuel salt would cause excessively high temperatures first in the fuel salt loop, and ultimately in the coolant salt loop, with resultant damage to equipment and, if unchecked, loss of primary containment	Scram control rods; Open vent valves; relieves filling pressure in fuel drain tanks The temperature level for safety-rod scram trip is less than 1400°F. Adjustment of the trip between 1300°F and 1400°F will require administrative approval.	[Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row II [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 5

Table A-5
What if the inflow temperature of fuel salt is relatively cooler than anticipated? / What if inflow of fuel salt contains a "cold slug" or partially frozen salt?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	If inlet temperature of fuel salt is too low, freezing could occur with potential to damage equipment If the fuel salt inlet temperature is decreasing, and the exit fuel salt temperature is increasing, then power production has slowed or stopped.	A corrective action when the median temperature decreases is to increase reactivity by addition of fissile material until desired operating median temperatures are reached. Operational procedures to prevent low inlet temperatures are to maintain reactivity levels and power production loads.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Information on procedural requirements could be added to the operational philosophy section (if incorporated into SDD). b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Section 3.6.4) b. Flibe Energy: Addressed (see Section 3.6.4)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: No hazard; warns that potential radiator freeze-up may be developing. Potential causes could be due to malfunction of load control system, cessation of power generation in core from any cause (scram, drain, and rupture in primary containment) or loss of coolant flow.	Corrective action would be to drop radiator doors. Redundancy in the three independent channels is present and any two will initiate safety action. Monitoring includes a thermocouple break or detachment from pipe that will produce a safety action in that channel.	[Beall 1964; ORNL-TM-0732] Report pg. 64, Table 2.2, Row XV
	No real hazard; if the graphite moderator channels have already been preheated and the fuel salt is added a significantly lower temperature, then heat transfer to salt from graphite occurs with slight increase to reactivity (2%) vs. the mandatory shutdown margin (3.2%).	Stop filling of fuel salt and allow for heat transfer from graphite to fuel salt.	[Engel 1966, ORNL-TM-0497] Report pg. 27
	If a "cold slug" enters the system, this could represent a concentrated fissile volume and could increase reactivity and temperature to unacceptable levels.	For the cold slug incident: Scram all rods Open vent valves; relieves filling pressure in fuel drain tank From the standpoint of reactor safety, the most important coefficients appear to be the temperature coefficients of reactivity for the fuel salt, the blanket salt, and the graphite moderator, and the duel concentration coefficient of reactivity…the temperature coefficient itself can add reactivity by means of "cold slug" type occurrences	[Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row I [Kasten 1967, ORNL-TM-1858] Report pg. 19

Table A-6
What if inflow of contaminants or unexpected isotopic ratio in the fuel salt enters the reactor core?

What if inflow of contaminants or unexpected isotopic ratio in the fuel salt enters the reactor core?			
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	If neutron poisons are present (generally fission products) at higher concentrations than anticipated, then reactivity is decreased. A potential sequence of events that could be consequential is that the accumulation of FPs would cause operators to increase the rate of fissile material addition to counteract neutron absorption of excess FPs, the accumulation of FPs could exit the reactor and a sudden spike in reactivity could occur, leading to overheating and reactor shutdown.	Operational/administrative procedures should be in place in order to implement changes to the rate of fissile material additions. Safety systems requiring fast control of reactivity will be used (graphite-tipped boron carbide control rods). Safety systems for different levels of reactivity control and redundant systems: (1) Shutdown: graphite-tipped boron carbide rods with continued circulation of coolant salt, (2) Slow control: change U-233 concentration by slowing introduction of U-233 into the inflow stream of the reactor, (3) Fast control: graphite-tipped boron carbide rods	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). b. Determine potential systems could accumulate fissile material by plate out, precipitation, or hydraulic flow inefficiencies. c. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Section 3.2.1.6, 3.4.2, and 3.5.1.4) b. Flibe Energy: Addressed (see Section 3.2.1.6, 3.4.1, 3.4.2, and 3.5.1.4) c. Flibe Energy: Addressed (see sections listed above in a. and b.)	

Table A-6 (continued)
What if inflow of contaminants or unexpected isotopic ratio in the fuel salt enters the reactor core?

What if inflow of contaminants or unexpected isotopic ratio in the fuel salt enters the reactor core?			
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: If a reactivity addition is large enough, a graphite tube separating the fuel and blanket fluids may break because of the pressure rise, with no other untoward effects. If the reactivity addition is so large that the reactor vessel ruptures and generates a disruptive force which results in penetration of reactor containment.	Reactor shutdown for repairs. “Prompt” protection is afforded by the negative temperature coefficient and “delayed” protection is provided by control rods and also by drainage of fuel salt from the core region. Reactor shutdown and emergency procedures for involved personnel and potentially nearby members of the public The maximum concentration of fissionable material in the fuel salt will not exceed by more than 5% the minimum required for full-power operation at 1200F with equilibrium xenon and the control rods poisoning 0.6% δk/k. The fuel salt will be sampled and the concentration measured at least once per week. At no time during critical operation of the reactor will the reactivity anomaly be allowed to exceed 0.5% δk/k. A “reactivity anomaly” is defined as a deviation from the reactivity which is expected on the basis of measured reactor physics constants and calculated effects of burnup and fission production accumulation. Fuel and coolant systems are provided with equipment for taking samples of molten salt through pipes attached to the pump tanks while the reactor is operating at power. The fuel sampler is also used for adding small amounts of fuel to the reactor while at power to compensate for burnup. Sometimes organic materials polymerize in the off-gas handling system under the intense beta radiation of the gaseous fission products to form the viscous liquids and solids that plugged the valves and the entrances to the carbon beds. This problem has been reduced by installing absolute filters for trapping solids and heavy liquids ahead of the control valves.	[Kasten 1967, ORNL-TM-1858] Report pg. 22-23 [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 5 [Briggs 1967, ORNL-TM-1851] Report pg. 63 [Briggs 1967, ORNL-TM-1851] Report pg. 69

Table A-7
What if reactor containment cell pressure greater than designed operational range?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Eventual loss of coolant salt with high temperature feedback into the core. Reactor shutdown required	Safety systems include blowout valves in the secondary gas heat exchanger design to prevent accidental pressurization of the reactor cell. Preventive measures: Keep water out of LFTR system (reactor vessel, containment cell, chemical processing units). In the event of gross reactor vessel damage a catch pan exists to direct fluids to the drain tank If entry of high pressure CO_2 into the coolant salt occurs from the power conversion stage, rupture disks are provided at points on the coolant salt loop as incorporated into the secondary gas heat exchanger design which would prevent a pressure surge from reaching the reactor cell in the event of interference in the gas heater. Normal LFTR design pressure is 3 atm inside of the reactor containment cell.	May 19-20, 2015 PPHA Discussion [VU 2015] [TB 2015b, FSP1 Report] Report pg. 39
	Recommendation(s):	a. Verify that these blowout valves are part of the revised conceptual design and the safety functions are equivalent to ones listed in the previous version of the conceptual design report. b. Incorporate information discussed above into Conceptual Design report/SDD and refer to potential useful reference identified in the footnotes of this table.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.3.1 and 3.4.3.1) b. Flibe Energy: Addressed (see sections listed above in a.)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: If reactor containment cell pressure greater than 2 psig, indication/evidence that a malfunction exists and a potential loss of secondary containment is possible If the reactivity addition is so large that the reactor vessel ruptures and generates a disruptive force which results in penetration of reactor containment	Keeping the reactor cell at negative pressure (-2 psig) [13 psia]; Close the instrument air block valves; Close liquid waste system block valve (from reactor cell sump to waste tank) Pressure suppression systems are provided, the reactor cell system being separate from the system used for the other compartments. Suppression systems contain water storage tanks so released vapors released into a cell would pass through these tanks and be condensed, maintaining cell pressure below the design value. Reactor shutdown and emergency procedures for involved personnel and potentially nearby members of the public. “Prompt” protection is afforded by the negative temperature coefficient and “delayed” protection is provided by control rods and also by drainage of fuel salt from the core region. The pressure in the reactor and drain tank cells will be maintained below atmospheric pressure during reactor operation. The building high-bay pressure will be maintained at slightly less than atmospheric pressure (~0.1 in. H2O) during all operations in which the high bay serves as the secondary containment… The cover-gas supply pressure will be kept at 30 psig or greater and the leak-detector system pressure above 50 psig to help prevent excessive exposure to operating personnel. The maximum coolant system cover-gas pressure is 50 psig.	[Beall 1964; ORNL-TM-0732] Report pg. 63, Table 2.2, Row XII [Kasten 1967, ORNL-TM-1858] Report pg. 9. [Kasten 1967, ORNL-TM-1858] Report pgs. 22-23 [Beall 1966, ORNL-TM-0733 Rev.2] Report pgs. 2,4,5

Table A-8
What if reactor vessel pressure is greater than designed operational range? / What if reactor vessel is overfilled with fuel salt and/or blanket salt?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Scenarios causing reactor vessel overpressurization (e.g., overfilling fuel salt into the reactor) could cause other lines to and from the reactor to be blocked and/or filled from excess fuel salt. Required shutdown and dumping of fuel salt into drain tank. If vessel pressure is higher than anticipated due to median temperature increase, the potential for the freeze valve to the drain tank to melt could occur. Required shutdown and dumping of fuel salt into drain tank would follow (See Table A-4 and Table A-6).	To prevent overpressurization from an overfill scenario, use safety systems like fill sensors in the pump bowl and/or size the surge capacitor (this may be the use of off-gas lines to the drain tank) large enough to handle outflow of fuel salt and transverse directional flow of gas that is being replaced with fuel salt. Overpressurization could occur from physical displacement of fuel salt from other causes other than times of fuel salt filling (such as unintentional control rod insertion, etc.). In the event of gross reactor vessel damage a catch pan exists to direct fluids to the drain tank	May 19-20, 2015 PPHA Discussion [VU 2015] [TB 2015b, FSP1 Report] Report pg. 7
	Recommendation(s):	a. Determine new sizing requirements for surge capacitors and how will this safety system be incorporated into the next LFTR design iteration within the Conceptual Design Report and SDDs. b. Determine potential design changes to accommodate prevention of overfilling accidents of blanket salt. Information on procedural/administrative requirements on filling procedures could be added to the operational philosophy section (if incorporated into SDD).	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Section 3.4.3.1) b. Flibe Energy: Addressed (see Section 3.5.1.1)	

Table A-8 (continued)
What if reactor vessel pressure is greater than designed operational range? / What if reactor vessel is overfilled with fuel salt and/or blanket salt?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
MSRE/ MSBR:	MSRE: Potentially an indication/evidence that a malfunction exists and a potential loss of primary containment is possible. Could lead to consequences similar to improper inflow isotopic ratios If a reactivity addition is large enough, a graphite tube separating the fuel and blanket fluids may break because of the pressure rise, with no other untoward effects. If the reactivity addition is so large that the reactor vessel ruptures and generates a disruptive force which results in penetration of reactor containment. During an overfilling incident of fuel salt there will be a loss of capacity to handle fuel expansion or overfill. The off gas line became plugged by fuel salt when the pump bowl was accidentally overfilled while the calibration of the liquid level indicators was being investigated. Salt was discharged into some of the lines attached to the pump bowl and froze in the cold sections.	Reactor shutdown for repairs. "Prompt" protection is afforded by the negative temperature coefficient and "delayed" protection is provided by control rods and also by drainage of fuel salt from the core region. Reactor shutdown and emergency procedures for involved personnel and potentially nearby members of the public The reactor vessel operates around 100psi, 100 psi less than the coolant salt lines so that in the event of a primary heat exchanger tube failure, leakage of radioactive fuel salt into the secondary circuit will be maintained Drain fuel if fuel salt overfilling incident occurs The maximum salt fill rate while filling the core is 1.0 ft^3/min. The normal fill rate is limited to under 0.5 ft^3/min (around 0.4 ft^3/min) which during normal fill operations, this should take around 3-4 hours. A filling operation can be interrupted at any time by any one of the three actions: venting the drain tank though the auxiliary charcoal bed, equalizing drain tank and loop pressures, and shutting off the gas addition to the drain tanks. In an emergency, all three would be done or attempted simultaneously. Either of the first two actions would not only stop the fill but would allow the salt in the loop to drain back to the tank. The third action, stopping gas addition, would be used if it were desired to hold up the fill at any point. Heaters were applied to the lines to remove most of the salt but it was necessary to open the off gas line and break up a small amount of material in part of the line. Careful attention to the interface between hot systems and cold systems in the breeder design.	[Kasten 1967, ORNL-TM-1858] Report pg. 22-23 [Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row IV [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 5 [Engel 1966, ORNL-TM-0497] Report Pg. 17, Pg. 26 [Engel 1966, ORNL-TM-0497] Report Pg. 19 [Briggs 1967, ORNL-TM-1851] Report pg. 69

Table A-9
What if breakage of one or more graphite tubes occurs?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	"To be Determined" status at the time of the May meeting (dependent on the pressure differential between the fuel and blanket salt).	"To be Determined" status at the time of the May meeting.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Determine potential consequences, safety systems, mitigative measures, and corrective actions if this issue arises. b. Determine a range of differences in operating pressures for the fuel and blanket salt loop in the LFTR design. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). c. Incorporate information above into Conceptual Design report/SDD and refer to potential useful references identified in the footnotes of this table.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Section 3.2.1.1, 3.7, 3.7.1, and 3.7.2) b. Flibe Energy: Addressed (see Section 3.2.1.3) c. Flibe Energy: Addressed (see sections listed above in a. and b.)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE and MSBR: Potential for further damage to core.	Scram any remaining functional control rods; Open vent valves; relieves filling pressure in fuel drain tanks	[Kasten 1967, ORNL-TM-1858] Report pg. 23
	The scenario that could potentially present the largest reactivity addition in an MSBR if net addition of fuel salt to core occurs from a rise in fuel salt loop. This could lead to excessively higher temperatures (> 1300°F) of the fuel salt would cause excessively high temperatures first in the fuel salt loop, and ultimately in the coolant salt loop, with resultant damage to equipment and, if unchecked, loss of primary containment	If breakage occurs under normal situations, addition of fertile blanket salt to the fuel region and reduce reactivity.	[Beall 1964; ORNL-TM-0732] Report pg. 61, Table 2.2, Row II
		All reactor and drain tank cell shield blocks shall be in place and secured by the hold-down devices whenever fuel salt is in the reactor vessel	[Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 4
		Recent experiments with molten salt under high temperatures led to an accident as a violent outburst of molten salt potentially caused by a blockage of a tubing connection or some failure in the connection fitting.	[Boardman 2013, TEV-1789] Molten Salt Gasifier Event Analysis, Report Executive Summary

Table A-10
What if inadvertent release of fission gas from reactor pressure vessel and/or reactor containment cell occurs?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Potential overexposure to facility workers	If leaked off-gases from off-gas handling system migrate to the containment cell, as of the May Meeting, only one barrier was present in the LFTR design. A safety system that could be implemented that includes a variety of sensors and alert systems to fission gas release: • Radiation sensors of argon (inert) atmosphere used for containment cell cover gas • Operate the off gas system at a lower pressure than the containment cell • A double walled pipe system with radiation sensors monitoring radiation levels in gas flow within the annular space.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Include redundant systems to prevent backflow of volatile/gaseous FPs from off gas line into the drain tank and then reactor cell. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix. b. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD).	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.5.1.4) b. Flibe Energy: Addressed (see Sections 3.4.1 and 3.4.3.1)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Potential for excessive exposure to operating personnel	Drain fuel. Close in-cell cooling air system vent (to stack) valve. Off-gas activity release will be limited to fission product concentrations averaging less than 1.4 x 10^{-4} μc/cc in the stack (based on 3 x 10-9 μc/cc as permissible concentration at ground level downstream of the stack. An atmospheric dilution of 0.5x10^5 is assumed). The ventilation system filters will be tested at least annually and after each change of filers. The measured efficiency of the filters must be greater than 99.9% for 0.5μ and larger particles. The cover-gas supply pressure will be kept at 30 psig or greater and the leak-detector system pressure above 50 psig to help prevent excessive exposure to operating personnel.	[Beall 1964; ORNL-TM-0732] Report pg. 62, Table 2.2, Row VI [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 3,4 [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 2

Table A-11
What if accidental loss of fuel/coolant salt occurs?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	No severe consequences anticipated related to loss of fuel salt if draining to drain tank due to partial melting of freeze valve. Much more severe consequences anticipated related to the loss of blanket salt. A temperature spike in the fuel salt will likely occur if the event of loss of coolant salt.	In the event of gross reactor vessel damage a catch pan exists to direct fluids to the drain tank Reactor shutdown by continued passive means by dumping fuel salt in drain tank	May 19-20, 2015 PPHA Discussion [VU 2015] [TB 2015b, FSP1 Report] Report pg. 7 [TB 2015b, FSP1 Report] Report pg. 28
	Recommendation(s):	a. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.2.1, 3.2.1.2, 3.4.3.1, 3.5.1.1, 3.5.3, and 3.6.4)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	Could represent a loss of primary containment. Contamination of coolant salt, coolant salt loop, and components therein, with possible contamination of area in the event radiator or other coolant system components fail. Otherwise, no hazard exists.	Drain Fuel Drop radiator doors A flow loss at full power will freeze the radiator in 2 minutes if no corrective action is taken Leakage from the primary system as indicated by the reactor and drain tank cell air activity will not exceed the equivalent of 4 liters of salt after 120 days of operation at full power, as estimated in the case of the "most probable accident" as described in [Beall 1964; ORNL-TM-0732]. The maximum reactor and drain tank cell leak rate will not be allowed to exceed 1% of the cell volume per day, calculated for the conditions of the Maximum Credible Accident as described in [Beall 1964; ORNL-TM-0732]. The in-leakage rate will be determined at least once per week	[Beall 1964; ORNL-TM-0732] Report pg. 62, Table 2.2, Row VII and Report pg. 64, Table 2.2, Row XIV [Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 3,4

Table A-12
What if electrical resistance heaters fail to operate within reactor containment cell?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	If failure occurs during normal operations, then no impact is foreseen. If failure occurs during maintenance shutdown mode, then impact will be the inability to start LFTR system operations.	"To be Determined" status at the time of the May meeting.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Include safety systems, mitigative measures, or corrective actions related to this incident and LFTR system component. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix. b. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD).	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.5.1.1, 3.6, 3.6.1) b. Flibe Energy: Addressed (see sections listed above within a.)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: If selective freezing of concentrated fissile material in the fuel salt due to inadequate heating occurs, the potential for premature criticality (see Table A-3, Table A-5, and Table A-6).	See Table A-3, Table A-5, and Table A-6)..	[Engel 1966, ORNL-TM-0497] Report pg. 28

Table A-13
What if NaK coolant comes into contact with salt solutions and incompatibility issues arise?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	"To be Determined" status at the time of the May meeting. Trade study on NaK and other potential coolant options must be done.	"To be Determined" status at the time of the May meeting.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Trade study on NaK and other potential coolant options must be done. Final coolant selection must be evaluated for compatibility with other chemicals used in LFTR design. Other considerations of final coolant selection are safe storage, handling, and intra-LFTR transport of such chemicals. b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. Chemical reactivity of fluorine and hydrogen gas stored inventories is discussed in Section 3.2.1.6. b. Flibe Energy: Not directly addressed. To be resolved in future design studies.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	High chemical energy and potential for large exothermic reactions when contacted with moisture in the air, excess water, and even the residual amounts of moisture within contacting concrete structures [Adams 1961, DOE 1996]. There is also potential for combustion of NaK if in contact with paraffinic oils (e.g., kerosene) that are commonly used in aqueous nuclear reprocessing systems [Adams 1961].	MSRE: The bearings on the fuel circulation pump are lubricated and parts of the pump are cooled by oil. The oil is separated from the pump tank by a rotary seal. Provision is made for directing the normal seal leakage of 1 to 10 cc per day of oil to a waste tank and preventing liquid or vapor from coming in contact with the salt or cover gas in the pump tank. Under special conditions, demonstrated in a pump test loop, this oil can leak through a gasketed seal in the pump presently in the MSRE and into the pump tank where it vaporizes. The vapors mix with the helium purge stream and flow into the off-gas handling system. The oil has no effect on the fuel salt, but the organic materials polymerize in the off-gas handling system under the intense beta radiation of the gaseous fission products to form the viscous liquids and solids that plugged the valves and the entrances to the carbon beds. This problem has been reduced by installing absolute filters for trapping solids and heavy liquids ahead of the control valves	[DOE 1996, DOE-STD-6003-96] [Adams 1961, ORNL-3147] [Briggs 1967, ORNL-TM-1851] Report pg. 69

Table A-14
What if dislodging or jam occurs during replacement of a graphite channel?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Shutdown reactor with the lid off would be required. Could not restart until maintenance and possibly replacement of reactor components would be required.	Shaping of graphite is discussed as an important manufacturing step for the successful LFTR system operations.	May 19-20, 2015 PPHA Discussion [VU 2015] [TB 2015d] DGM Report Report pg. 6,21
	Recommendation(s):	a. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix b. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD).	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see sections listed below in b.) b. Flibe Energy: Addressed (see Section 3.2.1.1, 3.7, 3.7.1, 3.7.2, and information in Table A-9)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	Consequences to reactor system could arise possibly due to radiation induced growth of graphite.	The maintenance philosophy should consider accumulation of radiation damage and information from Briggs 1965 reference.	[Briggs 1965, ORNL-3872], Report pg. 93

Table A-15
What if flushing of remaining fuel salt after draining reactor core is inadequate and excess residual working salt remains?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Potential shutdown of reactor and raised level of maintenance effort.	“To be Determined” status at the time of the May meeting.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Verify low elevation points in the piping design in LFTR with simulants before LFTR operations begin. Considerations of final coolant selection are safe storage, handling, and intra-LFTR transport of such chemicals. b. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). c. Incorporate information discussed above into Conceptual Design report/SDD and the Data Gaps Report. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. Chemical reactivity of fluorine and hydrogen gas stored inventories is discussed in Section 3.2.1.6. b. Flibe Energy: Addressed (see Section 3.7.2)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE/MSBR: Previous circuit fuel salt remains in the reactor pressure vessel, piping circuits and pumps with potential to disrupt system dynamics and chemical compositions of working fluids	Adequate amounts of flushing salt must be used	[Thoma 1971, ORNL-4658] report pg. 61 [Lindauer 1969, ORNL-TM-2578]

Table A-16
What if a fire outbreaks in the reactor building?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Reactor shutdown. Potential damage to equipment. Potential for incompatibility issues to arise with fire suppressant material and working fluids used within the LFTR system Uses of water as an extinguisher would react violently with any released NaK and subsequently hydrolyze any F_2 and produce HF (with potential to cause immediate serious injury to workers).	"To be Determined" status at the time of the May meeting.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Investigate potential fire suppressant material with respect to options that pose the least amount of reactivity potential with LFTR working fluids (focusing on avoiding water as the fire suppressant material). b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. To be resolved in future design studies. b. Flibe Energy: Not directly addressed. To be resolved in future design studies.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	No discernible information gleaned from the literature reviewed.	No discernible information gleaned from the literature reviewed.	

Table A-17

What if a heavy load drop occurs during maintenance where remote handling maintenance is required (e.g., reactor cell, drain tank, fuel processing cells, off-gas handling system components, venthouse)?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Potential damage to equipment and extensive repairs and maintenance to delay restart. Potential for overexposure of workers if radiation shielding is damaged	“To be Determined” status at the time of the May meeting.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Iterate design for “dense pack” of LFTR system (stacked configuration of reactor vessel, drain tank, primary heat exchanger, and primary coolant pump) b. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). c. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not addressed. “Dense pack” still shown as reference design in Section 3.5.2. b. Flibe Energy: Remote operations and maintenance were addressed in Sections 3.7 and 3.7.1. c. Flibe Energy: Partially addressed (see sections listed above in b.).	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	No discernible information gleaned from the literature reviewed.	Use in place shielding and plugs of penetrations for lighting, viewing devices, and tools.	[Blumberg 1968, ORNL-TM-0910] Report pg. 4

A.2 Fuel Salt Processing System

Table A-18
What if interruptions in fuel salt flow occur?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Batch fluorination not initiated and not moving material for the inflow – then leading to steady decrease in reactivity – then shut down over a few days Unnoticed interruption of flow would mean less material intended to be held – no anticipated deleterious impacts	Flow from drain tank to accumulator (separate tank) for batch processing to Fluorinator would occur; therefore a level indication in the accumulator would be required.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Information on maintenance requirements could be added to the maintenance philosophy section and information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified in the footnotes of this table.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed (see Sections 3.4.3.1, 3.5.1.3, 3.5.3, 3.6.1, and 3.6.5) b. Flibe Energy : Addressed (see sections listed above in a.)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE/ MSBR: Potential for excess decay heat buildup	Requirement for continuous cooling systems and fail-safe systems	[Carter 1972, ORNL-TM-3579] Report pg. 63

Table A-19
What if decay heat removal rates are lower than expected design rates?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Fuel salt processing would stop operations. No damage to equipment anticipated.	A 1-cm thick layer of frozen salt liner is used and NaK coolant will circulate continuously within the fuel salt fluorinator and fuel salt hydrogen reduction column	May 19-20, 2015 PPHA Discussion [VU 2015]
	Because the current LFTR design uses NaK as the coolant for fuel salt processing vessels, similar consequences affecting other LFTR components would apply here (See Table A-13)	There is potential to use the reaction vessels themselves as drain tanks in times of shutdown.	[TB 2015b, FSP1 Report] Report pg. 66
	Recommendation(s):	a. Trade study on NaK and other potential coolant options must be done (See Table A-13) b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Trade study on NaK not addressed. To be resolved in future design studies. Within Section 3.2.1.1, the use of the internal heat exchanger in the reactor vessel dedicated to blanket salt heat removal in case of an off-normal accident is included. b. Flibe Energy: Addressed. Discussion of normal operations of decay heat removal is found in Section 3.4.1, 3.4.2, 3.4.3.1, 3.4.3.2, and 3.5.1.3.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE/ MSBR: Potential for excess decay heat buildup	Requirement for continuous cooling systems and fail-safe systems	[Carter 1972, ORNL-TM-3579] Report pg. 63

Table A-20
What if hydrogen reaches the area where fluorine is stored and/or reactor containment cell?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Potential for severe consequences Most likely place to occur is where H_2 and F_2 are being separated and one is coming out of the anode and other cathode. LFTR high operating temperatures (600°C) bring the hazard potential closer to realization, but not an ignition source itself. Potential ignition sources are rotating equipment, pumps, and switches.	Careful separation of processes must be designed. Safety systems including engineering in the containment to mitigate potential consequences were discussed (e.g., keeping lines of H_2 separate and operate at a lower pressure with respect to containment system pressure).	May 19-20, 2015 PPHA Discussion [VU 2015] [TB 2015d, DGM Report] Report pg. 25
	Recommendation(s):	a. Look to industry experience for best practices on management of hydrogen storage and intra-movement of hydrogen between segments of the LFTR facility. b. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). c. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. To be resolved in future design studies. b. Flibe Energy: Addressed (see Section 3.2.1.6) c. Flibe Energy: Addressed (see Section 3.2.1.6)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE/ MSBR: Potential for explosions when mixtures of hydrogen and fluorine occur.	Care must be taken in utilizing these gases because of the hazards associated with obtaining explosive mixtures of hydrogen and oxygen, or fluorine. Thus, hydrogen must be isolated from the fluorine and from the reactor cell.	[Kasten 1967, ORNL-TM-1858], Report pg. 15

Table A-21
What if fluorine accidentally mixes with hydrogen or organic lubricants?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Potential for explosive reactions.	Available material for combustion is on the order of $1x10^0$ (single order of magnitude) gallons per minute for flow rates but the total inventory could be large. Accounting for lubricant inventory required for the LFTR will need to be performed. The idea was discussed to investigate solid lubricant options.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Accounting for lubricant inventory required for the LFTR will need to be performed. The idea was discussed to investigate solid lubricant options. b. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). c. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. To be resolved in future design studies. b. Flibe Energy: Addressed (see Section 3.2.1.6) c. Flibe Energy: Addressed (see Section 3.2.1.6)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Hydrocarbon lubricants used in MSRE with resultant lessons learned to avoid/ minimizing use due to potential for explosive reactions	Care must be taken in utilizing these gases because of the hazards associated with obtaining explosive mixtures of hydrogen and oxygen, or fluorine. Thus, hydrogen must be isolated from the fluorine and from the reactor cell. Also, fluorine must be isolated from the reactor system, and organic lubricants must not enter the fluorine system.	May 19-20, 2015 PPHA Discussion [VU 2015] [Kasten 1967, ORNL-TM-1858], Report pg. 15 [Briggs 1967, ORNL-TM-1851] Report pg. 63

Table A-22
What if excess pressure accumulates in the helium bubbler (sparger) used to remove fission products from the fuel salt?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	"To be Determined" status at the time of the May meeting.	It is anticipated that there will be an open interface with the bubble generator and overpressurization would be caused by a closed discharge valve. The safety margin for pressure increase is unknown. Potential overpressurization and limiting components is yet to be developed.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Further design on margins for safety for helium bubbler system. b. Incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed on topics related to margins of safety. To be resolved in future design studies. b. Flibe Energy: General system descriptions and requirements are found in Sections 3.2.1.2, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.4)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Inadequate removal of fission products	MSRE: Drain fuel. Close in-cell cooling air system vent (to stack) valve.	[Beall 1964; ORNL-TM-0732] Report pg. 62, Table 2.2, Row VI
	Recent experience: Recent experience included testing a new helium sparger in a molten salt environment when external pressure in the sparger increased up to ~70 to 100 psi. As a result of the accident, a violent outburst of molten salt took place through the top cover of the apparatus which was not sealed (bolted) properly to the body of the apparatus.	Off-gas activity release will be limited to fission product concentrations averaging less than 1.4 x 10^{-4} µc/cc in the stack (based on 3 x 10-9 µc/cc as permissible concentration at ground level downstream of the stack. An atmospheric dilution of $0.5x10^5$ is assumed). The ventilation system filters will be tested at least annually and after each change of filers. The measured efficiency of the filters must be greater than 99.9% for 0.5µ and larger particles…. All reactor and drain tank cell shield blocks shall be in place and secured by the hold-down devices whenever fuel salt is in the reactor vessel	[Beall 1966, ORNL-TM-0733 Rev.2] Report pgs. 3,4
		Recent Experience: Conclusions were drawn about a possible cause of the accident (sudden gas expansion): (1) an equipment failure, such as a rupture or complete failure of the porous sintered metal sparger; (2) Failure of either the Swagelok fitting on the tubing or the connection joint between the porous membrane and the sparger tube; (3) A plug in the steam line that allowed the pressure to rise until the plug was dislodged or disappeared;	[Boardman 2013, TEV-1789] Molten Salt Gasifier Event Analysis, Report Executive Summary

A.3 Primary Heat Exchanger

Table A-23
What if high pressures cause a minor failure within the primary heat exchanger?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Because the coolant loop pressure (~10-15 bar) is higher than the fuel salt (near atmospheric pressure ~1-2 bar), this would cause an injection of coolant salt into fuel salt and reduction of reactivity will occur. The median temperature of fuel salt would then trend downward.	The multiple potential root causes that can result with a decrease in reactivity places impetus on the need for a variety of sensors and instrumentation that can differentiate the actual problem so appropriate corrective actions can be taken (see Table A-36). There was also discussion that “sawtooth” trend in reactivity would be occurring due to batch processing and additions of fuel salt material). But a unique indicator will need to be developed further for a small leak. Impact on reactivity or level would increase in the surge tank for the primary heat exchanger pump (which would manifest itself first) because fissile inventory material is being added into the fuel loop on a routine basis. Monitoring system with built-in redundancies is needed for coolant salt inventory control (with the mass of coolant salt could be approximately 4x the mass of the fuel salt). A potential visual method to show that coolant salt had leaked into the fuel salt is to use a tracer (dye) with minimal impact on reactivity.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Same recommendation as Table A-36. b. Further research into visual monitoring methods and controls for coolant salt leakage into fuel salt. c. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). Incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed. (see Sections 3.2.1.3, 3.4.3.1, 3.7, and 3.7.2) b. Flibe Energy: Addressed. (see Section 3.2.1.3) c. Flibe Energy: Addressed. (see Sections 3.4.3.1 and 3.7)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: Overpressure in the coolant salt circuit which could then lead to damage to the reactor system	Rupture discs are provided on the shell side of the superheaters for venting the coolant system into the vapor condensing system.	[Kasten 1967, ORNL-TM-1858], Report pgs. 12-13
		The maximum coolant system cover-gas pressure is 50 psig over the free surface of the salt in the pump bowl.	[Beall 1966, ORNL-TM-0733 Rev.2] Report pg. 5
		The normal, or base, pressure of cover gas over the free surface of salt in the pump bowl is 5 psig. At the outlet of the pump, the maximum pressure is 70 psig.	[Briggs 1967, ORNL-TM-1851] Report pg. 63

Table A-24
What if a major failure within the primary heat exchanger occurs?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	The result of a major tube failure within the primary heat exchanger is a large and sudden increase of material in the fuel salt loop because of the pressure differential between the coolant and fuel salt (see Table A-23). The contamination of fuel salt with a large portion of coolant salt will cause a rapid and significant decrease in reactivity and median temperature. Reactor shutdown and draining of contaminated fuel salt and leaked coolant salt into drain tank would be required.	Acknowledgement that the primary heat exchanger may be the most vulnerable to failures because the walls are thin to maximize heat transfer. The analogy to a light water reactor (LWR) system was made such that this failure could be similar to a fuel pin leak and the metal/heat conduction is like the cladding in solid fueled reactors. Because LWR fuel cladding is replaced often, the same maintenance philosophy could be followed by replacing the primary heat exchanger on a set schedule (estimations of less than 10 years were given). Potential to add a redundant primary heat exchanger in parallel to maximize reliability/capacity factor numbers (while the previously used primary heat exchanger could cool in place until radiation lowered to more manageable levels). Drain tank needs to be appropriately sized to hold any/all coolant salt loop plus other working fluids in LFTR within proximity of fuel salt loop. Coolant salt would be recovered by treatment involving sending coolant salt through uranium removal chemical processing system.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Trade-offs of different design options for maintenance philosophy need to be further developed. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). b. Need to investigate proper engineering in redundancy for primary heat exchanger designs. c. Incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed. (see Sections 3.4.3.1 and 3.7) b. Flibe Energy: Addressed. (see Sections 3.2.1.3, 3.4.3.1, 3.7, and 3.7.2) c. Flibe Energy: Addressed. (see Sections 3.2.1.3, 3.4.3.1, 3.7, and 3.7.2)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: Fuel salt and coolant salt contact.	Replace entire heat-exchanger-pump assembly.	[Robertson 1970, ORNL-TM-4528] Report pgs. 44, 58

Table A-25
What if the primary fuel pump stops operating?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	The failure and magnitude of consequences would be design-specific. As of currently, the primary pump is internal to the primary heat exchanger as a long-shaft impeller pump design. No foreseeable damage to the primary heat exchanger, but freezing coolant salt in secondary coolant loop could occur while short term dynamics and feedback to power conversion system occurs later.	Potential to use in redundant primary heat exchangers with internal fuel pumps in parallel.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. A kinetics model needs to be developed to assess this type of failure. b. Need to investigate proper engineering in redundancy for primary pumps including but not limited to smaller, but off-the-shelf salt pump designs that can be used in series and/or in parallel. c. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not Directly Addressed. The need for modeling tools for loss of system controls was mentioned in Section 3.5.4. To be resolved in future design studies. b. Flibe Energy: Addressed. (see Section 3.7) c. Flibe Energy: Addressed (see Sections 3.4.3.1 and 3.7)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: The fuel salt will flow upward into the bottom of the startup tank and then through a 5-inch overflow pipe.	Overflow pipe must be opened and flow goes to the drain tank	[Robertson 1970, ORNL-TM-4528] Report pg. 47 [Donnelly 1965, ORNL-TM-1023]

Table A-26
What if the sealed housing for the electric drive motors for pumps fail?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Potential leak of radioactive contaminants into reactor building (escape of contaminated inert argon gas outside of containment because pump housing is outside of reactor containment). Potential exposure of facility personnel.	A vast and redundant set of radiation alarms is required (including above the structure containment) and evacuation procedures in place for facility personnel.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Need to investigate other containment methods, use of other barriers for leakages and breakthroughs of integral equipment that sits outside of the containment cells. b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. Need for protection of workers from radiation hazards with remote operations discussed in Sections 3.2.1.6 and 3.7.2. b. Flibe Energy: Not directly addressed (see sections mentioned above in a.). To be resolved in future design studies.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: Potential loss of integrity of reactor containment and potential for overexposure of facility personnel could occur.	All the pumps have the electric drive motors located in sealed housings at the operating floor level. This facilitates access to the motors for maintenance, and they can be shielded to protect electric insulation and lubricants from radiation damage. The motor housing is thus an integral part of the containment system and is subject to the same integrity requirements.	[Robertson 1970, ORNL-TM-4528] Report pg. 44

A.4 Blanket Salt Processing System

Table A-27
What if inadequate removal of Pa or U in the blanket salt occurs due to a failure of the first and/or second reductive extractive column?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Insufficient batch filling and shut down of processing and reactor system will occur. Fission events in the blanket from accumulated Pa and/or U will result with fission product accumulation not intended to be held in the blanket.	Appropriately sizing drain tanks to processing vessels is required. Condensation and heel forms of UF_6 in reduction vessels could cause some configuration that poses criticality concerns. Preventive measures would include keeping UF6 from solidifying	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Investigate sizing drain tanks to processing vessels and tanks can be designed to inhibit UF_6 solidification b. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Volume requirements are mentioned in Section 3.4.3.1. Solidification of material within holding tanks is not directly addressed, but the topic of bringing working fluids to operating temperatures is discussed in Sections 3.5.1.1, 3.6.1, and 3.6.2. b. Flibe Energy: General system descriptions and requirements are found in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.4)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	No discernible information gleaned from the literature reviewed.	No discernible information gleaned from the literature reviewed.	

Table A-28
What if the electrolytic cell is improperly operated?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Improper loading concentrations of metallic lithium and thorium into the metallic bismuth stream could prevent proper/designed contact with the blanket salt. Too much loading – high concentrations are already required and increased concentrations will not affect the reactivity significantly Too little will shut down the electrolytic reaction. If bismuth travels to the reactor, potential damage to the core could occur due to Hastelloy degradation when in contact with bismuth.	Chemistry of system must be maintained to keep Bi to ppm levels (as MSRP experience unfolded). Further supports the need for quality control and batch processing	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Further development of chemistry controls engineering, especially in this case for contaminants that could damage major LFTR components. b. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). c. Incorporate information above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. Chemistry control requirements described at a high-level in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.3. b. Flibe Energy: Addressed at a high-level in Section 3.2.1.6. c. Flibe Energy: Proper function and general system requirements listed in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.3.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE/MSBR: Potential to disrupt system dynamics and chemical compositions of working fluids	Adequate amounts of flushing salt must be used in between batches	[Thoma 1971, ORNL-4658] report pg. 61 [Lindauer 1969, ORNL-TM-2578]

Table A-29
What if blanket salt chemical processing does not occur at designed flow rate?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Overall consequence to operations would occur, but no severe consequences related to safety are foreseen.	"Blanket salt is drawn from the reactor's blanket at a rate which allows the entire blanket to be processed every four days… The blanket salt, containing small amounts of PaF4, and even smaller amounts of uranium as UF_4, enters a reductive extraction column"	May 19-20, 2015 PPHA Discussion [VU 2015] [TB 2015b, FSP1 Report pg. 12
	Recommendation(s):	a. Further evaluation of industry experience of salt chemistry and handling is required (potential to mine the DOE incidents database). b. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD). Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. To be resolved in future design studies. b. Flibe Energy: Proper function and general system requirements listed in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.3.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	No discernible information gleaned from the literature reviewed.	No discernible information gleaned from the literature reviewed.	

A.5 Off-gas Handling System

Table A-30
What if helium sparger for off-gas fuel salt treatment fails to add adequate/any helium into the fuel salt mixture before entering back into the reactor core?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Failure to add material into the off gas system would occur. Less effective removal of fission products in the off gas train (increased xenon effect), will manifest itself as a reactivity decrease.	Safety systems and potential mitigative measures still need to be identified as part of the LFTR design.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Pumps and other mechanical components that could be affected should be identified. b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not completely addressed. Mention of off-gas handling system and chemical processing systems and applicable safety systems to be designed can be found in Section 3.2.1.6. To be resolved in future design studies. b. Flibe Energy: General system descriptions and requirements are found in Sections 3.2.1.6, 3.2.1.7, 3.3.1, 3.4.1, 3.4.3.1, 3.4.3.2, and 3.5.1.4.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: The off gas line became plugged by fuel salt when the pump bowl was accidentally overfilled while the calibration of the liquid level indicators was being investigated. Salt was discharged into some of the lines attached to the pump bowl and froze in the cold sections.	Heaters were applied to the lines to remove most of the salt but it was necessary to open the off gas line and break up a small amount of material in part of the line. Careful attention to the interface between hot systems and cold systems in the breeder design.	[Briggs 1967, ORNL-TM-1851] Report pg. 69

Table A-31
What if potassium hydroxide (KOH) is unintentionally released?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	KOH is an industrial safety concern and will result with chemical exposure impacts to workers if released.	KOH is in containment, but exists at low operating temperatures (~120-150°F). How will this low temperature be maintained (perhaps by locating KOH container in an adjoining leg of the reactor containment cell). This may present a potential problem by requiring air conditioning system/ partition to the containment to lower ambient gas temperatures from 600°C to ~30°C. Storage and maintenance philosophy will need to be developed if reactive chemicals are chosen as part of the final LFTR design. This will include separation of chemical stocks and use of complex containment with interfaces/locks/pipes interchanges.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Storage and maintenance philosophy will need to be developed if reactive chemicals are chosen as part of the final LFTR design. b. Evaluate the magnitude of potential suite of problems related to the air conditioner system required to lower ambient gas temperature from 600°C to 30°C. c. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified in the footnotes of this table.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. Discussion of H2 and F2 inventories safe storage is found within Section 3.2.1.6. b. Flibe Energy: Not Addressed. To be resolved in future design studies. c. Flibe Energy: Addressed. (see Section 3.2.1.6).	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: The refrigeration requirements of the KOH storage area could cause accidental freezing of salt if interconnecting piping from LFTR working areas need to cross into refrigerated/climate controlled areas.	MSRE: Careful attention to the interface between hot systems and cold systems in the breeder design.	[Briggs 1967, ORNL-TM-1851] Report pg. 69

A.6 NEW Drain Tank

Table A-32
What if inadvertent thawing of the freeze valve holding fuel salt in the primary coolant loop occurs?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	Stopped operations and reactor shutdown. Risk to the equipment is relatively low. Thermal cycling shock may eventually degrade the freeze valve to the point of replacement and/or major repairs. Possibility of a gas surge from the drain tank and/or surge of fuel salt into off gas lines. The consequence of a gas surge from drain tank may indicate an outflow of gas from drain tank and that an open line to prevent vacuum in graphite tube is needed. Potential for fracturing of graphite from increase pressure from introduction of gas from drain tank and could then cause a surge of salt into off gas lines.	Recovery and maintenance from thermal cycling shock of the freeze valve might involve repairs to the blow pump and maintenance may be extensive. It was proposed that a diverse set of indicators would be used to alert operators that this particular event would be occurring. A combination of visual indicators plus use of strain gauges to indicate mass of salt in the reactor could be used. Lifetime of salt plug/freeze valve could be limited by thermal cycling caused by shutdown and restart (maybe a couple of hundred of restart times will degrade the freeze valve to the point of replacement)	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed. (see Sections 3.5.3 and 3.6.5) b. Flibe Energy: Addressed. (see Sections 3.2.1.1, 3.2.1.2, 3.5.3, and 3.6.5)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSRE: Loss of fuel salt	It was stated that the MSRE used strain gauges to gauge mass of fuel salt within the reactor core. Gas surges from excess fuel from refilling during normal operations that is discussed in ORNL-TM-0497 could be used as a base plan for the safety system in the LFTR design (see Table A-3 of this document)	May 19-20, 2015 PPHA Discussion [VU 2015] [Engel 1966, ORNL-TM-0497] Report pg. 10 of PDF

Table A-33
What if a piece of graphite enters in the drain tank in the event of an emergency drain tank?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	A modest piece might not alter criticality potential. Criticality geometry not likely as the graphite will float in fuel salt. A plugged line could cause the inability to drain core. Graphite floats in fuel salt so forced movement into the connecting piping would need to occur if graphite were plugging the drain pipe. Excess fuel salt that does not enter the drain tank could surge into the off gas line while meanwhile volatile fission product species could escape into core, thereby increasing the heat load in reactor core.	A potential safety system could be a strainer/ filter to catch foreign material. Visual inspection of mechanical strainer would need to be added to maintenance regime. Could add redundancy by including multiple drain lines dedicated to gas egress from the drain tank and ingress of fuel salt into the drain tank.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Compare advantages and disadvantages of hydraulic/thermal transport phenomena of iterative LFTR designs. b. Information on maintenance requirements could be added to the maintenance philosophy section (if incorporated into SDD). Incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not directly addressed. Discussion of fuel salt drainage to “non-moderated” structure (i.e., drain tank) can be found in Section 3.4.2. b. Flibe Energy: Not directly addressed. Separation of the fuel salt and blanket salt by the graphite channel structure as a safety system is discussed in Section 3.4.3. Not discussed if loss of the containment/separation mechanism (integrity of graphite) occurs.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: The fuel salt will flow upward into the bottom of the startup tank and then through a 5in overflow pipe	Overflow pipe must be opened and flow goes to the drain tank Gas surges from excess fuel from refilling during normal operations that is discussed in ORNL-TM-0497 could be used as a base plan for the safety system in the LFTR design (see Table A-3). Sometimes organic materials polymerize in the off-gas handling system under the intense beta radiation of the gaseous fission products to form the viscous liquids and solids that plugged the valves and the entrances to the carbon beds. This problem has been reduced by installing absolute filters for trapping solids and heavy liquids ahead of the control valves.	[Robertson 1970, ORNL-TM-4528] Report pg. 47 [Engel 1966, ORNL-TM-0497] Report pg. 10 of PDF [Briggs 1967, ORNL-TM-1851] Report pg. 69

Table A-34
What if the drain tank leaks fuel salt in the event of an emergency reactor shutdown?

Reference Technology	Consequences	Safety Systems, Mitigative Measures, Corrective Actions	References
LFTR:	This could represent a subset of loss of coolant accidents. Criticality is not of concern for the spilled salt, but cleanup will be burdensome	Use of concrete catch pan or similar structure to the UK EPR core catcher design could be included as part of the LFTR design.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Consider addition design changes to the LFTR to include catch pan safety system. b. Incorporate information discussed above into Conceptual Design report/SDD.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Not addressed. To be resolved in future design studies. b. Flibe Energy: Not addressed. To be resolved in future design studies.	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	Could represent a loss of primary containment. Contamination of coolant salt, coolant salt loop, and components therein, with possible contamination of area in the event radiator or other coolant system components fail. Otherwise, no hazard exists.	Leakage from the primary system as indicated by the reactor and drain tank cell air activity will not exceed the equivalent of 4 liters of salt after 120 days of operation at full power, as estimated in the case of the “most probable accident” as described in [Beall 1964; ORNL-TM-0732]. The maximum reactor and drain tank cell leak rate will not be allowed to exceed 1% of the cell volume per day, calculated for the conditions of the Maximum Credible Accident as described in [Beall 1964; ORNL-TM-0732]. The in-leakage rate will be determined at least once per week	[Beall 1966, ORNL-TM-0733 Rev.2] Report pgs. 3,4

Table A-35
What if improper or inadequate cooling of the drained fuel salt occurs in the event of an emergency shutdown?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Likelihood of this event may be very low due to the passive heat removal system	Primary safety system is the passive cooling system assigned to the reactor and drain tank during accident scenarios.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Sizing the heat exchanger (parabolic cooling tower) is required. b. Incorporate information discussed above into Conceptual Design report/SDD. Refer to potential useful references identified at the end of this Appendix.	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Indirectly addressed by mention of functional requirements and purpose of the cooling system for the drain tank (see Sections 3.2.1.2 and 3.4.3.1) b. Flibe Energy: Addressed. (see sections mentioned above in a.)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	No discernible information gleaned from the literature reviewed.	No discernible information gleaned from the literature reviewed.	

Table A-36
What if a partially thawed piece of the salt plug (or any other solid mass) obstructs piping to the drain tank occur during times of emergency shutdown?

Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
LFTR:	Freeze plug is predominantly solid and slow leakage of fuel salt into the drain tank occurs. If the leakage rate is too slow, LFTR system could lose the ability to circulate fuel salt.	A safety system that could be included is a fill sensor for the pump bowl heading combined with subsequent operational procedures/administrative controls before addition of fuel salt material is permitted. A corrective action preceding fuel salt addition is to add coolant salt to reduce potential criticality in the remaining geometry.	May 19-20, 2015 PPHA Discussion [VU 2015]
	Recommendation(s):	a. Incorporate design changes that can keep the following operations independent (with corresponding safety systems, sensors, etc.): (1) maintaining criticality, (2) partial draining, and (3) loss of fuel salt circulation. Incorporate information discussed above into Conceptual Design report/SDD. b. Information on procedural/administrative requirements could be added to the operational philosophy section (if incorporated into SDD).	
	Responsible Individual(s) & Resolution(s):	a. Flibe Energy: Addressed as part of design requirements in Section 3.4.3.1. b. Flibe Energy: Addressed (see section mentioned above in a.)	
Reference Technology	**Consequences**	**Safety Systems, Mitigative Measures, Corrective Actions**	**References**
MSRE/ MSBR:	MSBR: The fuel salt will flow upward into the bottom of the startup tank and then through a 5-inch overflow pipe	Overflow pipe must be opened and flow goes to the drain tank	[Robertson 1970, ORNL-TM-4528] Report pg. 47

A.6 Appendix A References

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B
CHEMICAL HAZARD INFORMATION

LFTR proposes to use several chemical compounds and species that have varying levels of inherent hazards. This section aims to briefly describe hazards and the potential impacts to human health that may occur from exposure to chemicals that may be used in the LFTR design. The information presented may be used as a very high-level characterization of source terms that would feed into the Mechanistic Source Term Analysis (MS) that describes non-radiological material reactivity that could lead to releases of radiological content. From [Sorensen 2014a, 2014b, TB 2015b], the list of chemicals intended to be used in the LFTR system follows (* denote the chemical species described in the following discussion due to their prevalence in the LFTR system and/or the level of hazard to human health warrants discussion):

- Fuel Salt Chemical Processing
  - beryllium (Be)*
  - bismuth (Bi)*
  - lithium (Li)*
  - protactinium (Pa)
  - uranium tetrafluoride (UF_4)*
  - uranium hexafluoride (UF_6)*
  - fluorine (as a gas: F_2)*
  - hydrogen fluoride (HF)*
  - hydrogen (as a gas: H_2) with potential to use ammonia (NH^{3+})* as the source of H_2
  - helium (He) for helium sparging of fission products
- Blanket Salt Processing:
  - thorium (Th)*
  - bismuth (Bi)*
  - lithium (Li)*
  - beryllium (Be)*
- Waste/Off-gas Handling System
  - potassium hydroxide (KOH)*
  - liquid nitrogen (N_2)

- Balance-of-Plant Systems
  - carbon dioxide (CO_2)
  - water (H_2O)
- Potential options for fuel-salt drain tank coolants
  - water and steam (H_2O)
  - liquid metals: sodium potassium (NaK)* and sodium (Na)
  - fused salts: fluorides*, carbonates, nitrate-nitrates
  - organics, diphenyls and polyphenyls
  - gases: carbon dioxide (CO_2), nitrogen (N_2), and argon (Ar)

Beryllium is a material with elevated hazards associated with handling and fabrication. The LFTR system is expected to use large amounts of beryllium in each of the blanket, fuel, and coolant salts. The U.S. Occupational Safety and Health Administration (OSHA) limits for beryllium and beryllium compounds are 0.002 mg/m^3 over an 8-hour work shift and 0.025 mg/m^3 as a maximum ceiling [NJ DHSS 2004]. In addition to its health hazards, elemental beryllium also reacts highly exothermically with water, and self-sustaining beryllium-steam reactions are thermodynamically feasible. Beryllium-related health challenges have been reviewed for nuclear systems as part of work for the International Thermonuclear Experimental Reactor (ITER) [ITER 2013].

Lithium will be used as a main component in the coolant/fuel salt and blanket salt. Lithium also has its challenges concerning human health and process safety. Elemental lithium in the liquid phase is highly flammable can spontaneously ignite in air if touching metal surfaces. Once ignited, conventional fire suppressants (e.g., water, carbon dioxide and carbon tetrachloride) will further ignite and increase the energy of the reaction. Due to the reactivity with water, lithium will react with moisture on the human body and cause chemical burns [Cameco 2011]. The lithium-fluoride-beryllium salt does not react violently to air or water [WNA 2014] but safety concerns remain when pure or highly-depleted streams of lithium-7 are inserted to the LFTR system. Lithium alone is not particularly toxic to humans [Léonard 1995, Aral 2008].

The LFTR system uses molten elemental bismuth during chemical processing. Bismuth is highly flammable in the solid phase and can ignite when exposed to an open flame. The potential impacts to human health are not well known and permissible exposure limits (PELs) have not been assigned by OSHA, NIOSH or ACGIH [Iowa 2002, ProSciTech 2014, Acros 2015].

Some insights can be drawn from the Molten Salt Gasifier accident at Idaho National Laboratory in 2013 [Boardman 2013]. The accident report states:

> “The accident happened when the new sparger was tested for work in molten salt environment when external pressure in the sparger increased up to ~70 to 100 psi. As a result of the accident, a violent outburst of molten salt took place through the top cover of the apparatus which was not sealed (bolted) properly to the body of the apparatus.”

Several possible causes were identified for the incident. The most probable cause of the incident was determined a pressure build-up impacted by a blockage near the sparger due to solidification of molten salt material via contact with relatively cool steam.

[Kolene 2004] identifies three primary hazard categories for processes which employ molten salts (not nuclear-specific): elevated temperatures, salt chemistry, and chemical fumes. Preventive measures for all three categories pertain to making sure the salt material does not have opportunities to come into contact with environmental factors outside the vessels that could lead to an initiating event. Such measures include:

- Selecting the right materials of construction (Inconel or certain steels)
- Incorporating blowers and ductwork to exhaust fumes and steam
- Using double-walled vessel designs
- Using solid (rather than hollow) tubing
- Using and properly maintaining reliable heating systems
- Using "lockout" procedures and devices for critical control panels.
- Storing vessels in dry, indoor areas
- Preheating or otherwise drying additional components to avoid introduction of water to system
- Preheating or otherwise drying salts that have been allowed to cool before returning them to operational portion of system
- Removing sludge or other deposits during maintenance to avoid having regions which heat disproportionately compared to others
- Avoiding introduction of a quantity of salt beyond capacity of system
- Keeping access points (doors, viewing windows, etc.) closed during operation, only opening when needed during maintenance, etc.
- Avoiding use of incompatible materials (e.g., Mg, Sn, Zn, Al) for system components

Mitigation measures (post-incident) include:

- Implementing on-site laboratory safety protocol (wearing eyeglasses, gloves, coats, etc.)
- Enabling access to proper respiratory equipment, as needed
- Enabling access to safety devices (eyewash, shower)
- Enabling access to cleanup devices and gear (thermally/chemically-resistant outfits)
- Implementing correct fire-fighting procedures (e.g., avoid use of water)

Hydrogen gas (H_2) is widely used in industry and an expansive amount of literature exists [NASA 1997, ISO 2004]. Hydrogen poses a hazard to human safety from potential detonations and fires when mixed with air. Inhalation of air containing a high concentration of hydrogen can cause asphyxiation. Hydrogen is explosive and highly flammable [IIFP 2011]. The OSHA reporting limit for regulating hydrogen ranges from 150-600 liters if stored within a building (Table H-3 [OSHA 2007b]). Required distances of separation from the hydrogen system to locations of potential exposure vary from 5-100 feet (Table H-4 [OSHA 2007b]). A distance of 100 feet is required when oxygen and other oxidizers are stored at the facility. For large-scale hydrogen production systems have much higher volumetric limits and vary by location relative to human receptors [OSHA 2007b]).

Fluorine is another important hazardous chemical which is present in large quantities in the LFTR system to convert UF_4 to UF_6. Fluorine (F_2) and is a pale yellow to greenish gas with a pungent irritating odor. Fluorine is not as acutely toxic as beryllium, but it is still detrimental in small quantities and has more intake pathways due to its volatility. It reacts violently with all combustible materials. Although fluorine is a non-flammable gas, it is an extremely strong oxidizer. Fluorine is a skin irritant and is corrosive to all living tissue. It can induce coughing and difficulty in breathing. Its effects on the eyes are similar to those of hydrogen fluoride (HF). Severe exposures to fluorine can cause extreme burning and destruction of the tissues or death [Kaiser 1988]. Since 1988, both NIOSH and OSHA recommend chronic or long term exposure limit for fluorine is 0.1 ppm (0.2 mg/m^3 over an 8-hour duration as the time weighted average (TWA) value). The acute or immediately dangerous to life and health concentration, applicable to respiratory failure, is 25 ppm [OSHA 2007a]. Nuclear fuel cycle facilities, such as nuclear conversion and enrichment facilities [Siman-Tov 1984, IAEA 2010], are acquainted with the hazards presented by fluorine and hydrogen fluoride.

Uranium hexafluoride (UF_6) is a product of the uranium ore conversion process and a material used for LFTR fuel salt chemical processing. UF_6 poses danger to workers when released to the atmosphere because UF_6 reacts with moisture (hydrolyzes) to form HF and uranyl fluoride [$UF_{6\,(gas)} + 2H_2O \rightarrow UO_2F_2 + 4\ HF + \text{heat}$]. The reaction of 1 kg of UF_6 combining with 0.1 kg of water, results in the formation of 0.88 kg of UO_2F_2 (containing 0.68 kg of uranium) and 0.23 kg of HF. The uranyl fluoride and hydrofluoric acid compounds are more of a chemical hazard than of UF_6 [Stoetzel 1981, 1982]. The UO_2F_2 particulate, which is easily transported in air, is very soluble. UO_2F_2 particles can deposit inside a facility. According to NUREG-1391 [McGuire 1991], the chemicals formed by the this reaction have three main toxic effects: (1) the uranyl ion, UO_2^{++}, acts as a heavy-metal poison that can affect the kidneys; (2) The HF can cause acid burns on the skin or lungs if concentrated; (3) The fluorides can cause fluorine poisoning if intakes are significantly large. HF is a strong oxidizing agent and a very corrosive material [Kaiser 1988].

Based on actual events and laboratory experiments, the health effects of UF_6 exposure are generally understood. Data have shown that damage to the kidneys is the most important toxic effect of uranium. High doses of uranium also affect the blood and may damage the capillary membranes. Uranium's effects on the nervous system are similar to those from poisoning by other heavy metals [Kaiser 1988].

Hydrogen fluoride (HF, also referred as hydrofluoric acid) is a strong acid and is acutely hazardous to workers. HF will react with water or steam to produce toxic and corrosive fumes. Unreacted vapor of UF_6 may desublime to form a solid [Kaiser 1988]. Moderate exposure to HF in air can cause acid burns of the skin, respiratory irritation, irritation of the conjunctiva, and pronounced taste. Significant exposure to HF can cause progressive destruction of the bronchial mucous membrane and swelling of the lung tissues, which can be fatal.

HF is used is a number of material streams within the LFTR system and is produced during the UF_6 reduction stage to produce UF_4. Hydrogen fluoride reacts with metals and water or steam and will attack glass and concrete [ATSDR 2001]. The recommended threshold for the amount of HF stored and used on-site in significant quantities is 450 kg of HF that prompts facility managers that an additional safety analyses should be performed [NRC 2011].

The amount of hazardous material stored on-site in order to support annual throughput for a typical conversion facility is found in Table B-1and can provide insight to the potential scale of feedstock to support online chemical reprocessing for the fuel salt. The current LFTR system lists around 0.022 UF_6 grams per second[41] and if conservatively approximated by conversion to mass per year, this equates to approximately 700 kg per year of UF_6 circulated throughout the LFTR system. The stored on-site inventory would still need to be determined while keeping in mind that the regulatory documentation will eventually need to include an integrated safety analysis (ISA) [NRC 2001]. Recent updates to the ISA Guidance for nuclear fuel cycle facilities that will store on-site more than 2,000 kg of UF_6 should also be considered [NRC 2011]. The recommendation of such updates to the ISA guidance were originally considering conversion and deconversion facilities, but could be potentially applicable to the LFTR site due to the amount of UF_6 mass that is contained within 1 UF_6 vaporizer and a still feed tank that is used at a conversion facility may be used at the LFTR site and exceeds 2,000 kg of UF_6 [Kaiser 1988].

Table B-1
Typical Hazardous Material Inventory at UF_6 Conversion Plants

Chemical (Symbol)	Container Size (kg)	Site Inventory (kg)	Storage Conditions
Ammonia (NH_3)	26,000	60,000	Tank farm
Fluorine (F_2)	20	20	Not stored on site
Hydrogen fluoride (HF)	55,000	190,000	Tank farm
Potassium hydroxide (KOH)	23,000	47,000	Off-gas scrubbers
Uranium hexafluoride (UF_6)	12,000	2,000,000	Model 48 cylinders
Sulfuric Acid (H_2SO_4)	120,000	120,000	Tanks

Source: [Kaiser 1988]

Table B-2
Typical UF_6 Inventories in Process Vessels

Process Vessel	Inventory (kg)
UF_6 vaporizer	4,500
UF_6 cylinder fill	12,000
Fluorinator	9
Condenser	90
Fluorination filter	23
Still feed tank	27,000
Cold Trap	20,000

Source: [Kaiser 1988]

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[41] 0.0324 UF_6-F_2 gram per second was reported but 66.6% is the mass of UF_6: 0.0326 gram/s * 0.666 =~ 0.022 UF_6 grams per second

Table B-3
Concentration Limits of Selected Chemicals Applicable Nuclear Fuel Cycle Facilities

Chemical (Symbol)	**Concentration (ppm), unless noted otherwise**		
	Permissible exposure limit[a]	**Threshold limit value**[b]	**Immediately dangerous to life and health concentration level**[c]
Ammonia (NH_3)	50	25	500
Nitric acid (HNO_3)	2	--[d]	100
Hydrogen fluoride (HF)	3	3	30
Hydrogen (H_2)	--[d]	--[d]	--[d]
Fluorine (F_2)	0.1	1	25
Hydrogen chloride (HCl)	5	5	100
Hydrogen Peroxide (H_2O_2)	1	1	75
Uranium hexafluoride (UF_6)	0.05 mg/m^3	0.2 mg-U/m^3	--[d]

Notes: [a] Source: 29 CFR 1910.1000; [b] Source ACGIH (1992); [c] Source: US DHHS (1990); [d] No value has been established for this substance. Source: [Kaiser 1988]

Table B-4
Threshold Planning Quantities for Hazardous Chemicals Used at Fuel Cycle Facilities

Chemical (Symbol)	**OSHA threshold planning quantity**[a] **kg (lb)**	**EPA threshold planning quantity**[b] **kg (lb)**
Ammonia (NH_3)	4,500 (10,000)	4,500 (10,000)
Nitric acid (HNO_3)	-	450 (1,000)
Hydrogen fluoride (HF)	450 (1,000)	45 (100)
Hydrogen (H_2)	-[d]	4,500 (10,000)
Uranium hexafluoride (UF_6)[c]	2,000 (4,400)	200 (440)
Fluorine (F_2)	450 (1000)	230 (500)
Hydrogen chloride (HCl)	2,300 (5,000)	230 (500)
Hydrogen Peroxide (H_2O_2)	3,400 (7,500)	450 (1,000)

[a] Source: Appendix A of 29 CFR 1910.119 [OSHA 2011]

[b] Source: 59 FR 4478 [EPA 1994]

[c] UF_6 is not on the EPA and OSHA lists for threshold planning quantities. Estimated value is based on the mass of HF released following complete hydrolysis of UF_6: $UF_6 + 2H_2O \rightarrow UO_2F_2 + 4\ HF$. Source: [Kaiser 1988]

[d] OSHA limit for regulating hydrogen: 150 Liters Source: [OSHA 2007b].

The use of anhydrous ammonia in conversion processes in order to reduce U_3O_8 to UO_2, may present a situation where chemical exposure occurs to workers. The use of ammonia may be applicable to the LFTR if the H_2 that is within the UF_6 reduction step and as the hydrogen supply in fluidized-bed reactors during fuel salt processing is sourced from cracking ammonia. Throat irritation may occur when inhalation of ammonia occurs at levels of 125-400 ppm. Conversion facilities within the U.S. reported to usually contain air concentrations of 5-10 ppm. The maximum allowable limit is 25 ppm. Pungent odor is detected at ranges from 1-5 ppm. Other chemicals that become airborne through small releases are at low enough levels that are not of high concern. Some of these chemicals are NO_2-NO_X, HF, Fluorides, and welding fumes [Stoetzel 1982, Kaiser 1988]. Industry now tends to use urea as a safer method for storing and using ammonia on site. Avoiding accumulation of hazardous anhydrous ammonia onsite is achieved by converting stored urea to ammonia on demand [Bell 2003, Wheeler 2010, Moretti 2012].

Thorium poses relatively low toxicological impacts compared to the impacts due to radiation. The oxide form of thorium, thorium dioxide, is mostly insoluble in the human body and therefore the retention is very low (~0.001%) if ingested [Steindler 1962]. The earliest reference on potential radiological impacts from the sourcing of thorium from mining and milling is presented in [Tennery 1978] and remains to be updated as indications of production of thorium could be produced as a by-product of other minerals [Ault 2015a, 2015b]. There are no recommended listed OSHA permissible exposure levels specific to elemental thorium or thorium compounds [OSHA 2012]. Much of the literature on occupational hazards of handling thorium have come from the 1960s [Steindler 1962]. A more recent paper by Haley (1991) corroborates these findings by studying the toxicity and pulmonary impacts of rare earth elements with and without the presence of thorium. Negative impacts to the lung were significantly correlated to the sole presence of non-radioactive lanthanides and without the presence of thorium. However, rare earth elements will be produced as fission products and will be extracted from the fuel salt of the LFTR system, thereby the potential negative health effects should be considered as related to the co-extraction of rare earth elements and thorium.

Sodium potassium (NaK) and sodium potassium alloy are highly reactive with water causing a violent reaction and potential for causing flash fires [Callery 2000]. NaK must be stored separately from other chemicals and away from water sources. At the Idaho National Laboratory, there is a separate vault that contains NaK [DOE 1994].

Potassium hydroxide (KOH) is used to remove HF off-gas produced during hydrofluorination in the conversion process and would be similar for the LFTR system. KOH is highly corrosive and causes irritation of the skin and eye if workers come into direct contact [Iowa 2000]. The most likely ways exposures occur are in manufacturing facilities or in industrial facilities that use potassium hydroxide. When exposures occur, they are typically skin or eye exposures. Good industrial hygiene practices and personal protective equipment minimize the risk of exposure [Occidental 2008, ASHTA 2014].

An often overlooked non-radiological occupational hazard at conversion facilities is heat stress due to high operating temperatures. Heat build-up and associated hazards are often exacerbated by facilities that place high-heat producing processes on the lower floors of buildings [Kaiser 1988]. This occupational hazard could be applicable to the LFTR system because there are multiple fluorination stages and steps involving high heat applications associated with the fuel and blanket salt chemical conversion processes.

Process hazards that pose potential adverse health effects for workers within the typical conversion plant and may be applicable for the proposed LFTR system are: (1) Corrosion of storage equipment that enables leaks and atmospheric releases of utilized chemicals; (2) Potential acid burns to any of the areas within the conversion facility, including pre-treatment facilities and product packaging areas; (3) Stack emissions and accidental releases from sampling and storage, ore concentrates preparation, hydro fluorination, and fluorination process areas; (4) The use of hydrogen gas (H_2) could cause fires and explosions at certain concentrations and mixture of oxygen; (5) The potential contact between F_2 or UF_6 with oil can initiate an uncontrolled chemical reaction; (6) Heating of cold traps containing excessive amounts of UF_6 could over-pressurize the containment vessels and cylinders leading to rupture and release UF_6 from the vessel [Kaiser 1988]. Accidental release scenarios of UF_6 are widely-studied within Safety Evaluation/Demonstration Reports and analyses published by both DOE and NRC [Siman-Tov 1984; NRC 1986; Honeywell 2005].

There are several chemicals used within the LFTR system similar to the nuclear chemical separations processes [Chester 1979]: fluorine, nitric acid, uranium metal, UF_6, uranium dust, bromine, hydrobromic acid, HCl, and HF. Information on safe handling and management practices is available and will be applicable to the LFTR system.

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C

SYSTEM DESIGN DESCRIPTIONS, CONTENT, AND STRUCTURE (USE OF DOE STANDARDS)

During the review of LFTR technical design reports, EPRI and Vanderbilt suggested that the next iteration of the design report follow a more consistent structure within each section. DOE has made available many guidance documents; the following documents appear appropriate and relevant:

- Information on system descriptions can be found most concisely in DOE-STD-3024-2011, *DOE Standard: Content of System Design Descriptions* [DOE 2011]; the concept of system descriptions implements the systems engineering approach and DOE Order 420.C, *Facility Safety* (with attendant guide DOE-G-420.1-1A, Non-Reactor Nuclear Safety Design).
- DOE-STD-1189-2008, *Integration of Safety into the Design Process*, provides a recent an accessible reference for integrating project management and design; note particularly p11-15, 19-26, and Appendix H; the status of the design effort for the TMSR is estimated to be at the conceptual/preliminary design stage transition, as a reactor design concept has been selected

DOE-STD-3024-2011, Chapter 4 reviews the objective, purpose, and content of system design descriptions (SDDs), and was summarized in the PPHA section of the main body of this report:

Given the very early design stage of LFTR, it was anticipated that much of this information is yet to be determined and can be so noted in the report. DOE-STD-3024-2011 (Chapter 5, Section 5.9) notes:

> "For a new facility or system, the SDD scope and level of detail may change throughout the design and construction. Initially [at conceptual design, either Critical Decision-1 or early Critical Decision-2 stage], the SDD may include information on primary system functions and boundaries. It may contain preliminary data and indicators of "to be determined" (TBD) that should be refined as the design matures."

DOE-STD-3024-2011 provides guidance on the format of SDDs and further development of the *LFTR Technical Feasibility Study Phase I Interim Report* may benefit from the guidance found within the bulleted list in DOE-STD-3024-2011, Appendix D, "Format of System Design Descriptions" as design documentation evolves. The following list was suggested as the structure, tailored to this early design stage, for each section of the updated LFTR report.

Chapter 1: Introduction of an SDD

1.1 System Identification

1.2 Limitations of this SDD

Chapter 2: General Overview

2.1 System Functions/Safety Significance

2.2 Basic Operational Overview

Chapter 3: Requirements and Bases

3.1 Requirements

3.2 Bases of Design

3.2.1 System Functional Requirements

3.2.2 Subsystems and Major Components

3.2.3 Boundaries and Interfaces

3.2.4 Operability

3.2.5 Performance Criteria

3.3 References

3.4 Testing and Maintenance Requirements

3.5.1 Testability for Operations

3.5.2 Surveillances for Safety Functions

3.5.3 Maintenance

Chapter 4: System Description

4.1 Configuration Information

4.1.1 Description of System, Subsystems, Major Components

4.1.2 Boundaries and Interfaces

4.1.3 Physical Layout and Location

4.1.4 Principles of Operation

4.1.5 System Reliability Features

4.1.6 System Control Features

4.2 Operations

4.2.1 Initial Configuration (Pre-startup)

4.2.2 System Startup

4.2.3 Normal Operations

4.2.4 Off-normal Operations

4.2.5 System Shutdown

4.3 Testing and Maintenance

4.3.1 Temporary Configurations

4.3.2 Safety Required Surveillances

4.3.3 Operating Inspections and Testing

4.3.4 Maintenance

4.4 Supplemental Information

Suggested topics that are discussed at least once for the entire system as part of safety and security requirements:

- Radiation and Other Hazards
- Nuclear Criticality Safety
- Industrial Hazards
- Operating Environment and Natural Phenomena
- Human Interface Requirements
- Security and Special Nuclear Material Protection
- Reliability, Availability, and Failure Modes
- Quality Assurance
- Safety Management Programs, Administrative Controls

Appendix C References

[DOE-STD-1189-2008] US Department of Energy (DOE) (2008). DOE Standard 1189-2008: Integration of Safety into the Design Process. DOE-STD-1189-2008.

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