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SCIENCE DIRECT®
Nuclear Engineering and Design 230 (2004) 151–167
Nuclear Engineering and Design
www.elsevier.com/locate/nucengdes

The design and safety features of the IRIS reactor

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Received 8 May 2003; received in revised form 2 October 2003; accepted 13 November 2003

Abstract

Salient features of the International Reactor Innovative and Secure (IRIS) are presented here. IRIS, an integral, modular, medium size (335 MWe) PWR, has been under development since the turn of the century by an international consortium led by Westinghouse and including over 20 organizations from nine countries. Described here are the features of the integral design which includes steam generators, pumps and pressurizer inside the vessel, together with the core, control rods, and neutron reflector/shield. A brief summary is provided of the IRIS approach to extended maintenance over a 48-month schedule. The unique IRIS safety-by-design approach is discussed, which, by eliminating accidents, at the design stage, or decreasing their consequences/probabilities when outright elimination is not possible, provides a very powerful first level of defense in depth. The safety-by-design allows a significant reduction and simplification of the passive safety systems, which are presented here, together with an assessment of the IRIS response to transients and postulated accidents.

1. Introduction

The IRIS plant conceptual design was completed in 2001 and the preliminary design is currently underway. The pre-application licensing process with NRC started in October 2002 and IRIS is one of the designs considered by US utilities as part of the Early Site Permit (ESP) process.

Details of the IRIS design and supporting analyses have been previously reported and the reader is directed to the listed references. Purpose of this article is to provide an overall review of the IRIS characteristics.

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0029-5493/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2003.11.022

Acronyms

ADS	automatic depressurization system
ATWS	anticipated transient without scram
CRDM	control rod drive mechanism
CV	containment vessel
DID	defense in depth
DOE	Department of Energy
DVI	direct vessel injection
EBT	emergency boration tank
EHRS	emergency heat removal system
IRIS	International Reactor Innovative and Secure
LOCA	loss of coolant accident
MIT	Massachusetts Institute of Technology
NERI	Nuclear Energy Research Initiative
NRC	Nuclear Regulatory Commission
O&M	operation and maintenance
PBMR	pebble bed modular reactor
PRA	probabilistic risk assessment
PSS	pressure suppression system
PWR	pressurized water reactor
RCCA	rod control cluster assembly
RCP	reactor coolant pump
RCS	reactor coolant system
RV	reactor vessel
RWST	refueling water storage tank
SG	steam generator

IRIS is a pressurized water reactor that utilizes an integral reactor coolant system layout. The IRIS reactor vessel houses not only the nuclear fuel and control rods, but also all the major reactor coolant system components including pumps, steam generators, pressurizer, control rod drive mechanisms and neutron reflector. The IRIS integral vessel is larger than a traditional PWR pressure vessel, but the size of the IRIS containment is a fraction of the size of corresponding loop reactors, resulting in a significant reduction in the overall size of the reactor plant.

IRIS has been primarily focused on achieving design with innovative safety characteristics. The first line of defense in IRIS is to eliminate event initiators that could potentially lead to core damage. In IRIS, this concept is implemented through the "safety-by-design" approach, which can be simply described as "design the plant in such a way as to eliminate accidents from occurring, rather than coping with their consequences." If it is not possible to eliminate certain accidents altogether, then the design inherently reduces their consequences and/or decreases their probability of occurring. The key difference in the IRIS "safety-by-design" approach from previous practice is that the integral reactor design is conducive to eliminating accidents, to a degree impossible in conventional loop-type reactors. The elimination of the large LOCAs, since no large primary penetrations of the reactor vessel or large loop piping exist, is only the most easily visible of the safety potential characteristics of integral reactors. Many others are possible, but they must be carefully exploited through a design process that is kept focused on selecting design characteristics that are most amenable to eliminate accident initiating events.

The IRIS design builds on the proven technology provided by over 40 years of operating PWR experience, and on the established use of passive safety features pioneered by Westinghouse in the NRC certified AP600 plant design. The use of passive safety systems provides improvements in plant simplification, safety, reliability, and investment protection over conventional plant designs. Because of the safety-by-design approach, the number and complexity of these passive safety systems and required operator actions are further minimized in IRIS. The net result is a design with significantly reduced complexity and improved operability, and extensive plant simplifications to reduce construction time.

2. The IRIS approach and the IRIS consortium

When Westinghouse started the conceptual design of a new reactor in answer to the DOE solicitation, the overriding objective was to develop a commercially viable concept and thus avoid producing just one more paper reactor like so many of its predecessors. It was evident that the era of a single company, or even a single nation, developing and deploying a nuclear plant had past. Also, it was apparent that many utilities, as well as developing nations, are interested in capping their capital investment in a power plant project to only a few hundred million dollars, thus driving them to concentrate on smaller capacity additions. Larger plants, however, have economy of scale and a new dimension has to appear for smaller plants to become more economical and true market competitors.

Smaller, modular gas cooled reactors had already been proposed as commercial market entries, the PBMR (Nicholls, 2001) and the gas turbine-modular helium reactor (GT-MHR) (LaBar, 2002). For the PBMR, Exelon had made a strong case of the inherent advantage of small plants in introducing new power to the grid in limited increments, thus finely tailoring supply and demand and limiting the utilities' financial exposure. The same considerations apply to IRIS. Also common to the modular reactors is the fact that, in addition to being simpler to construct and operate, these smaller plants have to be fabricated in series. Thus, it is readily apparent that to fabricate and deploy an economically large enough number of multiple, identical modules, the market has to be one global, international arena.

Once it was established that this new reactor was to be deployed world-wide, it followed that to be readily accepted internationally, it had to be developed internationally, i.e., it had to address international requirements, needs and even cultures. Hence, the IRIS approach, as emphasized by the first letter (International) of its acronym: from the very beginning, IRIS was going to be designed and subsequently fabricated, deployed and serviced by an international partnership, where all team members were stakeholders in the project.

This approach immediately found a positive resonance, as the IRIS team kept growing in its first 3 years from the initial 4 members and 2 countries to the

Table 1
Member organizations of the IRIS consortium

Industry		
Westinghouse	USA	Overall coordination, core design, licensing
BNFL	UK	Fuel and fuel cycle
Ansaldo Energia	Italy	Steam generators design
Ansaldo Camozzi	Italy	Steam generators, CRDMs fabrication
ENSA	Spain	Pressure vessel and internals
NUCLEP	Brazil	Containment, pressurizer
Bechtel	USA	BOP, AE
OKBM	Russia	Testing, desalination
Laboratories		
ORNL	USA	I&C, PRA, shielding, pressurizer, core analyses
CNEN	Brazil	Pressurizer design, transient and safety analyses, desalination
ININ	Mexico	PRA support
LEI	Lithuania	Safety analyses, PRA, district heating co-gen
Universities		
Polytechnic of Milan	Italy	Safety analyses, shielding, thermal hydraulics, steam generators design, internal CRDMs, desalination
MIT	USA	Advanced cores, maintenance
Tokyo Institute of Technology	Japan	Advanced cores, PRA
University of Zagreb	Croatia	Neutronics, safety analyses
University of Pisa	Italy	Containment analyses
Polytechnic of Turin	Italy	Human factors, reliability availability maintainability support
University of Rome	Italy	Radwaste system, occupational doses
Power producers		
TVA	USA	Maintenance, utility perspective
Eletronuclear	Brazil	Developing country utility perspective
Associated US universities (NERI Programs)		
University of California Berkeley	USA	Neutronics, advanced cores
University of Tennessee	USA	Modularization, I&C
Ohio State University	USA	In-core power monitor, advanced diagnostics
Iowa State University (& Ames Lab)	USA	On-line monitoring
University of Michigan (& Sandia Labs)	USA	Monitoring and control

present over 20 members from 10 countries. The original team of Westinghouse, two American universities (University of California Berkeley and MIT) and one Italian university (Polytechnic of Milan) was joined by other reactor designers and component manufacturers, fuel and fuel cycle vendors, architect engineers, power producers, universities, and laboratories. Table 1 provides a summary of the IRIS team partnership with the areas of responsibility of each team member. Associate members are US universities and laboratories currently working on DOE funded NERI projects, which, while of general interest, use IRIS as the example application of the technology being investigated.

While associated members are DOE funded via NERI, all other IRIS consortium members (including international universities) are currently self-funded and provide to the project both design effort and previous know-how. Currently, approximately 100 people across the IRIS consortium are contributing to the project.

The contribution of the universities to the IRIS program cannot be emphasized enough. Innovative design solutions have been proposed and developed by universities, and IRIS is perhaps the first and only commercial reactor project where academia and industry are in a partnership equally co-responsible for the design. The partnership with universities (and laboratories) has also a potentially very important long-term effect, in making IRIS a "living and contemporary" design. In fact, once the IRIS preliminary design is completed, its implementation becomes essentially the responsibility of the industrial partners, while the universities and laboratories will shift to work on future improved designs incorporating the most recent technological advancements. As they are readied, industry can then implement them in a new series of IRIS modules. A key reason that this can conceivably be done and accepted by the market is that the size of an IRIS module is only about one-third to one-fourth of today's large light water reactors (LWRs) and thus the financial exposure is much more limited.

3. The integral reactor coolant system

The IRIS reactor vessel (Collado, 2003) houses not only the nuclear fuel and control rods, but also all the major reactor coolant system components (see Fig. 1): eight small, spool type, reactor coolant pumps; eight modular, helical coil, once through steam generators; a pressurizer located in the RV upper head; the control rod drive mechanisms; and, a steel reflector which surrounds the core and improves neutron economy, as well as it provides additional internal shielding. This integral RV arrangement eliminates the individual component pressure vessels and large connecting loop piping between them, resulting in a more compact configuration and in the elimination of the large loss-of-coolant accident as a design basis event. Because the IRIS integral vessel contains all the RCS components, it is larger than the RV of a traditional loop-type PWR. It has an i.d. of 6.21 m and an overall height of 22.2 m including the closure head. Water flows upwards through the core and then through the riser region (defined by the extended core barrel). At the top of the riser, the coolant is directed into the upper part of the annular plenum between the extended core barrel and the RV inside wall, where the suction of the reactor coolant pumps is located. Eight coolant pumps are employed, and the flow from each pump is directed downward through its associated helical coil steam generator module. The primary flow path continues down through the annular downcomer region outside the core to the lower plenum and then back to the core completing the circuit.

The major in-vessel components are described below:

- *Pressurizer*—The IRIS pressurizer (Barroso et al., 2003) is integrated into the upper head of the reactor vessel (see Fig. 2). The pressurizer region is defined by an insulated, inverted top-hat structure that divides the circulating reactor coolant flow path from the saturated pressurizer water. This structure includes a closed cell insulation to minimize the heat transfer between the hotter pressurizer fluid and the subcooled primary water. Annular heater rods are located in the bottom portion of the inverted top-hat which contains holes to allow water insurge and outsurge to/from the pressurizer region. These surge holes are located just below the heater rods so that insurge fluid flows up along the heater elements.

  By utilizing the upper head region of the reactor vessel, the IRIS pressurizer provides a very large water and steam volume, as compared to plants with a traditional, separate, pressurizer vessel. The IRIS

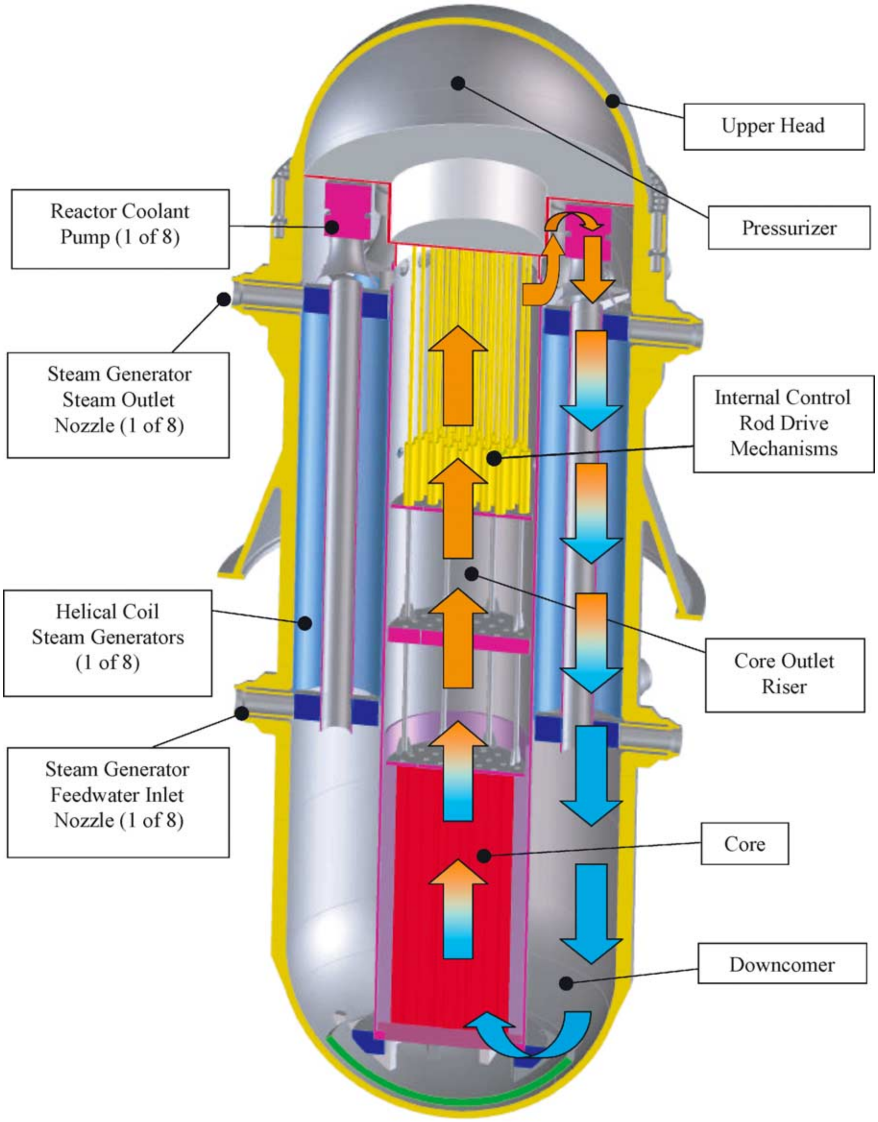

Fig. 1. IRIS integral layout.

pressurizer has a total volume of ~71 m^3, which includes a steam volume of ~49 m^3. The steam volume is about 1.6 times bigger than the AP1000 pressurizer steam space, while IRIS has less than 1/3 the core power. The large steam volume to power ratio is a key reason why IRIS does not require pressurizer sprays, which are used in current PWRs to prevent the pressurizer safety valves from lifting for any design basis heatup transients.

- *Reactor core*—The IRIS core (Petrovic et al., 2002) and fuel assemblies are similar to those of a loop type Westinghouse PWR design. Specifically, the IRIS fuel assembly design is similar to the Westinghouse 17 × 17 XL Robust Fuel Assembly design and AP1000 fuel assembly design. An IRIS fuel assembly consists of 264 fuel rods with a 0.374 in. o.d. in a 17 × 17 square array. The central position is reserved for in-core instrumentation, and 24 positions have

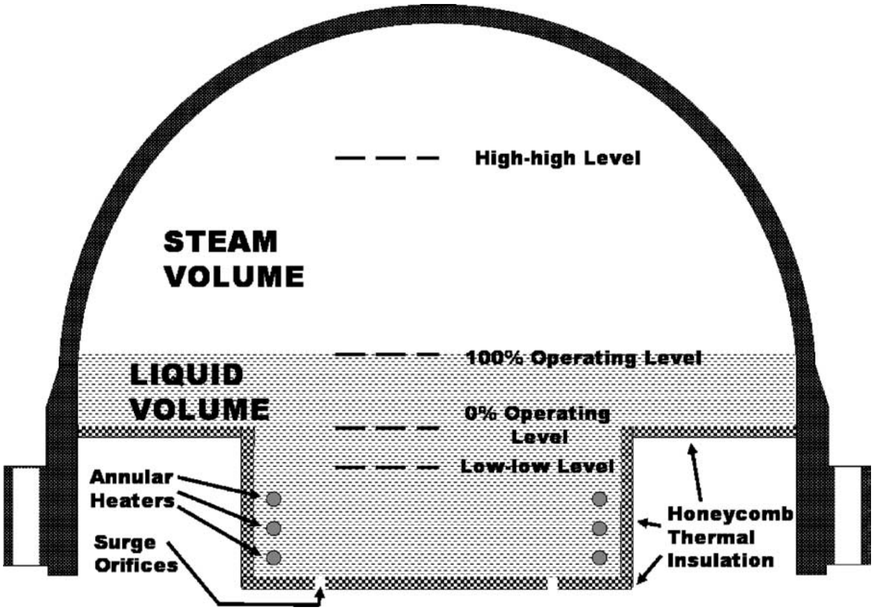

Fig. 2. IRIS pressurizer.

guide thimbles for the control rodlets. Low-power density is achieved by employing a core configuration consisting of 89 fuel assemblies with a 14-ft (4.267 m) active fuel height, and a nominal thermal power of 1000 MWt. The resulting average linear power density is about 75% of the AP600 value. The improved thermal margin provides increased operational flexibility, while enabling longer fuel cycles and increased overall plant capacity factors.

The IRIS core will use UO_2 fuel, enriched to 4.95 w/o in ^{235}U, with lower enrichment in the axial blankets and at the core periphery. The fission gas plenum length is increased (roughly doubled) compared to current PWRs, thus eliminating potential concerns with internal overpressure. The integral RV design permits this increase in the gas plenum length with practically no penalty, because the steam generators mainly determine the vessel height. The 89 assembly core configuration has a relatively high fill-factor (i.e., it closely approximates a cylinder), to minimize the vessel diameter.

Reactivity control is accomplished through solid burnable absorbers, control rods, and the use of a limited amount of soluble boron in the reactor coolant. The reduced use of soluble boron makes the moderator temperature coefficient more negative, thus increasing inherent safety. The core is designed for a 3–3.5-year cycle with half-core reload to optimize the overall fuel economics while maximizing the discharge burnup. In addition, a 4-year straight burn fuel cycle can also be implemented to improve the overall plant availability, but at the expense of a somewhat reduced discharge burnup.

- *Reactor coolant pumps*—The IRIS RCPs (Kujawski et al., 2002) are of a "spool type," which has been used in marine applications, and are being designed and will soon be supplied for chemical plant applications requiring high flow rates and low developed head. The motor and pump consist of two concentric cylinders, where the outer ring is the stationary stator and the inner ring is the rotor that carries high specific speed pump impellers. The spool type pump is located entirely within the reactor vessel, with only small penetrations for the electrical power cables and for water cooling supply and return. Further, significant qualification work has been completed on the use of high temperature motor windings. This and continued work on the bearing materials has the potential to eliminate even the need for cooling water and the associated piping penetrations through the RV. This pump compares very favorably to the typical canned motor RCPs, which have the pump/impeller extending through a large opening in the pressure boundary with the motor outside the RV. Consequently, the canned pump motor casing becomes part of the pressure boundary and is typically flanged and seal welded to the mating RV pressure boundary surface. All of this is eliminated in IRIS. In addition to the above advantages derived from its integral location, the spool pump geometric configuration maximizes the rotating inertia and these pumps have a high run-out flow capability. Both these attributes mitigate the consequences of LOFAs. Because of their low developed head, spool pumps have never been candidates for nuclear applications. However, the IRIS integral RV configuration and low primary coolant pressure drop can accommodate these pumps and together with the assembly design conditions can take full advantage of their unique characteristics.

- *Steam generators*—The IRIS SGs are once-through, helical-coil tube bundle design with the primary fluid outside the tubes (Cinotti et al., 2002). Eight steam generator modules are located in the annular space between the core barrel (outside diameter 2.85 m) and the reactor vessel (inside diameter 6.21 m). Each IRIS SG module consists of a central inner column which supports the tubes, the lower feed water header and the upper steam header. The enveloping outer diameter of the tube bundle is 1.64 m. Each SG has 656 tubes, and the tubes and headers are designed for the full external RCS pressure. The tubes are connected to the vertical sides of the lower feedwater header and the upper steam header. The SG is supported from the RV wall and the headers are bolted to the vessel from the inside of the feed inlet and steam outlet pipes. Fig. 3 illustrates the IRIS helical coil SG upper steam discharge header and the tube bundle arrangement.

  The helical-coil tube bundle design is capable of accommodating thermal expansion without excessive mechanical stress, and has high resistance to flow-induced vibrations. A prototype of this SG was successfully tested by Ansaldo in an extensive test campaign conducted on a 20 MWt full diameter, part height, test article. The performance characteristics (thermal, vibration, pressure losses) were investigated along with the determination of the operating characteristics domain for stable operation.

- *Control rod drive mechanisms*—The integral configuration is ideal for locating the CRDMs inside the vessel, in the region above the core and surrounded by the steam generators. Their advantages are in safety and operation.

  Safety-wise, the uncontrolled rod ejection accident (a class IV accident) is eliminated because there is no potential 2000-psi differential pressure to drive out the CRDM extension shafts. Operation-wise, the absence of CRDM nozzle penetrations in the upper head eliminates all the operational problems related with corrosion cracking of these nozzle welds and seals which have intermittently plagued the industry, and most recently have extensively flared up (e.g., the Davis–Besse plant). The design and manufacturing of the upper head is also simpler and cheaper. Integral reactor designs featuring internal CRDMs were small, low power, like the Argentinean CAREM (Mazzi et al., 2001) and the Chinese NHR (Batheja et al., 1987; Hanliang et al., 2000) which employ hydraulically driven rods, and the Japanese MRX (Ishizaka, 1992) which uses an electromagnetic drive mechanism. Very recently, however, they have been proposed in Japan for large BWRs (Narabayashi et al., 2003).

  Thus, IRIS has adopted the internal CRDMs as reference (traditional CRDMs remaining as backup) because (1) they eliminate the corrosion problem, (2) they are one more implementation of the safety-by-design, and (3) advancement of internal CRDMs development in regard to the electromagnetic concept in Japan, while internally to the IRIS project, Polytechnic of Milan has further advanced the hydraulic drive concept. IRIS is currently evaluating candidate concepts for the internal CRDMs, and will be proceeding soon to the preliminary design of the chosen one.

- *Neutron reflector*—IRIS features a stainless steel radial neutron reflector to lower fuel cycle cost and to extend reactor life. This reflector reduces neutron leakage thereby improving core neutron utilization, and enabling extended fuel cycle and increased discharge burnup. The radial reflector has the added benefit of reducing the fast neutron fluence on the core barrel, and, together with the thick downcomer region, it significantly reduces the fast neutron fluence on the reactor vessel as well as the dose outside the vessel to the extent of yielding, for

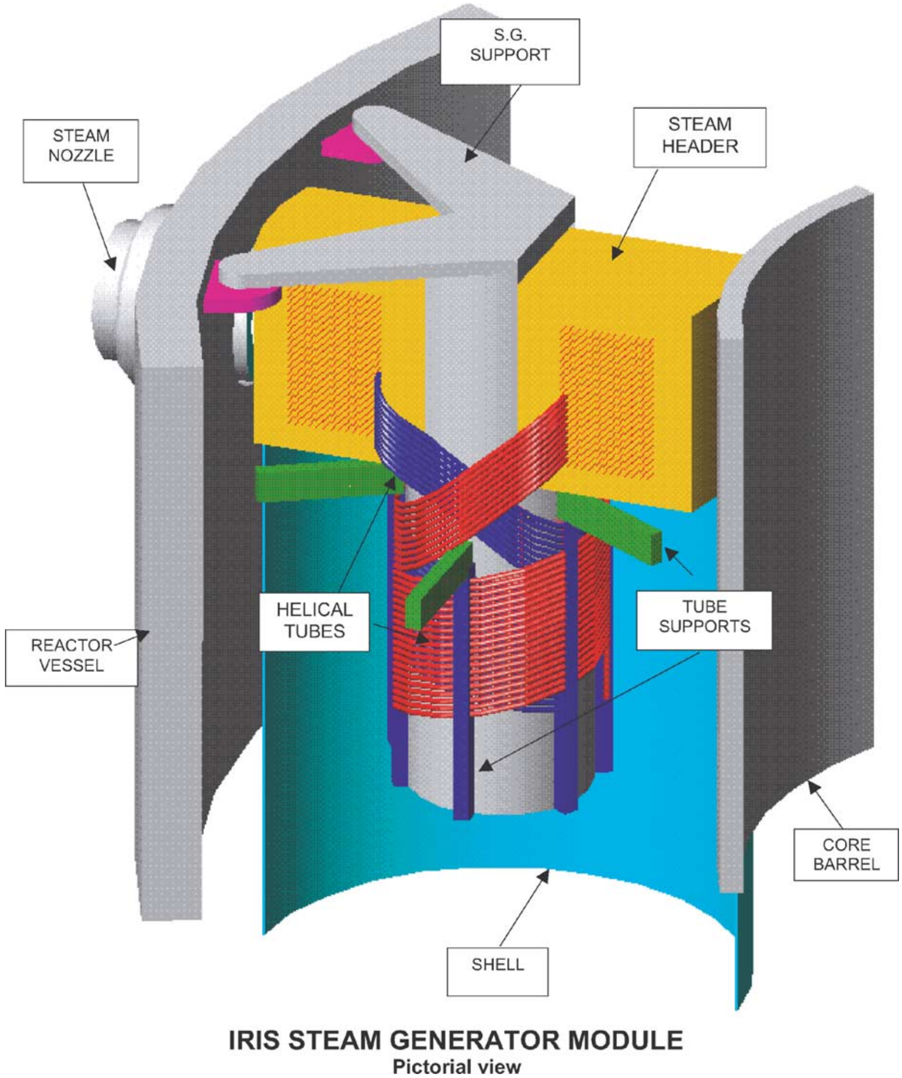

Fig. 3. IRIS helical coil steam generator.

any practical purposes, a "cold" vessel. This has obvious beneficial impacts on costs (very long life vessel, no need for the embrittlement surveillance program, reduced biological shield), operational doses, and decommissioning.

4. Extended maintenance

As mentioned, a distinguishing characteristic of IRIS is its capability of operating with long cycles. Even though the reference design features a two-batch, 3-year fuel cycle, selected on the basis of ease of licensing and US utilities preference, IRIS is capable of eventually operating in straight burn with a core lifetime of up to 8 years. However, the significant advantages connected with a long refueling period in reducing O&M costs are lost if the reactor still has to be shut down on a 18–24-month interval for routine maintenance and inspection. Thus, first and foremost, the IRIS primary system components are designed to have very high reliability to decrease the incidence of equipment failures and reduce the frequency of required inspections or repairs. Next, IRIS has been designed to extend the need for scheduled maintenance outages to at least 48 months. The basis of the design has been a study (McHenry et al., 1997) performed earlier by MIT for an operating PWR to identify required actions for extending the maintenance period from 18 to 48 months. The strategy was to either extend the maintenance/testing items to 48 months or to perform maintenance/testing on line. MIT identified 3743 maintenance items, 2537 of them off-line and the remaining 1206 on-line. It was also confirmed that 1858 of the off-line items could be extended from 18 to 48 months, while 625 could be recategorized from off-line to on-line. Further, out of the 1858 items there were 1499, which were electrical surveillances and had a strong potential for also being performed on-line. This left only 54 items which still needed to be performed off-line on a schedule shorter than 48 months. Starting from this MIT study and factoring in the specific IRIS conditions (for example, there is no need to change the RCP oil lubricant, since the spool type pumps are lubricated by the reactor coolant), only seven items were left as obstacles to a 48-month cycle (Galvin et al., 2003). These items have been addressed and either have been resolved or a plan of action has been identified (Boroughs et al., 2003).

Because of the 4-year maintenance cycle capability, the capacity factor of IRIS is expected to comfortably satisfy and exceed the 95% target, and personnel requirements are expected to be significantly reduced. Both considerations will result in decreased O&M costs.

Uninterrupted operation for 48 months requires reliable advanced diagnostics. The IRIS project is currently investigating various technologies, either already proven or in advanced phase of development, to monitor the behavior of the in-vessel components. Promising, but more distant technologies, are being pursued by associated universities.

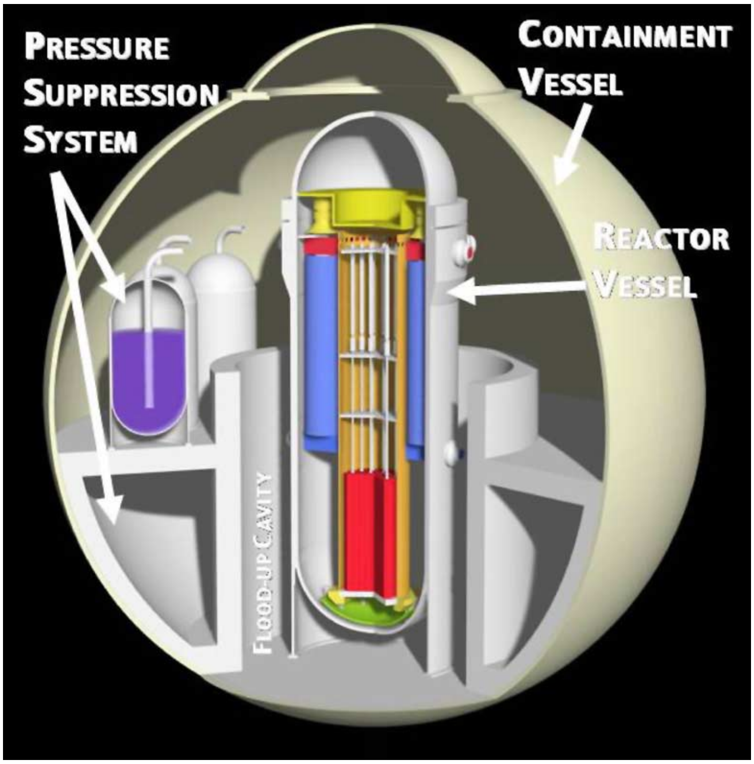

Fig. 4. IRIS spherical steel containment arrangement.

5. Containment system

Because the IRIS integral RV configuration eliminates the loop piping and the externally located steam generators, pumps and pressurizer with their individual vessels, the footprint of the patent-pending IRIS containment system is greatly reduced. This size reduction, combined with the spherical geometry, results in a design pressure capability at least three times higher than a typical loop reactor cylindrical containment, assuming the same metal thickness and stress level in the shell. The current layout features a spherical, steel containment vessel that is 25 m (82 ft.) in diameter (see Fig. 4). The CV is constructed of $1 - 3/4$ in. steel plate and has a design pressure capability of 1.4 MPa ($\sim$190 psig). The containment vessel has a bolted and flanged closure head at the top that provides access to the RV upper head flange and bolting. Refueling of the reactor is accomplished by removing the containment vessel closure head, installing a sealing collar between the CV and RV, and removing the RV head. The refueling cavity above the containment and RV is then flooded, and the RV internals are removed and stored in the refueling cavity. Fuel assemblies are vertically lifted from the RV directly into a fuel handling and storage area, using a refueling machine located directly above the CV. Thus, no refueling equipment is required inside containment and the single refueling machine is used for all fuel movement activities.

Fig. 4 also shows the pressure suppression pool that limits the containment peak pressure to well below the CV design pressure. The suppression pool water is elevated such that it provides a potential source of elevated gravity driven makeup water to the RV. Also shown is the RV flood-up cavity formed by the containment internal structure. The flood-up level is 9 m and ensures that the lower section of the RV, where the core is located, is surrounded by water following any postulated accident. The water flood-up height is sufficient to provide long-term gravity makeup, so that the RV water inventory is maintained above the core for an indefinite period of time. It also provides sufficient heat removal from the external RV surface to prevent any vessel failure following beyond design basis scenarios.

Almost half of the IRIS containment vessel is located below ground, thus leaving only about 15 m above the ground (i.e., several times less than the containment of a large LWR). This very low profile makes IRIS an extremely difficult target for aircraft flying terrorists; in addition, the IRIS containment is inconspicuously housed in and protected by the reactor building. The cost of putting the entire reactor underground was evaluated; it was judged to be prohibitive for a competitive entry to the power market and unnecessary since the IRIS design characteristics are such to offer both an economic and very effective approach to this problem.

6. The IRIS safety-by-design approach

The IRIS design provides for multiple levels of defense for accident mitigation (defense in depth), resulting in extremely low core damage probabilities. In addition to the traditional DID levels (barriers, redundancy, diversity, etc.) IRIS introduces a very basic level of DID, i.e., elimination by design of accident initiators or reduction of their consequences/probability. This is implemented through the "safety-by-design" approach, which was briefly presented in the introduction.

Several features of the design form the basis of the safety-by-design approach. These features are summarized in Table 2 and are discussed in the following. Table 3 provides an overview of how the safety-by-design features listed in Table 2 will impact the typical design basis events.

The adoption of an integral reactor coolant system eliminates the large loop piping required for other designs, and thus the potential for postulated large loss of coolant accidents is eliminated by design. The elimination of large break LOCAs is only the most evident safety-by-design feature of IRIS; others are presented here as they are a fundamental part of the IRIS defense in depth.

The adoption of an integral layout requires the design of a large vessel compared to other PWRs, with a tall riser above the core to allow sufficient space for the placements of the steam generators and reactor coolant pumps in the pressure vessel. This provides a large coolant inventory in the reactor coolant system, that is the basis of the IRIS response to small and medium break LOCAs, i.e., to rely on "maintaining water inventory" rather than "providing coolant injection." Also, the large coolant inventory provides

Table 2
Implications of safety-by-design approach

IRIS design characteristic	Safety implication	Accidents affected
Integral layout	No large primary piping	LOCAs
Large, tall vessel	Increased water inventory	LOCAs Decrease in heat removal
	Increased natural circulation	Various events
	Accommodates internal CRDMs	RCCA ejection, eliminate head penetrations
Heat removal from inside the vessel	Depressurizes primary system by condensation and not by loss of mass	LOCAs
	Effective heat removal by SG/EHRS	LOCAs All events for which effective cooldown is required ATWS
Reduced size, higher design pressure containment	Reduced driving force through primary opening	LOCAs
Multiple coolant pumps	Decreased importance of single pump failure	Locked rotor, shaft seizure/break
High design pressure steam generator system	No SG safety valves	
	Primary system cannot over-pressure secondary system	Steam generator tube rupture
	Feed/steam system piping designed for full RCS pressure reduces piping failure probability	Steam line break Feed line break
Once through steam generator	Limited water inventory	Steam line break Feed line break[a]
Integral pressurizer	Large pressurizer volume/reactor power	Overheating events, including feed line break ATWS

[a] Only accident which is potentially affected in a negative way.

a large heat sink that acts to effectively mitigate cooldown and heatup events.

The tall riser and the reduced pressure losses in the reactor coolant system yield a large natural circulation ratio. This provides an effective circulation of coolant in the reactor coolant system to remove decay heat from the core. Finally, the tall riser provides sufficient space to accommodate internal CRDMs. Not only this allows to eliminate the potential for an RCCA ejection, but it also allows to eliminate the CRDMs penetrations through the vessel upper head. Thus, the operational concerns associated with boron-induced corrosion of the vessel head nozzles (which have idled the Davis–Besse power station since February 2002) are eliminated by design.

Another IRIS specific feature that has been used to inherently mitigate the consequences of postulated events is the location of the steam generators inside the pressure vessel. Coupled with the large inventory, this is a fundamental feature to shape the IRIS response to postulated small and medium break LOCAs. The large heat surface available inside the vessel is used to remove the heat produced in the core during the event, and provides a mean for depressurizing the reactor coolant system by condensing inside the vessel the steam produced, as opposite to a depressurization system that relies on mass loss outside the vessel. Thus, coolant inventory is maintained. Also, the effective heat removal through the steam generators and the emergency heat removal

Table 3
IRIS response to PWR Class IV events

Class IV design basis events		IRIS design characteristic	Results of IRIS safety-by-design
1	Large break LOCA	Integral RV layout—no loop piping	Eliminated by design
2	Steam generator tube rupture	High design pressure once-through SGs, piping, and isolation valves	Reduced consequences, simplified mitigation
3	Steam system piping failure	High design pressure SGs, piping, and isolation valves. SGs have small water inventory	Reduced probability, reduced (limited containment effect, limited cooldown) or eliminated (no potential for return to critical power) consequences
4	Feedwater system pipe break	High design pressure SGs, piping, and isolation valves. Integral RV has large primary water heat capacity	Reduced probability, reduced consequences (no high pressure relief from reactor coolant system)
5	Reactor coolant pump shaft break	Spool pumps have no shaft	Eliminated by design
6	Reactor coolant pump seizure	No DNB for failure of 1 out of 8 RCPs	Reduced consequences
7	Spectrum of RCCA ejection accidents	With internal CRDMs there is no ejection driving force	Eliminated by design
8	Design basis fuel handling accidents	No IRIS specific design feature	No impact

system (see Section 6.1) provide effective mitigation for all the events that require safety grade decay heat removal.

As discussed in Section 5, the adoption of an integral layout provides an overall reduction in the dimensions of the reactor coolant system, and thus allows designing a compact, higher design pressure containment system. During the initial phases of a loss of coolant accident, the pressure in the IRIS containment is allowed to increase early in the accident, and thus the higher back-pressure provides an inherent limitation to the inventory loss from the reactor coolant system. This goes hand-in-hand with the previously discussed depressurization inside the vessel, effectively and quickly zeroing the differential pressure across the break and thus terminating the small/medium LOCA. The core remains safely covered without any water makeup or injection. It should be noted that a large margin (almost 30%) to the containment design pressure is provided for all design basis accidents, and that the effective reactor coolant system and containment cooling provided by the EHRS rapidly reduces the pressure in the containment to minimize containment leakage following a postulated LOCA.

The IRIS once-through steam generators, with the primary coolant on the shell side provide a reduced volume of the secondary side, and this allows designing the IRIS steam system up to the isolation valves for full reactor coolant system design pressure. This in turn allows to eliminate the steam generator safety valves, since the steam system is protected by the reactor coolant system safety valves; prevents the reactor coolant system from overpressurizing the steam system; and, reduces the probability for piping failures since the steam and feed lines are designed for full pressure. These features play an important role in the mitigation of both the probability and the consequences of postulated steam generator tubes ruptures. Not only the potential for failures is reduced since the tubes are mostly in compression (primary coolant on the shell side), but also failure propagation is highly improbable due to tube collapse. Additionally, an effective mitigation is provided simply by isolating the faulted steam generator.

Another feature of IRIS steam generators is the limited available water inventory: while it limits the consequences of cooldown events, this feature also limits the available inventory in the steam generators to mitigate heatup events, like a feed line break. However, other IRIS design features, and in particular the large primary coolant inventory, more than compensate for this drawback. Also, the rapid loss of mass from the steam generators provides a means for rapid

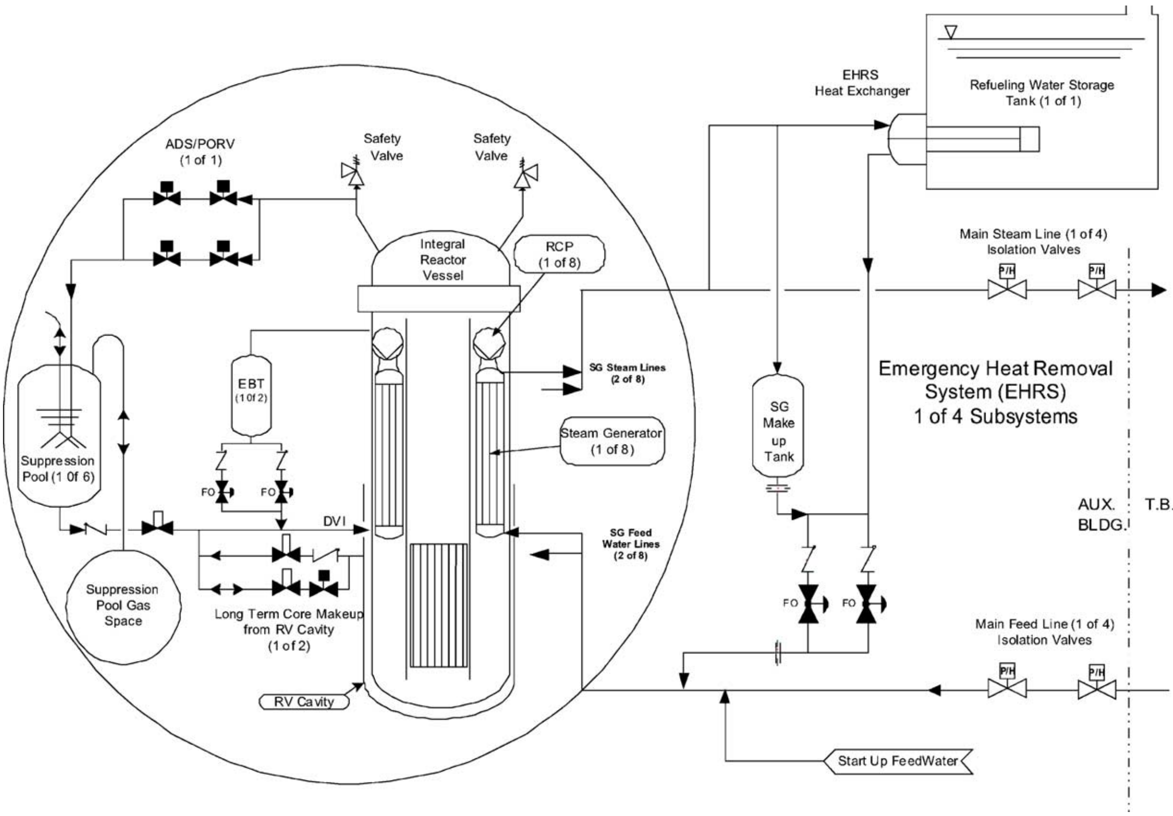

Fig. 5. IRIS passive safety system schematic.

detection of the fault and thus for a rapid actuation of the safety features.

An effective means for mitigating the consequences of heatup events is provided by another IRIS design characteristic of the integral layout. A large volume is available in the reactor vessel head for the pressurizer, which is thus designed with a large steam volume, to provide an inherent mitigation to events causing a pressurization of the reactor coolant system. Not only this allows to simplify the design (IRIS does not feature a spray system nor automatic power-operated relief valves), but it also provides an inherent protection against reactor coolant system overpressurization.

6.1. IRIS safety features

To complement its safety-by-design, IRIS features limited and simplified passive systems as shown in Fig. 5. They include:

- A passive emergency heat removal system made of four independent subsystems, each of which has a horizontal, U-tube heat exchanger connected to a separate SG feed/steam line. These heat exchangers are immersed in the refueling water storage tank located outside the containment structure. The RWST water provides the heat sink to the environment for the EHRS heat exchangers. The EHRS is sized so that a single subsystem can provide core decay heat removal in the case of a loss of secondary system heat removal capability. The EHRS operates in natural circulation, removing heat from the primary system through the steam generators heat transfer surface, condensing the steam produced in the EHRS heat exchanger, transferring the heat to the RWST water, and returning the condensate back to the SG. The EHRS provides both the main post-LOCA depressurization (depressurization without loss of mass) of the primary system and the core cooling functions. It performs these functions by condensing the steam produced by the core directly inside the reactor vessel. This minimizes the break flow and actually reverses it for a portion of the LOCA response, while transferring the decay heat to the environment.

- Two full-system pressure emergency boration tanks to provide a diverse means of reactor shutdown by delivering borated water to the RV through the direct vessel injection lines. By their operation these tanks also provide a limited gravity feed makeup water to the primary system.
- A small automatic depressurization system from the pressurizer steam space, which assists the EHRS in depressurizing the reactor vessel when/if the reactor vessel coolant inventory drops below a specific level. This ADS has one stage and consist of two parallel 4 in. lines, each with two normally closed valves. The single ADS line downstream of the closed valves discharges into the pressure suppression system pool tanks through a sparger. This ADS function ensures that the reactor vessel and containment pressures are equalized in a timely manner, limiting the loss of coolant and thus preventing core uncovery following postulated LOCAs even at low RV elevations;
- A containment pressure suppression system which consists of six water tanks and a common tank for non-condensable gas storage. Each suppression water tank is connected to the containment atmosphere through a vent pipe connected to a submerged sparger so that steam released in the containment following a loss of coolant or steam/feed line break accident is condensed. The suppression system limits the peak containment pressure, following the most limiting blowdown event, to less than 1.0 MPa (130 psig), which is much lower than the containment design pressure. The suppression system water tanks also provide an elevated source of water that is available for gravity injection into the reactor vessel through the DVI lines in the event of a LOCA.
- A specially constructed lower containment volume that collects the liquid break flow, as well as any condensate from the containment, in a cavity where the reactor vessel is located. Following a LOCA, the cavity floods above the core level, creating a gravity head of water sufficient to provide coolant makeup to the reactor vessel through the DVI lines. This cavity also assures that the lower outside portion of the RV surface is or can be wetted following postulated core damage events.

As in the AP600/AP1000, the IRIS safety system design uses gravitational forces instead of active components such as pumps, fan coolers or sprays and their supporting systems.

The safety strategy of IRIS provides a diverse means of core shutdown by makeup of borated water from the EBT in addition to the control rods; also, the EHRS provides a means of core cooling and heat removal to the environment in the event that normally available active systems are not available. In the event of a significant loss of primary-side water inventory, the primary line of defense for IRIS is represented by the large coolant inventory in the reactor vessel and the fact that EHRS operation limits the loss of mass, thus maintaining a sufficient inventory in the primary system and guaranteeing that the core will remain covered for all postulated events. The EBT is capable of providing some primary system injection at high pressure, but this is not necessary, since the IRIS strategy relies on “maintaining” coolant inventory, rather than “injecting” makeup water. This strategy is sufficient to ensure that the core remains covered with water for an extended period of time (days and possibly weeks). Thus, IRIS does not require and does not have the high capacity, safety grade, high pressure safety injection system characteristic of loop reactors.

Of course, when the reactor vessel is depressurized to near containment pressure, gravity flow from the suppression system and from the flooded reactor cavity will maintain the RV coolant inventory for an unlimited period of time. However, this function would not be strictly necessary for any reasonable recovery period since the core decay heat is removed directly by condensing steam inside the pressure vessel, thus preventing any primary water from leaving the pressure vessel.

The IRIS design also includes a second means of core cooling via containment cooling, since the vessel and containment become thermodynamically coupled once a break occurs. Should cooling via the EHRS be defeated, direct cooling of the containment outer surface is provided and containment pressurization is limited to less than its design pressure. This cooling plus multiple means of providing gravity driven makeup to the core provides a means of preventing core damage and ensuring containment integrity and heat removal to the environment that is diverse from the EHRS operation.

IRIS is designed to provide in-vessel retention of core debris following severe accidents by assuring that the vessel is depressurized, and by cooling the outside vessel surface. The reactor vessel is cooled by containing the lower part of the vessel within a cavity that always will be flooded following any event that jeopardizes core cooling. Also, like in AP1000, the vessel is covered with stand-off insulation that forms an annular flow path between the insulation and the vessel outer surface. Following an accident, water from the flooded cavity fills the annular space and submerges and cools the bottom head and lower side walls of the vessel (Scobel et al., 2002). A natural circulation flow path is established, with heated water and steam flowing upwards along the vessel surface, and single-phase water returning downward along the outside of the vessel insulation, to the bottom of the flood-up cavity. AP1000 testing has demonstrated that this natural circulation flow is sufficient to prevent corium melt-through. Application of AP1000 conditions to IRIS is conservative, due to the IRIS much lower core power to vessel surface ratio. The design features of the containment ensure flooding of the vessel cavity region during accidents and submerging the reactor vessel lower head in water since the liquid effluent released through the break during a LOCA event is directed to the reactor cavity. The IRIS design also includes a provision for draining part of the water in the PSS water tanks directly into the reactor cavity.

6.2. Assessment of the IRIS response to transients and postulated design basis accidents

The safety-by-design features of the reactor, with their vastly enhanced defense in depth provide an effective means of satisfying regulatory requirements for design basis events. The main effects of this approach on IRIS safety were listed in Tables 2 and 3 and are discussed here in some detail. All the events that are typically studied as part of Section 15 of the Safety Analysis Report according to the NRC Standard Review Plan (SRP) (NRC, 2002), and for which IRIS will present significant differences from current active and passive PWRs, are briefly discussed here.

- *Loss of coolant accidents (LOCAs)*—The integral RV eliminates by design the possibility of large break LOCAs, since no large primary system piping is present in the reactor coolant system. Also, the probability and consequences of small break LOCA are lessened because of the drastic reduction in overall piping length, and by limiting the largest primary vessel penetration to a diameter of less than 4 in. The innovative strategy developed to cope with a postulated small break LOCA by fully exploiting the IRIS design characteristics is discussed in the following.

  IRIS is designed to limit the loss of coolant from the vessel rather than relying on active or passive systems to inject water into the RV. This is accomplished by taking advantage of the following three features of the design:

  - The initial large coolant inventory in the reactor vessel.
  - The EHRS which removes heat directly from inside the RV thus depressurizing the RV by condensing steam, rather than depressurizing by discharging mass.
  - The compact, small diameter, high design pressure containment that assists in limiting the blowdown from the RV by providing a higher backpressure in the initial stages of the accident and thus rapidly equalizing the vessel and containment pressures.

  After the LOCA initiation, the RV depressurizes and loses mass to the CV causing the CV pressure to rise (blowdown phase). The mitigation sequence is initiated with the reactor trip and pump trip; the EBTs are actuated to provide boration; the EHRS is actuated to depressurize the primary system by condensing steam on the steam generators (depressurization without loss of mass); and finally, the ADS is actuated to assist the EHRS in depressurizing the RV. The containment pressure is limited by the PSS and the reduced break flow due to the EHRS heat removal from the RV.

  At the end of the blowdown phase, the RV and CV pressure become equal (pressure equalization) with a CV pressure peak less than 8 bar_g. The break flow stops and the gravity makeup of borated water from the suppression pool becomes available.

The coupled RV/CV system is then depressurized (RV/CV depressurization phase) by the EHRS (steam condensation inside the RV exceeds decay heat boiloff). In this phase the break flow reverses since heat is removed not from the containment, but directly from inside the vessel, and this increases the liquid level in the vessel. As steam from the containment is condensed inside the pressure vessel (RV and CV pressure reduced to less than 2 bar_g within 12 h), the containment pressure is reduced, and a portion of suppression pool water is pushed out through the vents and assists in flooding the vessel cavity.

The depressurization phase is followed by the long term cooling phase where the RV and CV pressure is slowly reduced as the core decay heat decreases.

During this phase of the accident recovery, gravity makeup of borated water from both suppression pool and RV cavity is available as required. Since decay heat is directly removed from within the vessel and the vessel and containment are thermodynamically coupled, the long term break flow does not correspond to the core decay heat, but it is in fact limited to only the containment heat loss.

- *Steam generator tube rupture*—In IRIS, the steam generator tubes are in compression (the higher pressure primary fluid is outside the tubes) and the steam generators headers and tubes are designed for full external reactor pressure. Thus, tube rupture is much less probable and if it does occur, there is virtually no chance of tube failure propagation. Beside reducing the probability of the event occurrence, IRIS also provides by design a very effective mitigation to this event.

  Since the steam generators, the feed and steam piping and the isolation valves are all designed for full reactor coolant system pressure, a tube rupture event is rapidly terminated by closure of the faulted SG main steam and feed isolation valves upon detection of the failure. Once the isolation valves are closed, the primary water will simply fill and pressurize the faulted steam generator terminating the leak. Given the limited volume of the steam generators and piping, no makeup to the RV is even required; and since the faulted SG is immediately isolated, the release of radioactivity (primary fluid) to the environment will be minimized.
- *Increase in heat removal from the primary side*—The limited water inventory in the once through steam generator has an important effect on the events in this category. Increases in heat removal due to increased steam flow are eliminated since the steam flow from the once through steam generators cannot exceed feed water flow rate. Also, the consequences of a design basis steam line break event are significantly lessened. Not only is the impact on the containment limited by the reduced discharge of mass/energy, but also no return to power due to the cooldown of the primary system is possible.
- *Decrease in heat removal from the secondary side*—Events in this category (which include loss of offsite power, loss of normal feedwater, turbine trip and feed system piping failure) could potentially have larger consequences in IRIS than in loop type PWRs because of the limited water inventory in the once through steam generators. However, the IRIS design compensates for the limited SG water inventory.

  The limited heat sink provided by the steam generators is in fact more than balanced by the large thermal inertia in the primary system (the IRIS water inventory is more than five times larger than advanced passive PWRs like AP1000 on a coolant mass-per-MWt basis), and by the large steam volume in the IRIS pressurizer (steam volume-to-power ratio is also more than five times that of the AP1000). The reactor trip setpoint is rapidly reached on a low feedwater signal, and the EHRS connected to the steam generators effectively removes sufficient heat to prevent any pressurizer overfill or high pressure relief from the reactor vessel to the containment.
- *Decrease in reactor coolant flow rate*—The IRIS response to a complete loss of flow is comparable to that of the AP600/AP1000, where the coast down of the reactor coolant pumps is sufficient to maintain core cooling until the control rods are inserted and power is decreased. For the design basis locked rotor event, the IRIS response is improved over other PWRs by the increased number of reactor coolant pumps, which reduces the relative importance of a loss of a single pump flow. This design choice allows IRIS to prevent fuel damage (i.e., no departure from nucleate boiling) following a postulated locked rotor event even without a reactor

trip. Of course a shaft break accident cannot occur, because spool pumps do not have shafts.

- *Spectrum of postulated rod ejection accidents*—Locating the CRDMs internally to the reactor vessel eliminates by design the rod ejection accident since there is no significant driving differential pressure over the driveline.
- *Increase in reactor coolant inventory*—This category of events is eliminated in IRIS since IRIS does not utilize high pressure coolant injection following a LOCA. The inadvertent actuation of the small emergency boration tanks can be accommodated by the large pressurizer volume with no overpressure or overfill of the RV.

7. Conclusions

An overview of the status of the IRIS design has been provided, with particular emphasis on the integral layout of the reactor coolant system and on the innovative IRIS approach to safety.

The integral layout offers very significant advantages in terms of performance, simplicity, and compactness. It has been demonstrated that it has an extremely positive impact on the overall reactor safety response to postulated accidents. It is also expected to have a positive economic impact and work has been initiated for its verification.

Because of the safety-by-design approach, the number and complexity of the safety systems and required operator actions are minimized in IRIS. The net result is a design with significantly reduced complexity, improved operability, and extensive plant simplifications.

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