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THE DESIGN AND SAFETY FEATURES OF THE IRIS REACTOR

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ABSTRACT

The pressurized light water cooled, medium power (1000 MWt) IRIS (International Reactor Innovative and Secure) reactor plant has been under development for three years by an international consortium of over 20 organizations from nine countries. The 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 ESP (Early Site Permit) process.

Major characteristics of the IRIS design and supporting analyses have been previously reported. This paper focuses on the status of the design and licensing process.

1. INTRODUCTION

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 and a 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 a design with innovative safety characteristics. The first line of defense in IRIS is to eliminate event initiators that could convincibly 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 decrease 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 an appropriate design 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 enhance construction.

2. INTEGRAL REACTOR COOLANT SYSTEM DESCRIPTION

The IRIS reactor vessel (RV) is an integral configuration which houses not only the nuclear fuel and control rods, but also all the major reactor coolant system (RCS) components (see Figure 1a). This includes: eight (8) small, spool type, reactor coolant pumps (RCPs); eight (8) modular, helical coil, once through steam generators (SGs); a steel reflector which surrounds the core and improves neutron economy, as well as provides additional internal shielding, with the latter that may be further enhanced by circumferential steel plates located beyond the barrel in the downcomer region; and a pressurizer located in the RV upper head. 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 ID of 6.20 meters (20'-4") and an overall height of 23.52 meters (77'-2") including the closure head. Equipos Nucleares, S.A. (ENSA) of Spain is responsible for developing the design of the IRIS reactor vessel and reactor internals [1].

The primary coolant main flow path is illustrated in Figure 1(b). Water flows upwards through the core and upward 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 flow path continues down through the annular downcomer region outside the core to the lower plenum and then back to the core completing the primary coolant flow path.

The major in-vessel components are described below:

- **Pressurizer** – The IRIS pressurizer is integrated into the upper head of the reactor vessel. 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 water in the primary water circulating flow path. Heater rods are located in the bottom portion of the inverted top-hat and are positioned outside the control rod drive mechanism (CRDM) drive lines. The bottom of this inverted top-hat 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 pressurizer has a total volume of ~71 m^3, which includes a steam volume of ~49 m^3. This steam volume is about 1.6 times bigger than the AP1000 pressurizer steam space, while the IRIS has less than 1/3 the core power. This large steam volume to power ratio is a key reason why IRIS does not require the use of a pressurizer spray function to prevent the pressurizer safety valves from lifting for any design basis heatup transients. The Brazilian Comissao Nacional de Energia Nuclear (CNEN) and the equipment manufacturer Nuclebrás Equipa-mentos Pesados (NUCLEP) are responsible for the design and analysis of the IRIS pressurizer [2].

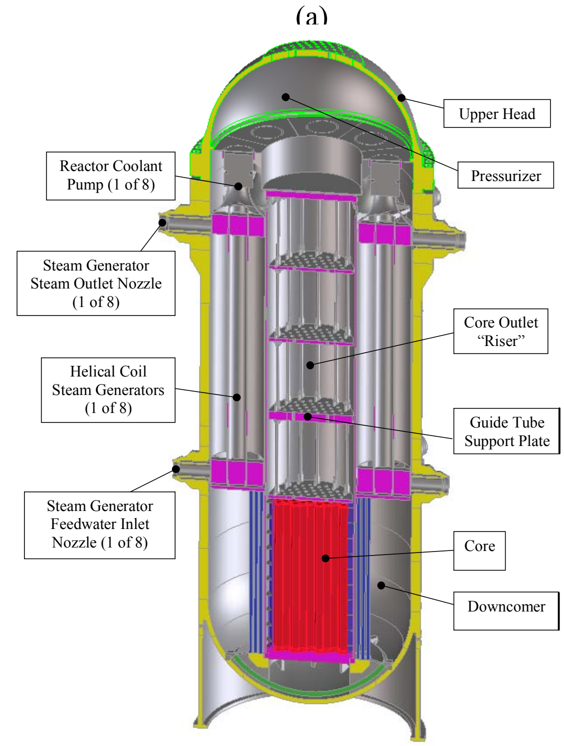

Figure 1: IRIS integral layout: (a) main components; (b) main flow path

Reactor core - The IRIS core and fuel characteristics are similar to those of a conventional Westinghouse PWR design. An IRIS fuel assembly consists of 264 fuel rods in a 17x17 square array. The central position is reserved for in-core instrumentation, and 24 positions have guide thimbles for the control rodlets. The IRIS fuel assembly design is similar to the Westinghouse 17x17 XL Robust Fuel Assembly design and AP1000 fuel assembly design. Low-power density is achieved by employing a core configuration consisting of 89 fuel assemblies with a 14-foot (4.267 m) active fuel height, and a nominal thermal power of 1,000 MWt. This results in reduction of the average linear power density by about 25 percent as compared to AP600. 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 as high as 4.95 w/o in U235, with axial blankets and lower enrichment at the core periphery. The fuel pellet diameter is similar to the Westinghouse 17x17 fuel assembly design and the fuel rod diameter is 0.374". 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 six-year lifetime (three-year cycle with half-core shuffling) to optimize the overall fuel economics while maximizing the discharge burnup. In addition, a four-year straight burn fuel cycle has been evaluated as a means to improve the overall plant availability.

- **Reactor coolant pumps** - An advanced primary reactor coolant pump (RCP) has been adopted for the IRIS reactor [3]. This “spool type” pump has been used in marine and 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 piping required. Further, the use of high temperature motor windings and bearing materials are being investigated in order to eliminate even the need for cooling water and the associated piping penetrations through the RV. This compares 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 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 Loss-Of-Flow Accidents (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 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 [4]. They are being designed by Ansaldo Energia and the Polytechnic Institute of Milan, with manufacturing expertise provided by Ansaldo-Camozzi. 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 6.2 m). Each IRIS SG module consists of a central inner column which supports the tubes and 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. Figure 2 illustrates the IRIS helical coil SG upper steam discharge header and the tube bundle arrangement.

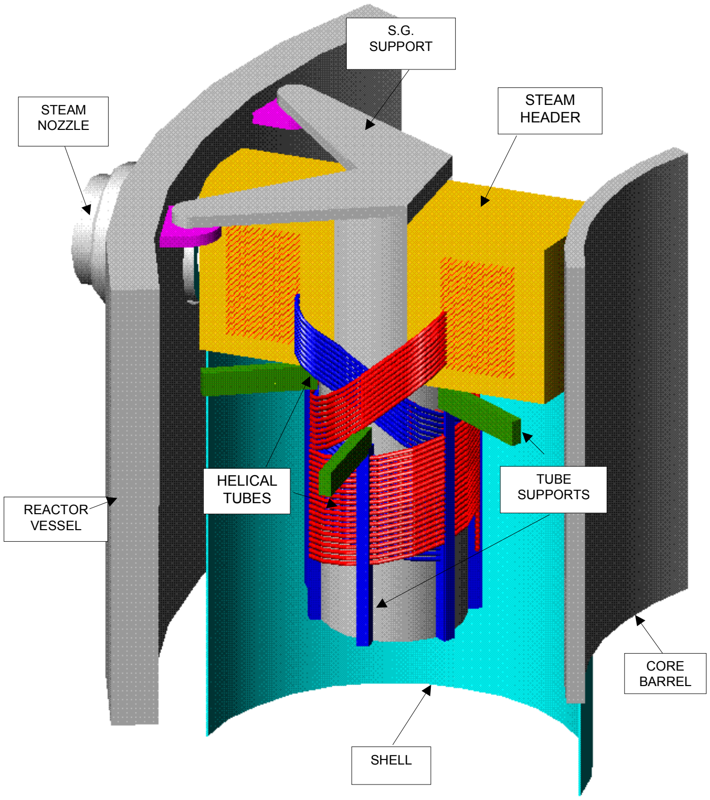

Figure 2: IRIS helical coil steam generator

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.

3. CONTAINMENT DESIGN

Because the IRIS integral RV configuration eliminates the loop piping and the externally mounted steam generators and pumps, the IRIS RV can be placed in a smaller diameter containment structure. 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 utilizes a spherical, steel containment vessel (CV) that is 25 meters (82') in diameter (see Figure 3). The CV is constructed of 1 ¾" steel plate and has a design pressure capability of 1.4 MPa (~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 and 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.

Figure 3 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 source of elevated gravity driven makeup water to the RV following postulated small/medium LOCA events (large LOCAs are impossible). Also shown is the RV flood-up cavity formed by the containment internal structure which contains the lower 9 meters (~30') of the reactor vessel. This flood-up cavity insures that the lower section of the RV, where the core is located, is surrounded by water following any LOCA event. 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.

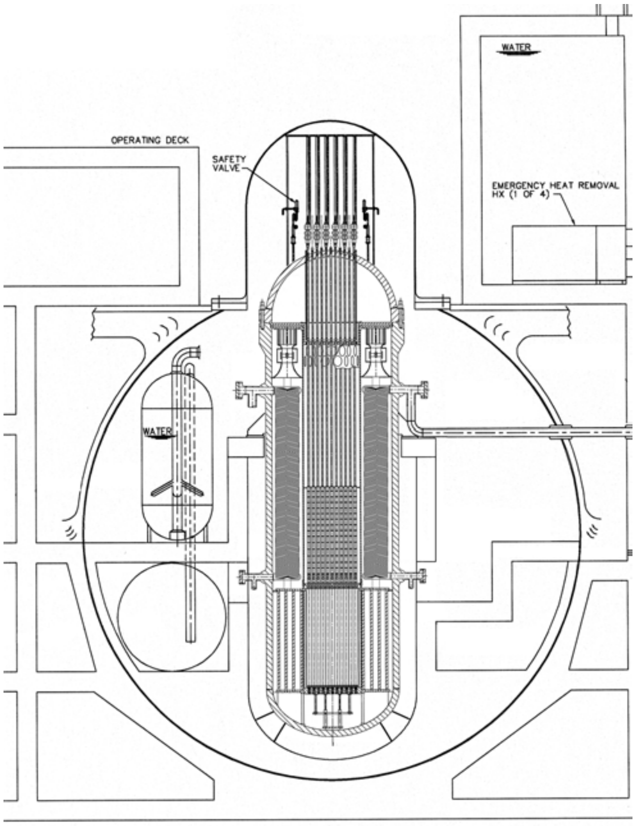

Figure 3 - IRIS Spherical Steel Containment Arrangement

4. THE IRIS SAFETY BY DESIGN APPROACH

IRIS has been primarily focused on featuring a design with innovative safety characteristics. The IRIS design provides for multiple levels of defense for accident mitigation (defense-in-depth), resulting in

Table 1 - IRIS response to PWR Class IV Events

	Condition IV Design Basis Events	IRIS Design Characteristic	Result 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	No DNB for failure of 1 out of 8 RCPs	Reduced consequences
6	Reactor Coolant Pump Seizure		
7	Spectrum of RCCA ejection accidents	Requires development of internal CRDM	Can be eliminated by design
8	Design Basis Fuel Handling Accidents	No IRIS specific design feature	No impact

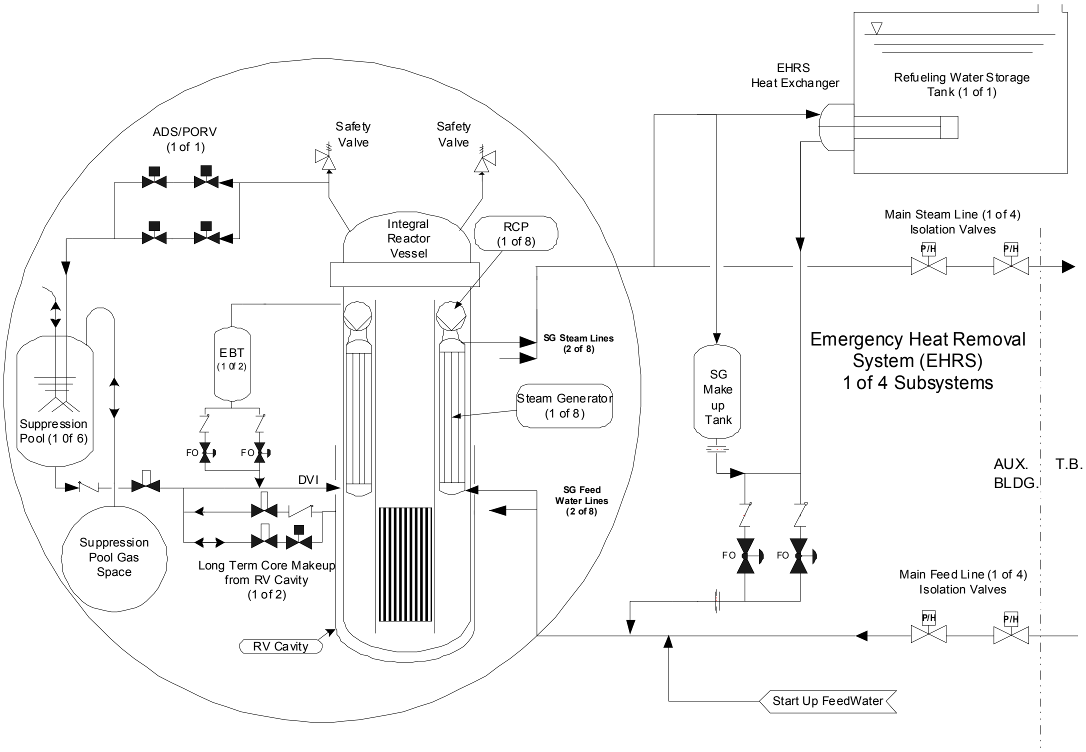

Figure 4 - IRIS Passive Safety System Schematic

extremely low core damage probabilities, but first of all it aims at eliminating accident initiators that could convincibly lead to core damage. This is implemented through the "safety by design" approach, briefly presented in the introduction.

The effect of the safety by design approach for IRIS is summarized in Table 1, which shows how the most severe design basis events considered for LWRs, the Condition IV events, are either eliminated or their consequences or frequency of occurrence lessened.

4.1 IRIS SAFETY FEATURES

The IRIS passive systems configuration is shown schematically in Figure 4, and includes:

- A passive emergency heat removal system (EHRS) 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 located in the Refueling Water Storage Tank (RWST) located outside the containment structure. The RWST water provides the heat sink for the EHRS heat exchangers to the environment. 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 by natural circulation, removing heat from the primary system through the steam generator's 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 coolant makeup function to the primary system. It performs these functions by condensing the steam produced by the core directly inside the reactor vessel. This minimizes (and actually reverses break flow for a portion of the LOCA response), while transferring the decay heat to the environment. Thus, the EHRS performs the functions of both core cooling and containment depressurization;

- Two (450 ft^3) full-system pressure emergency boration tanks (EBTs) to provide a diverse means of reactor shutdown by delivering borated water to the RV through the direct vessel injection (DVI) lines. By their operation these tanks also provide a limited gravity feed makeup water to the primary system;

- A small automatic depressurization system (ADS) 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 inch 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 (PSS) which consists of 6 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 <1.0 Mpa (130 psig), which is much less 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 loss of coolant accident (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.

Thus the IRIS passive systems provide the same safety functions as the active systems in current reactors and as the AP600/AP1000 passive systems. As the AP600/AP1000, the IRIS safety system design uses natural 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 LOCAs. The EBT is capable of providing some primary system injection at high pressure, but 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 the high capacity, safety grade, high pressure injection emergency core cooling system (ECCS), 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 containment cooling should cooling via the EHRS be defeated. In this event, 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 (IVR) of core debris by depressurizing and cooling the outside of the reactor vessel following severe accidents. With the reactor vessel intact and debris retained in the lower head, phenomena that may occur as a result of core debris being relocated to the reactor cavity are prevented. The reactor vessel has insulation that promotes in-vessel retention and surface treatment that promotes wetability of the external surface. The design features of the containment ensure flooding of the vessel cavity region during accidents and submerging the reactor vessel lower head in water. 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 pressure suppression system (PSS) water tanks water directly into the reactor cavity.

4.2 Assessment of the IRIS response to Transients and Postulated Design Basis Accidents

The application of the safety by design approach to IRIS has led to a design that presents several innovative features with regards to the response to transients and postulated accidents. The main effects of this approach on IRIS safety were listed in Table 1 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 [5], and for which IRIS will present significant differences from current active and passive PWRs, are discussed.

- **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 limiting the largest primary piping to a diameter of less than 4 inches. The innovative strategy developed to cope with a postulated small break LOCA by fully exploiting the IRIS design characteristics is illustrated in Figure 5.

  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:

  1. The initial large coolant inventory in the reactor vessel;
  2. The EHRS which removes heat directly from inside the RV thus depressurizing the RV by

condensing steam, rather than depressurizing by discharging mass;

3. The compact, small diameter, high design pressure containment that assists in limiting the blowdown from the RV by rapidly equalizing the vessel and containment pressures.

After the LOCA initiation, the reactor vessel (RV) depressurizes and loses mass to the containment vessel (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 Pressure Suppression System 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 <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. Thus the CV pressure is thus reduced following the RV depressurization as steam from the containment is condensed inside the pressure vessel (RV and CV pressure reduced to <2 bar$_g$ in <12 hours). As the containment pressure is reduced, 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.

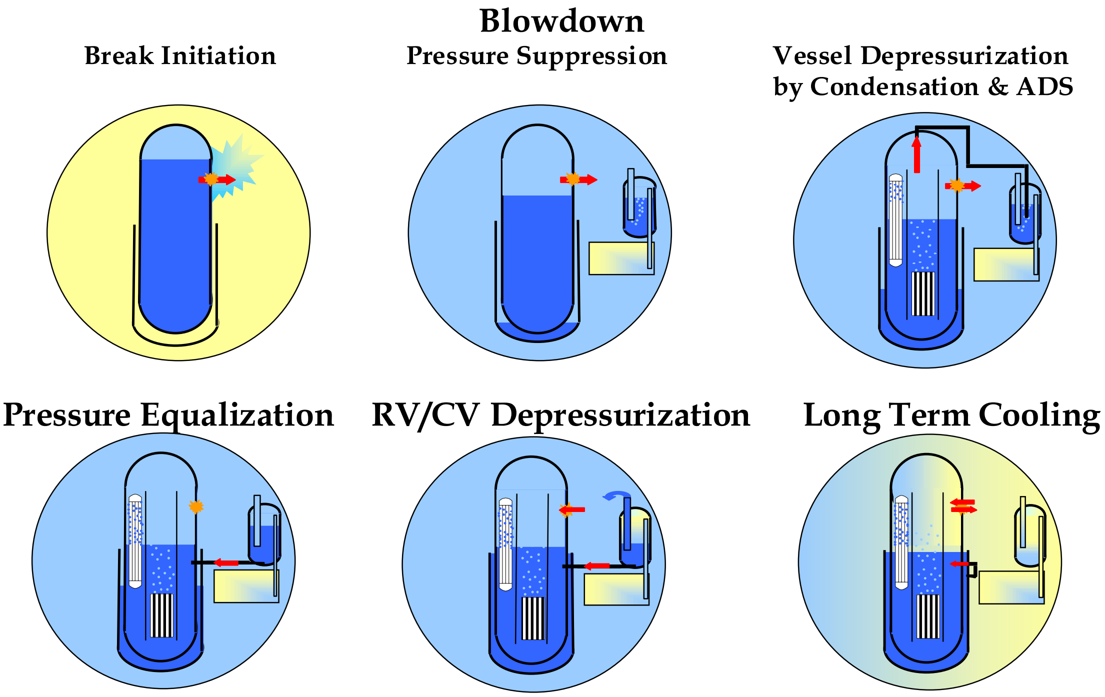

Figure 5: Overview of IRIS response to loss of coolant accident sequence

During this phase of the accident recovery, gravity makeup of borated water from both suppression pool and RV cavity are available as required. Since decay heat is directly removed from within the vessel, the long term break flow does not correspond to the core decay heat, but in fact it is 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 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 isolation of the faulted SG can occur immediately upon detection, the release of radioactivity (primary fluid) to the environment will be minimized.

  Compared to current and advanced PWRs, the IRIS response to a tube rupture is such that no steam generator overfill-overpressure-water relief/safety valve failure, resulting in an unisolable containment bypass scenario, is possible. Also, the number of tubes assumed to fail has a limited effect on the system response and does not impact the final plant state.

- **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 basis is more than 5 times larger than other advanced passive PWRs on a coolant mass-per-MWt), and by the large steam volume in the IRIS pressurizer (steam volume-to-power ratio is more than 5 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 coolant flow is comparable to that of the AP600/AP1000, where the coastdown 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, 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.

- **Spectrum of Postulated Rod Ejection Accidents** - The integral reactor vessel has a large volume above the core that can be utilized by locating the control rod drive mechanisms (CRDMs) inside the vessel. This in-vessel CRDM location would eliminate the rod ejection accident by design. Additionally, the operational failures associated with the vessel head penetrations would also be eliminated since the large CRDM drive line penetrations are eliminated. Some low power, integral reactor designs already feature internal CRDMs, including the Argentinean CAREM and Chinese NHR which employ hydraulically driven rods, and the Japanese MRX which uses an electromagnetic drive mechanism. However, the internal CRDMs have still not been proven for larger reactors and their state of development is perceived to be incompatible with the current IRIS deployment schedule. Thus, the reference IRIS design features a traditional control rod drive mechanism. The development of in vessel CRDMs is actively being pursued and the option is left open to modify the reference design if warranted by technical developments.

- **Increase in reactor coolant inventory** - This category of events is all but eliminated in IRIS since the 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.

5. 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 further minimized in IRIS. The net result is a design with significantly reduced complexity and improved operability, and extensive plant simplifications to enhance construction.

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