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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) power 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 primary 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.

IRIS has been primarily focused on featuring 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 should be such as to inherently reduce their consequences and/or decrease their probability of occurring.

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

This paper presents an overview of the IRIS safety concept, describing the simplified engineered safeguards features of the plant and how the safety systems interact with the safety by design concept in providing an improved response to various transients and design basis accidents. This will provide the necessary background to better focus the computational aspects and challenges addressed in companion IRIS papers presented at the conference.

Key Words: IRIS, Safety, Passive Systems, Safety-by-Design

1. INTRODUCTION

IRIS (International Reactor Innovative and Secure) is a pressurized light water cooled, medium power (1000 MWt) reactor. The IRIS development program was originally sponsored by the US Department of Energy (DOE) as part of the NERI (Nuclear Energy Research Initiative) program and has now been selected as an International Near Term Deployment (INTD) reactor, within the Generation IV International Forum activities. The IRIS concept also addresses the top-requirements defined by the US DOE for next generation reactors, i.e. enhanced reliability and safety, and improved economics. IRIS is an innovative design, but it does not require new technology development, since it relies on the proven light water reactor technology.

IRIS is being developed by an international consortium which is led by Westinghouse Electric Co. and includes a number of US and international companies, universities and national laboratories and organizations. The following organizations are members of the IRIS consortium: Westinghouse Electric Co.(USA), BFNL (UK), Bechtel (USA), ENSA (Spain), Ansaldo Energia (Italy), Ansaldo Camozzi (Italy), NUCLEP (Brazil), Curtiss-Wright (USA), TVA (USA), Eletronuclear (Brazil), CNEN (Brazil), National Institute for Nuclear Studies (Mexico), Oak Ridge National Laboratory (USA), University of Zagreb (Croatia), Polytechnic of Milan (Italy), University of Pisa (Italy), Tokyo Institute of Technology (Japan).

The IRIS design features an integral reactor vessel that contains all the reactor coolant system components, including the pressurizer, steam generators, and reactor coolant pumps. The IRIS integral layout has been previously reported [1,2], and is shown in Figure 1.

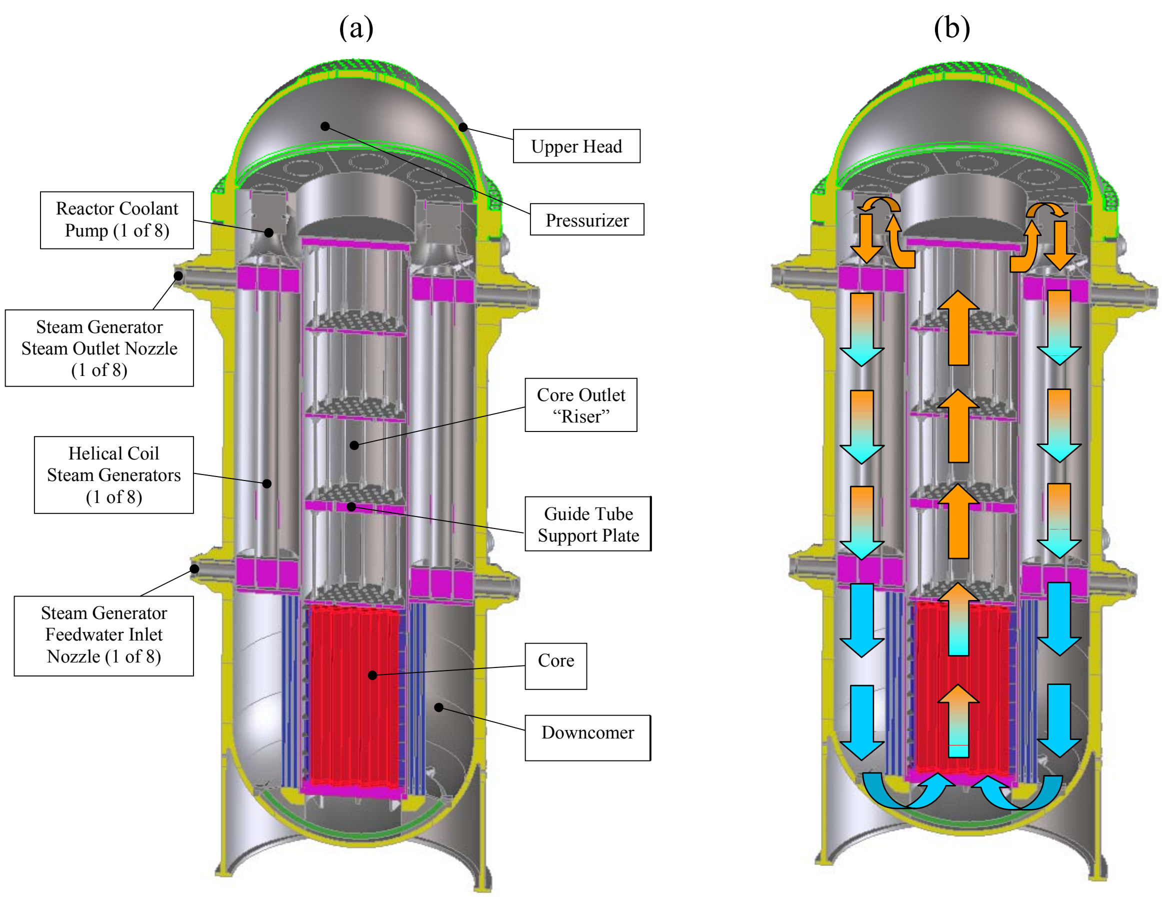

Figure 1. IRIS Integral Reactor Coolant System. Main components (a) and coolant flow path (b)

This integral reactor vessel configuration allows the use of a small, high design pressure, spherical steel containment resulting in a high level of safety and economic attractiveness. Figure 2 shows a pictorial view of the IRIS containment.

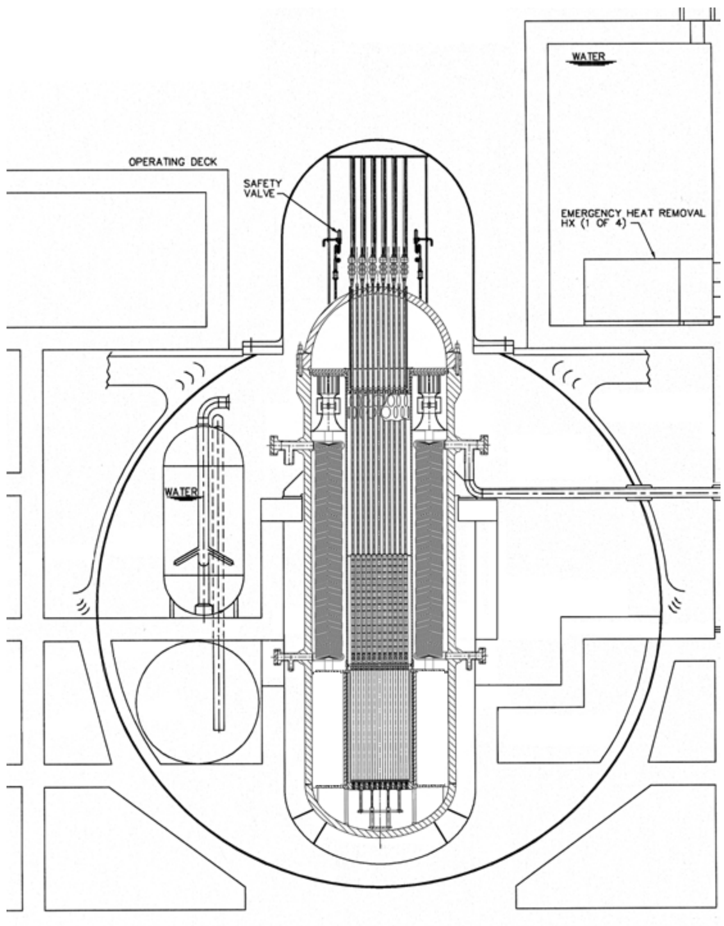

Figure 2. IRIS Containment overview

The IRIS design has been primarily focused on establishing a design with innovative safety characteristics, and to achieve this goal the IRIS reactor development has employed a "safety by design" approach [3, 4] that has eliminated or reduced the frequency and/or consequences of most serious accident sequences. IRIS also provides multiple levels of defense for accident mitigation (defense-in-depth), resulting in extremely low core damage probabilities while minimizing the occurrences of containment flooding, pressurization, and heat-up situations.

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. IRIS has strived to achieve that and some of the main results are summarized in Table I, which illustrates the implications of the safety by design approach, and in Table II, which describes the effect of safety by design on the most significant design basis events for LWRs. A substantial effort has been exerted and is still underway to perform safety analyses and quantitatively substantiate the behavior summarized in Tables 1 and 2.

2. ENGINEERED SAFETY FEATURES OF IRIS

The IRIS design builds on the proven technology provided by 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. IRIS follows the AP600/AP1000 approach and uses passive safety systems to improve the safety of the plant and to satisfy safety criteria of regulatory authorities. The IRIS passive safety systems require no operator actions to mitigate design basis accidents. Once actuated, these systems rely only on natural forces such as gravity and natural circulation for continued operation. These safety systems do not use any active components (such as pumps, fans or diesel generators) and are designed to function without safety-grade support systems (such as AC power, component cooling water, service water, or HVAC). A few simple valves align and automatically actuate the passive safety systems. To provide high reliability, these valves are designed to actuate to their safeguards positions upon loss of power or upon receipt of a safeguards actuation signal wherever possible. However, they are also supported by multiple, reliable power sources to avoid unnecessary actuations. The passive systems are designed to meet the single-failure criteria, and probabilistic risk assessment (PRA) techniques are used to verify their reliability.

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.

The IRIS passive systems design takes full advantage of the safety by design approach and the consequential elimination of some postulated design basis events (large LOCAs) and the inherent mitigation of several other (steam generator tube rupture, steam line break, locked rotor,…) with a safety strategy that is specifically tailored to respond to those remaining accident initiators, that are the more important contributors to core damage frequencies. This design approach allows the licensing safety criteria to be satisfied with a greatly simplified plant design.

The IRIS passive safety systems are even simpler than previous passive safety designs since they contain significantly fewer components, reducing the required tests, inspections, and maintenance, require no active support systems, and their readiness is easily monitored.

Table I. 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 Increased natural circulation Can accommodate internal CRDMs	- LOCAs - Decrease in heat removal - Various events - RCCA ejection, eliminate head penetrations
Heat Removal from inside the vessel	Depressurizes primary system by condensation and not by loss of mass Effective heat removal by SG/EHRS	- LOCAs - 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 Feed/Steam System Piping designed for full RCS pressure reduces piping failure probability	- Steam generator tube rupture - Steam line break - Feed line break
Once Through steam generator	Limited water inventory	- Steam line break - {Feed line break}
Integral Pressurizer	Large pressurizer volume/reactor power	- Overheating events, including feed line break. - ATWS

Table II. IRIS response to PWR Class IV Events

Design Basis Condition IV Events		Effect of IRIS Safety-by-Design
1	Large Break LOCA	- Eliminated by design (no large piping)
2	Steam Generator Tube Rupture	- Reduced consequences, simplified mitigation
3	Steam System Piping Failure	- Reduced probability, reduced (limited containment effect, limited cooldown) or eliminated (no potential for return to critical power) consequences
4	Feedwater System Pipe Break	- Reduced probability, reduced consequences (no high pressure relief from reactor coolant system)
5	Reactor Coolant Pump Shaft Break	- Reduced consequences
6	Reactor Coolant Pump Shaft Seizure	
7	Spectrum of RCCA ejection accidents	- [Eliminated by design, requires development of internal CRDM]
8	Design Basis Fuel Handling Accidents	- No impact

2.1 Passive Core and Containment Cooling

IRIS has a unique method for mitigating the consequences of postulated accidents. The IRIS passive systems configuration is presented in Figure 3, and includes:

- A passive emergency heat removal system (EHRS) made of four independent trains, each including a horizontal, U-tube heat exchanger located in the refueling water storage tank (RWST) located outside the containment structure that is connected to one of the four separate SG feed/steam lines. The RWST provides the heat sink for the EHRS heat exchangers. The EHRS is sized so that a single train can provide 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 generators heat transfer surface. The steam produced in the steam generators is condensed in the EHRS heat exchanger, transferring the heat to the RWST water, and returning the condensate back to the SG. Following a LOCA where the loss of mass uncovers the SG tubes, the EHRS depressurizes the RV (depressurization without loss of mass) by condensing steam on the SG tubes.

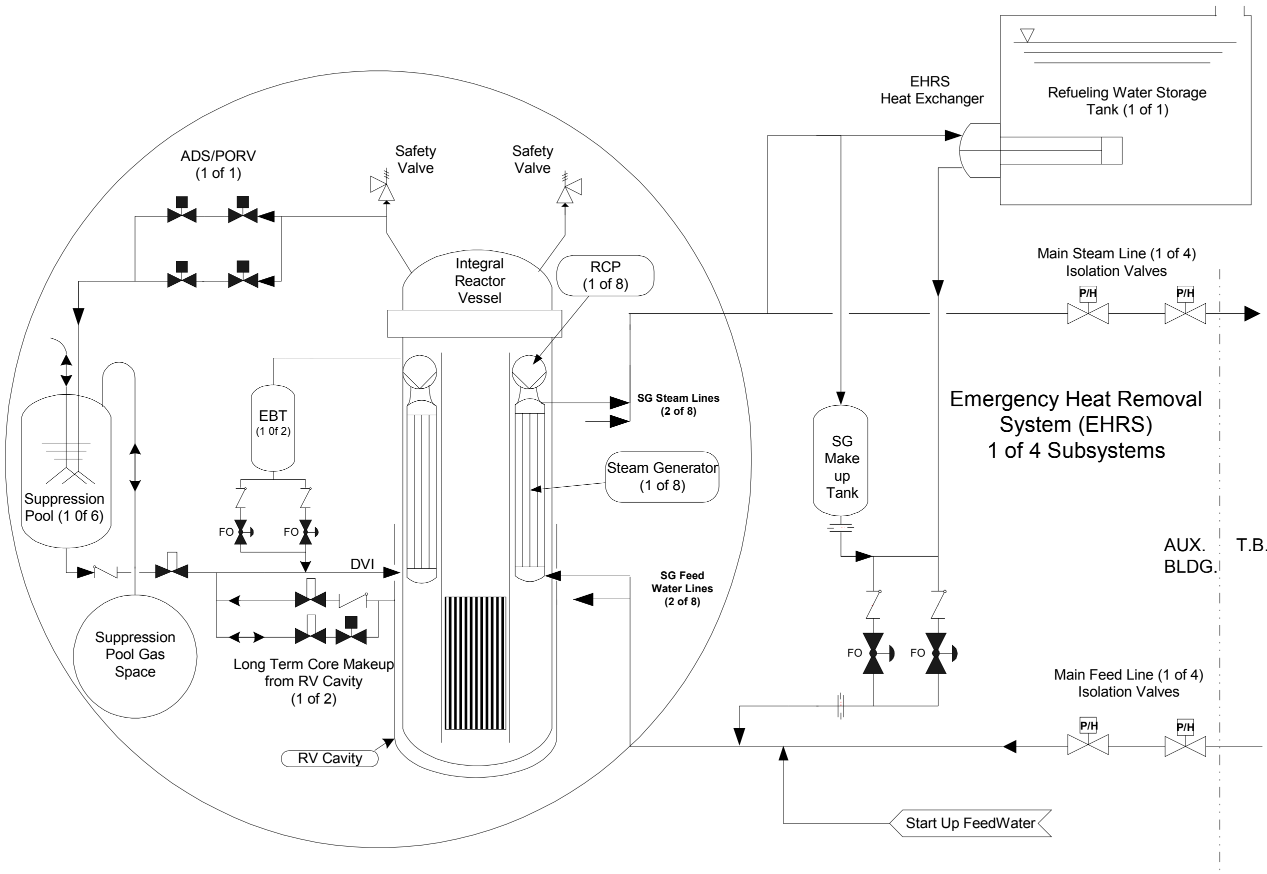

Figure 3. Engineered Safety Features of IRIS

Thus the EHRS provides a coolant makeup function for IRIS because it condenses the steam produced by the core directly inside the reactor vessel minimizing the break flow, while transferring the decay heat to the environment. Also, in limiting the break flow by depressurizing the RV, the EHRS also limits containment pressurization and causes the containment pressure to decrease. Thus, the EHRS performs the functions of both core cooling and containment depressurization;

- Two compact (450 ft^3) full-system pressure emergency boration tanks (EBTs) which can deliver borated water to the RV through the direct vessel injection (DVI) lines for transient events. 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 setpoint. This ADS has one stage and consist of two parallel 4 inch lines, 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;

- 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 to condense steam released in the containment following a loss of coolant or steam/feed line break accident. The suppression system limits the peak containment pressure following a blowdown event to 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. During a LOCA, the cavity floods above the core level, creating a gravity head of water sufficient to provide gravity driven coolant makeup to the reactor vessel through the DVI lines.

Thus, the IRIS passive systems provides the same safety functions as the active systems in current reactors and as the AP600/AP1000 passive systems. As in 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(s) and core cooling and heat removal to the environment through the EHRS 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 in IRIS the RV depressurization is attained with a limited 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). Of course, when the reactor vessel is depressurized to near containment pressure, gravity flow from the suppression system and from the reactor will maintain the 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 minimizing the amount of primary water leaving the pressure vessel.

3. 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 2 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 here.

3.1 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 the largest primary piping is limited to a diameter of less than 4 inches. The innovative strategy developed to fully exploit the IRIS design characteristics in coping with a postulated small break LOCA is illustrated in Figure 4.

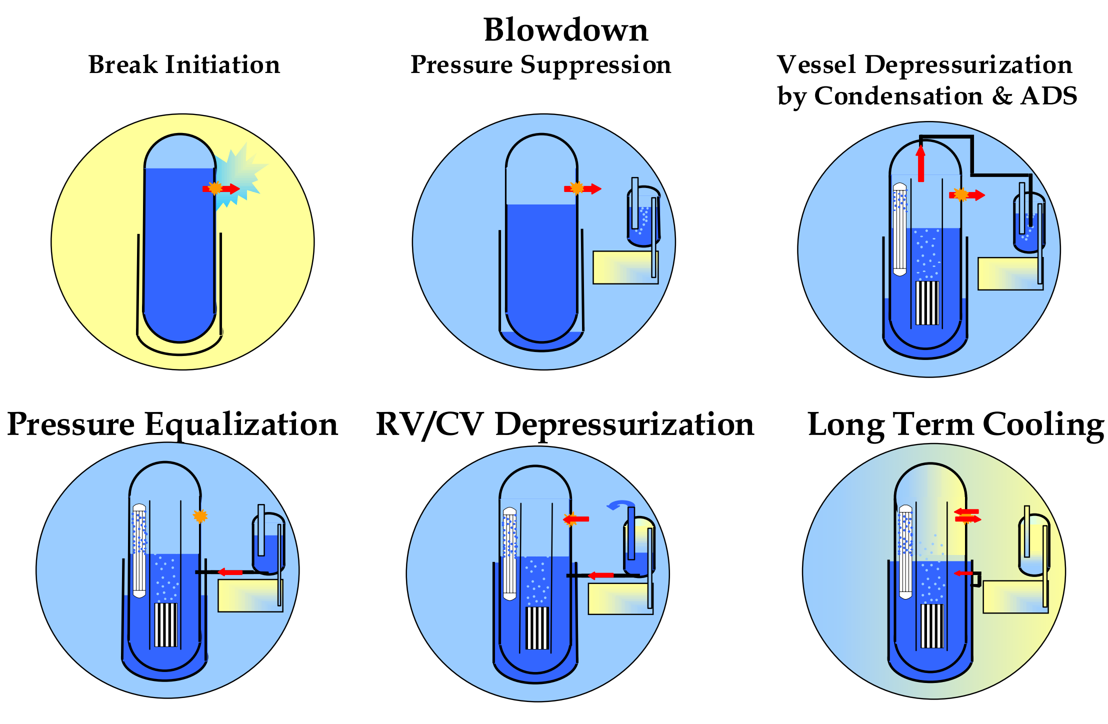

Figure 4. Overview of IRIS response to loss of coolant accident sequence

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 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.

At the end of the blowdown phase the RV and CV pressure become equal (Pressure Equalization) with a CV pressure peak <0.8 MPa_g. The break flow stops and the gravity makeup of borated water from 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 inside the vessel: 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 <0.2 MPa_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. 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.

3.2 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.

3.3 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 (Section 15.1 of the SRP). Increases in heat removal due to increased steam flow are eliminated since the steam flow from the once-through steam generators cannot exceed the 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.

3.4 Decrease in Heat Removal from the Secondary Side

Events in this category (section 15.2 of the SRP, and including loss of offsite power, loss of normal feedwater, turbine trip, 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 amply compensates for the limited heat sink provided by the steam generators with the large thermal inertia in the primary system (IRIS water inventory on a coolant-per-MWt basis is more than 5 times larger than other advanced passive PWRs), 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.

3.5 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.

3.6 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 large CRDM drive lines the vessel head penetrations would also be 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.

3.7 Increase in reactor coolant inventory

This category of events is all but 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.

3.8 Severe accidents (Beyond design basis accidents)

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. IRIS has reactor vessel insulation that promotes in-vessel retention and surface treatment that promotes wettability 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 into the reactor cavity.

The IRIS design also includes a second means of containment cooling should cooling via the EHRS be postulated to fail. In this event, direct cooling of the containment outer surface is provided and containment pressurization is limited to less than its design pressure. This system plus multiple means of providing gravity driven makeup to the core provides a diverse means of preventing core uncovery and damage and ensuring containment integrity and heat removal to the environment.

4. CONCLUSIONS

The IRIS program has been primarily focused on featuring a design with innovative safety characteristics. The safety by design approach has allowed to take full advantage of the integral RV layout, developing a safety concept that relies more on eliminating accidents and minimizing their consequence potential by design rather than designing a complex set of safety systems to cope with their consequences.

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. IRIS follows the AP600/AP1000 approach and uses passive safety systems to improve the safety of the plant and to satisfy safety criteria of regulatory authorities. The IRIS passive safety systems require no operator actions to mitigate design basis accidents.

While IRIS is solidly based on the extensive experience matured in the past 50 years on PWRs, the innovative design features (integral reactor coolant system, helical coil steam generators) and the new approach in the response to design basis accidents (for example the strong coupling between containment and reactor coolant system during LOCAs) will pose new computational challenges compared to other PWRs, as discussed in companion papers presented in this conference.

ACKNOWLEDGMENTS

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LIST OF ACRONYMS AND ABBREVIATIONS

ADS	Automatic Depressurization System
ATWS	Anticipated Transient without SCRAM
CRDM	Control Rod Drive Mechanism
CV	Containment Vessel
DOE	Department of Energy
DVI	Direct Vessel Injection
EBT	Emergency Boration Tank
EHRS	Emergency Heat Removal System
HVAC	Heat, Ventilation and Air Conditioning
INTD	International Near Term Deployment
IRIS	International Reactor Innovative and Secure
IVR	In Vessel Retention
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
PWR	Pressurized Water Reactor

NERI	Nuclear Energy Research Initiative
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
PSS	Pressure Suppression System
RCCA	Reactivity Control Cluster Assembly
RCS	Reactor Coolant System
RV	Reactor Vessel
RWST	Refueling Water Storage Tank
SRP	Standard Review Plan

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