PIONEERING ROLE OF IRIS IN THE RESURGENCE OF SMALL MODULAR REACTORS*

FISSION REACTORS

KEYWORDS: *IRIS, small modular reactors, Safety-by-Design*

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This paper presents an overview of the first 10 years of the IRIS project, summarizing its main technical achievements and evaluating its impact on the resurgence of small modular reactors (SMRs). SMRs have been recurrently studied in the past, from early days of nuclear power, but have never gained sufficient traction to reach commercialization. This situation persisted also in the 1990s; the focus was on large reactors based on the presumed common wisdom of this being the only way to make the nuclear power plants competitive. IRIS is one of several small reactor concepts that originated in the late 1990s. However, the specific role and significance of IRIS is that it systematically pursued resolving technology gaps, addressing safety, licensing, and deployment issues and performing credible economics analyses, which ultimately made it possible—together with other SMR projects—to cross the "skepticism threshold" and led the making of a convincing case—domestically and internationally—for the role and viability of smaller reactors. Technologically, IRIS is associated with a number of novel design features that it either introduced or pursued more systematically than its predecessors and ultimately brought them to a new technical level. Some of these are discussed in this paper, such as the IRIS Safety-by-Design, security by design, the innovative thermodynamic coupling of its vessel and containment, systematic probabilistic risk assessment–guided design, approach to seismic design, approach to reduce the emergency planning zone to the site boundary, active involvement of academia, and so on. Many individuals and organizations contributed to that work, too many to list individually, and this paper attempts to pay tribute at least to their collective work.

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*This paper summarizes the work of many who contributed their talent, time, and efforts to advance the IRIS project as well as the small modular reactor technology and nuclear power in a broader sense. The leading force in envisioning, guiding, and directing the IRIS project from its inception was Mario Carelli, chief scientist at Westinghouse Electric Company. Additionally, more than a hundred experts in their respective fields, from more than 20 IRIS team "core organizations" and about 10 additional organizations, participated in IRIS development, together with more than a hundred students who performed research related to IRIS. Their work is documented in more than 500 journal and conference papers, technical reports, and theses. Regretfully, it is not feasible to give the well-deserved credit by name to all individuals and organizations. Instead, we tried to point out only a selected subset of activities and contributions. A limited number of references provided at the end of the paper may serve as a starting point to IRIS literature search to interested readers.

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I. INTRODUCTION

Historically, after Generation I (small reactors) and early Gen-II (small and medium reactors), in Gen-III [passive light water reactors (LWRs)] and Gen-III+ (larger passive LWRs), the trend has been to favor larger-power nuclear power plants[1] (NPPs) based on the presumption that because of the economy of scale, only large plants can be competitive with other power generation sources. However, because of specific attractive features, interest in smaller plants remained high in some segments of the technical community and for some applications, and although it has resurfaced from time to time, it never got sufficient traction to lead to its commercialization. The term SMR has been used by the International Atomic Energy Agency (IAEA) to denote "small- and medium-power reactors," with power below 300 and 700 MW(electric), respectively, recognizing that the boundary between them is somewhat arbitrary. SMR has also been extensively used to denote "small modular reactors," emphasizing their natural suitability for modular deployment. Both definitions are quite compatible, and in this paper we use the term accommodating both interpretations.

We start by noting that the power level of most of the earlier Gen-II reactors would qualify them today as SMRs, even if they were not intended as SMRs at that time. These include early boiling water reactors (BWRs), two-loop pressurized water reactors (PWRs), VVER-440, and most CANDUs. They have operated successfully, not only technically but also economically, providing a real-life proof that a moderate power level reactor may be viable from all points of view. Many SMR concepts have been developed over time. Several IAEA reports (Refs. 2 through 5, published in 1995, 1997, 2005, and 2006, respectively) summarize then-current SMR design efforts. Reference 5 points out that not only are about one-third of operating reactors SMRs, but also the new construction includes about one-third SMRs. Fundamentally, SMRs allow simpler designs and are more conducive to passive safety, since their surface-to-power ratio, and therefore passive residual heat removal potential, is enhanced. However, most of the previous efforts failed to adequately address the economic aspects of SMRs.

The current wave of renewed SMR design efforts[6] started in the late 1990s. Reinforced with the concerns raised after the recent Fukushima accident, it seems to have gained more traction and a realistic chance of eventually leading to SMR construction. Among the reasons that have contributed to this, two may be—in the authors' opinion—specifically linked to IRIS:

1. Extensive IRIS safety analyses and preapplication licensing with the U.S. Nuclear Regulatory Commission (NRC) strengthened deployment credibility of SMRs.

2. Extensive work (summarized later in this paper) of the IRIS team on SMR economics provided credible arguments to support the potential for economic competitiveness of SMRs.

Moreover, the international technical and programmatic activities on SMRs coordinated by IAEA supported worldwide interest in SMRs. Additionally, several recent SMR-related initiatives in Europe and Asia, even in countries where large-size reactors are historically preferred, gave a strong support message. One indication of the traction finally achieved by SMRs is the mushrooming over the past two years of top-level programmatic and technical conferences on SMRs, including workshops on financing, commercialization, supply chain, and licensing, in addition to those on "classical" technical areas.

II. IRIS PROJECT

II.A. Start of the Project

In 1999, a team led by Westinghouse and including the Massachusetts Institute of Technology (MIT), the University of California at Berkeley, and the Polytechnic of Milan, Italy, was awarded a Nuclear Energy Research Initiative (NERI) grant from the U.S. Department of Energy to develop a Gen-IV advanced LWR. (For further details, see Ref. 7, written by Mario Carelli, chief scientist at Westinghouse Electric Company and the driving force behind the IRIS project from its inception.) Although started under the Gen-IV umbrella, the IRIS soon realized its somewhat different position and goals and redefined itself as a Gen-III++ design, i.e., a further evolution and improvement of Gen-III+. First, IRIS aimed to be deployment ready sooner than Gen-IV reactors, in the 2015–2020 time frame rather than after 2030. Second, although highly innovative, IRIS was firmly based on proven LWR technology. Third, contrary to the assumed Gen-IV goal of a capital cost below \$1000/kW(electric), to which many other ongoing efforts subscribed at that time, IRIS promoted a more realistic cost estimate of ~\$2000/kW(electric) in 2002 U.S. dollars for *N*'th of a kind—for which it was more frequently penalized than recognized in comparative evaluations.

II.B. The IRIS Team

The proposed IRIS concept proved to be quite attractive, and many organizations from around the world joined under their own funding. By late 2001, the IRIS team included 14 organizations from six countries. The four original partners were joined in successive order by Japan Atomic Power Company (JAPC), Japan; Mitsubishi Heavy Industries (MHI), Japan; British Nuclear Fuel (BNFL), United Kingdom; Tokyo Institute of Technology, Japan; Bechtel, United States; University of Pisa, Italy; Ansaldo, Italy; NUCLEP, Brazil; National Institute for Nuclear Studies, Mexico; and University of Zagreb, Croatia.

TABLE I

IRIS Team Core Members

Industry		
Westinghouse[a]	United States	Overall coordination, core design, safety analyses, licensing, commercialization
BNFL[a]	United Kingdom	Fuel and fuel cycle
Ansaldo Energia/Ansaldo	Italy	SG* design
Ansaldo Nucleare/Camozzi/Mangiarotti	Italy	SG fabrication
ENSA	Spain	Pressure vessel and internals
NUCLEP	Brazil	Containment, pressurizer
Rolls Royce[b]	United Kingdom	CRDMs
Laboratories		
Oak Ridge National Laboratory	United States	Instrumentation and control, PRA, desalination, shielding, pressurizer
CNEN	Brazil	Pressurizer design, transient analyses, desalination
ININ	Mexico	PRA, neutronics support
LEI	Lithuania	PRA, district heating cogeneration
ENEA	Italy	Testing, integral facility, seismic, shielding
Universities		
Polytechnic of Milan	Italy	Safety analyses, shielding, thermal hydraulics, SG design, internal CRDMs, economics, biofuel cogeneration
MIT	United States	Advanced cores, maintenance
Tokyo Institute of Technology	Japan	Advanced cores, PRA, seismic
University of Zagreb	Croatia	Neutronics, safety analyses
University of Pisa	Italy	Containment analyses, severe accident analyses, neutronics, CFD, seismic
Polytechnic of Turin	Italy	Source term, thermal hydraulics
Georgia Institute of Technology[b]	United States	Advanced core designs, shielding, dose reduction
Power Producers and Architect-Engineer Companies		
Bechtel[a,b]	United States	BOP, Architect-engineer
Tennessee Valley Authority[a,b]	United States	Maintenance, utility perspective
Eletronuclear	Brazil	Developing country utility perspective
Empresarios Agrupados[b]	Spain	Architect-engineer
Esti Energia[b]	Estonia	Smaller country/grid utility perspective

*Acronyms in this table are defined as follows: SG = steam generator; CRDMs = control rod drive mechanisms; PRA = probabilistic risk assessment; CDF = core damage frequency; BPO = balance of plant.

[a] No longer members at the end of 2010.

[b] Members participating for a shorter time (typically several years).

The French Commissariat à l'Energie Atomique (CEA) also was briefly (until October 2000) a participant. By summer 2002, the team had expanded to include about 20 members from 10 countries, and remained of approximately that size.[8]

Table I lists the IRIS team members that remained active for a significant period. The table also indicates focus areas of involvement of specific organizations, whether an organization was an IRIS team member at the end of 2010, and whether its involvement was for a shorter time than the project's duration (but still over several years). Not included in this table are organizations that participated only informally or for a rather limited period: JAPC, MHI, CEA, University of Rome, Italy, and OKBM, Russia. Table II lists U.S. universities and laboratories associated with the IRIS project through NERI funding of specific joint projects, typically over 3 to 4 years during the period 1999–2005.

Additional organizations or country representatives expressed interest in the project and IRIS technology and were invited to participate as observers at the team meetings, bringing the total number of countries that were involved in one way or another to more than 25.

II.C. Programmatic Progress

Conceptual and trade-off studies were completed within the first year and a half.[7,9] Integral primary layout and emphasis on enhanced safety (with its Safety-by-Design approach) were nonnegotiable, but a number of

TABLE II

U.S. Universities and Laboratories Associated with IRIS Through NERI Funding of Joint Projects

University	Joint Project Area
University of California at Berkeley (initial team member)	Neutronics; advanced cores
University of Tennessee–Knoxville	Modularization; instrumentation and control
Ohio State University	In-core power monitor, advanced diagnostics
Iowa State University and Ames Laboratory	Online monitoring
University of Michigan and Sandia National Laboratories	Monitoring and control

choices needed to be made and justified. The electric power level initially considered was 100 MW(electric), but after preliminary economic assessments and consultations with utilities, it was increased to ~350 MW(electric) [with the corresponding thermal power of 1000 MW(thermal)] and selected as the reference point design. At the same time a lower-power 50 MW(electric) design was identified for specialized applications.[10,11] The next decision was related to natural versus forced circulation. Based on careful technical studies, forced circulation was selected for the thermal power level of 1000 MW(thermal); natural circulation may be considered below ~150 MW(thermal). Another study evaluated soluble boron versus boron-free reactivity control. There is no unique optimum answer, but economics indicate that soluble boron is preferable for thermal power >300 MW(thermal); thus, it was selected for IRIS.

Extensive studies were devoted to fuel selection, from fuel type to geometry to fissile content. Driven by the programmatic requirement to be licensable and then deployable before 2020, a standard, already licensed PWR UO_2 fuel design with fuel enrichment up to 5% was selected for the near/middle term. Based on the utilities' feedback, less frequent shutdown for maintenance and refueling would be desired, yet practical maintenance issues make very long continued operation (e.g., 10 years and longer) not credible. Technical analyses indicated that 4 years is a realistic goal with tangible economic benefit. Pushing it further would have only a marginal impact on economics but would lead to significant technology issues.

Thus, the IRIS design moved from the concept, through trade-off studies and preliminary design toward a "mature design" phase (Table III), marked by licensing considerations and preapplication interaction with NRC, plans for testing and manufacturing of components, and shifting of focus to economics and deployment issues.[12–15] The initial, "technical" phases were completed more or less according to the original schedule. Schedule targets for testing and deployment readiness did shift by a few years, for programmatic more than technical reasons.

Table III and this paper present the status of the IRIS project as of 2010. Recently, Westinghouse has decided not to pursue IRIS any further, but the rest of the IRIS team believes in its potential, and several of the team members are planning to continue pursuing it, even carrying out large experimental campaigns. Thus, although the future of the project is not clear due to a variety of commercial and programmatic considerations of the team members as well as national policies toward nuclear power, IRIS has undoubtedly led the resurgence of SMRs.

TABLE III

Development Schedule Targets*

Completed	
Program started	1999
Assessed key technical and economic feasibility	2000
Performed conceptual design, preliminary cost estimate	2001
Initiated NRC preapplication licensing for design certification	2002
Completed NSSS preliminary design	2005
Initiated testing for NRC design certification	2006
Targets (pending programmatic decision and funding)	
Complete testing for NRC design certification	2012
Submit application for NRC design certification	2013
Obtain final design approval from NRC	2016–2018
Ready for deployment	2020

*As of 2010.

II.D. Innovations, "Firsts," and Technical Contributions Developed by the IRIS Project

Although firmly based on the proven LWR technology, the IRIS project has developed many engineering and project innovations. In some cases, IRIS has developed and introduced novel solutions; in others, it has advanced a known feature to a new level. Of course, IRIS has not emerged out of a vacuum but has also incorporated many innovations previously developed by other designs and researchers. Some of the more prominent IRIS innovations and contributions are enumerated here, with further details provided in Sec. III:

1. development by an integrated international team, including industry and academia as equal partners, with a true win-win collaboration
2. using the synergy of safety-simplicity-reliability-economics as the leading design principle
3. Safety-by-Design, implemented systematically from the first day to a level not approached in other designs, eliminating or reducing severity of seven out of eight class IV accidents
4. simple operation, minimizing the need for operator action in incident situations
5. security by design
6. probabilistic risk assessment (PRA)–guided design from the very beginning, enabling significant reduction of core damage frequency (CDF) and large early release frequency (LERF) probabilities
7. systematic use of phenomena identification and ranking tables (PIRT) and scaling as part of the design; use of the new NRC fractional scaling
8. optimized operation and maintenance (O&M), based on considering close to 4000 required maintenance actions, allowing credible extended operation without shutdown up to 4 years
9. systematic dose reduction to personnel in operation, maintenance, and decontamination and decommissioning (D&D)
10. potential to eliminate off-site emergency planning zone requirements, due to its exceptional safety
11. elimination of large loss-of-coolant accidents (LOCAs); patented thermodynamic coupling of pressure vessel and containment vessel to inherently mitigate consequences of small LOCAs
12. a single standard seismic design supplemented by site-specific seismic isolators
13. suitability for cogeneration applications (water desalination, district heating, process heat, biofuels)
14. extensive economic studies, providing credible indication of economic competitiveness.

Moreover, some specific design features and innovations include the following:

1. Internal helical steam generators, with tubes in compression, eliminate stress corrosion cracking (SCC) and improve safety characteristics.

2. Fully immersed primary coolant pumps eliminate possibility of leaks.

3. Internal control rod drive mechanisms (CRDMs) eliminate head penetrations.

4. Integrated pressurizer with large volume-to-power ratio mitigates pressure transients and eliminates the need for spray.

5. Thick downcomer (1.7 m) reduces radiation damage and activation of reactor vessel by several orders of magnitude.

6. Refueling period is extended to up to 4 years with standard fuel/enrichment.

7. Load follow capability without soluble boron concentration variation.

8. Potential to use UO_2, mixed oxide (MOX), and UN fuel forms (after adequate fuel qualification), together with several advanced burnable absorber options.

III. IRIS Design

III.A. The Leading Design Principle

The leading principle imposed on the IRIS design (Fig. 1) is that safety is based on eliminating as many systems (that could be prone to failure) as possible, using a few simple passive systems rather than a multitude of complex active systems. This simplicity also results in an economical design; i.e., the increased safety is achieved in IRIS at a reduced rather than increased cost.

III.B. Integral Nuclear Steam Supply System

IRIS is a pressurized light water–cooled integral design where all the primary system components are located within the reactor vessel.[16,17] This is not an IRIS innovation, because many other preceding designs had internal components, starting with the Swedish PIUS in the mid to late 1980s, followed by the Anglo-American SIR, the Argentinean CAREM, the Italian ISIS, the South Korean SMART, to name a few. The innovative characteristics of IRIS are that every primary system component is integrated in the vessel (including fully internal primary pumps); the containment is

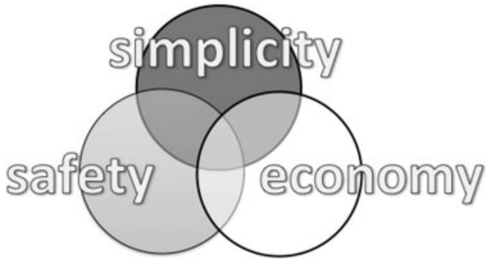

Fig. 1. IRIS design philosophy.

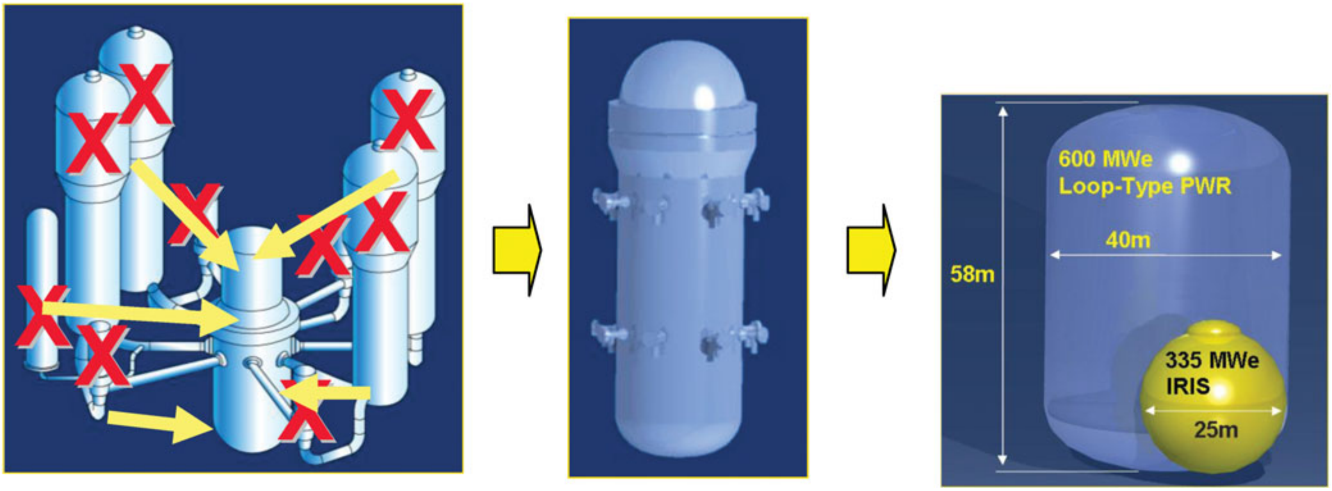

Fig. 2. IRIS compact integral layout. Components located outside the vessel in a loop configuration (left) are relocated into the integral vessel (middle), resulting in a more compact containment (right).

designed so as to be thermodynamically coupled with the integrated primary system during accident conditions; and the overall design is focused first and foremost on simplicity.[13] Although it leads to a larger reactor vessel, the integral layout results in a smaller containment (as illustrated in Fig. 2) and overall a more compact site, with positive impact on safety, security, and economics. IRIS major design parameters are summarized in Table IV.

III.B.1. Integral Reactor Vessel

The IRIS reactor vessel (RV), shown in Fig. 3, houses not only the nuclear fuel and control rods but also all the major reactor coolant system (RCS) components: eight small, axial flow, reactor coolant pumps (RCPs); eight modular, helical coil, once-through steam generators (SGs); a pressurizer located in the RV upper head; the CRDMs; and a steel reflector that surrounds the core and improves neutron economy while providing additional internal shielding. Water flows upward 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 RCPs is located. The flow from each pump is directed downward through its associated SG. The primary flow path continues down through the annular downcomer region to the lower plenum and then back to the core, completing the circuit. 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 large LOCAs as design-basis events.

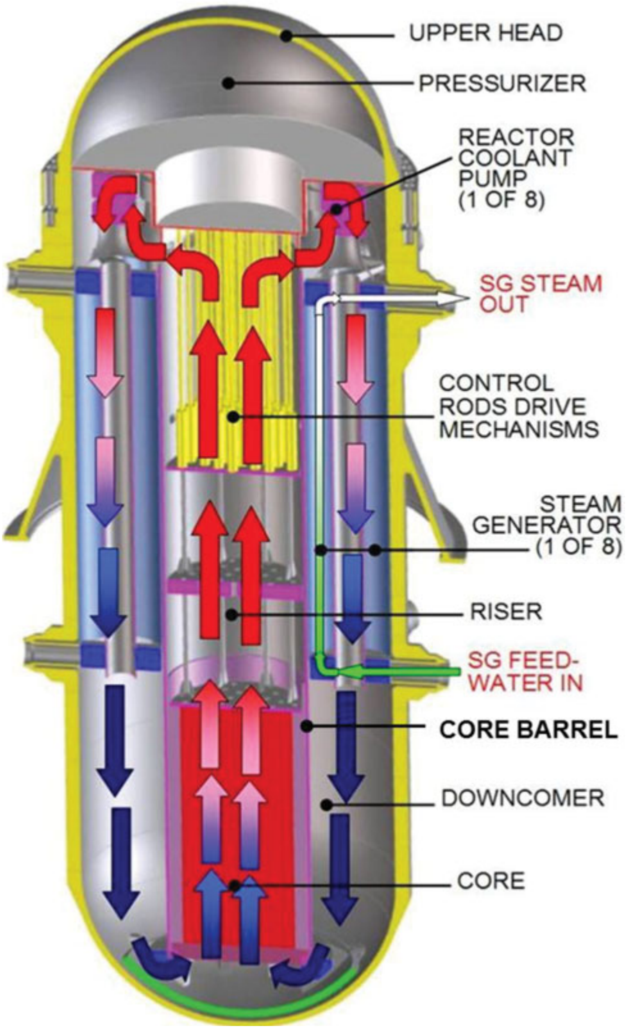

Fig. 3. IRIS integral reactor configuration.

TABLE IV

IRIS Major Design Parameters*

- General plant data
  - Power plant output: 335 MW(electric) (net)
  - Core thermal output: 1000 MW(thermal)
- Nuclear steam supply system
  - Type: integral RCS
  - Primary circuit volume, including pressurizer: 455 m^3
  - Steam flow rate at nominal conditions: 503 kg/s
  - Feedwater flow rate at nominal conditions: 503 kg/s
  - Steam temperature/pressure: 317°C/5.8 MPa
  - Feedwater temperature/pressure: 224°C/6.4 MPa
- Reactor coolant system
  - Primary coolant flow rate: 4700 kg/s
  - Reactor operating pressure: 15.5 MPa
  - Coolant inlet temperature, at core inlet: 292°C
  - Coolant outlet temperature, at riser outlet: 328.4°C
  - Mean temperature rise across core: 38°C
- Reactor core
  - Active core height: 4.267 m
  - Equivalent core diameter: 2.413 m
  - Heat transfer surface in the core: 2992 m^2
  - Fuel inventory: 48.5 tonne U
  - Average linear heat rate: 9.97 kW/m
  - Average fuel power density: 20.89 kW/kg U
  - Average core power density (volumetric): 51.26 kW/ℓ
  - Thermal heat flux peak factor: $Fq = 2.60$
  - Enthalpy rise hot channel factor: $F_{\Delta H} = 1.65$
  - Fuel material: sintered UO_2
  - Fuel assembly total length: 5207 mm
  - Rod arrays: square, 17 × 17
  - Number of fuel assemblies: 89
  - Number of fuel rods/assembly: 264
  - Number of control rod guide tubes: 25
  - Number of structural spacer grids: 10
  - Number of intermediate flow mixing grids: 4
  - Enrichment range of first core: 2.6 to 4.95 wt% ^{235}U
  - Reload fuel enrichment at equilibrium: $\leq$5.0 wt% ^{235}U
  - Operating fuel cycle length: 30 to 48 months
  - Average discharge burnup (nominal): 40 to 65 GWd/tonne
  - Cladding tube material: ZIRLO
  - Cladding tube wall thickness: 0.57 mm
  - Outer diameter of fuel rods: 9.5 mm
  - Active length of fuel rods: 4267 mm
  - Burnable absorber material: IFBA and Er; other options
  - Number of control rods: 37
  - Absorber rods per control assembly: 24
  - Absorber material 1: Ag-In-Cd (black)
  - Absorber material 2: Ag-In-Cd/Type 304 stainless steel (gray)
  - Drive mechanism: magnetic jack
  - Positioning rate: 45 steps/min
  - Soluble neutron absorber: boric acid
- Reactor vessel
  - Cylindrical shell inner diameter: 6210 mm
  - Wall thickness of cylindrical shell: 285 mm
  - Total height: 21 300 mm
  - Base material: cylindrical shell carbon steel
  - Head: carbon steel
  - Liner: stainless steel
  - Design pressure/temperature: 17.2 MPa/360°C
  - Transport weight (lower part): 1045 tonne
  - Pressure vessel head: 167 tonne
- Steam generators
  - Type: once through, vertical, helical coil
  - Number of SGs: 8
  - Thermal capacity: 125 MW(thermal) each
  - Heat transfer surface: 1150 m^2
  - Number of heat exchanger tubes: 656
  - Tube dimensions: 17.5/13.2 mm
  - Shroud outer diameter: 1640 mm
  - Total height: 8500 mm
  - Transport weight: 35 tonne
  - Shroud and tube sheet material: stainless steel
  - Tube material: INCONEL® alloy 690-TT[a]
- Reactor coolant pump
  - Type: spool (axial)
  - Number of pumps: 8
  - Design pressure/temperature: 17.2 MPa/343.3°C
  - Design flow rate (at operating conditions): 587.5 kg/s
  - Pump head: 19.8 m
  - Power demand at coupling, cold/hot: 225 kW
  - Pump casing material: N.A.
  - Pump speed: 1800 rpm
- Pressurizer
  - Type: integrated with RV
  - Total volume: 71.41 m^3
  - Steam volume: full power/zero power: 48.96 m^3
  - Design pressure/temperature: 17.2 MPa/360°C
  - Heating power of the heater rods: 2400 kW
  - Number of heater rods: 90
- Primary containment
  - Type: pressure suppression
  - Material: steel
  - Overall form: spherical
  - Dimensions (diameter/height): 25/32 m
  - Free volume: 4540 m^3
  - Design pressure/temperature
    - Design basis events: 1300 kPa/200°C
    - Severe accident situations: 1300 kPa/200°C
  - Design leakage rate: $<$0.1 vol%/day
  - Missile protection and release filtration: provided

*Reference 17.

[a] INCONEL is a registered trademark of the Special Metals Corporation group of companies.

III.B.2. Reactor Core

The IRIS fuel assemblies are similar to those of 17 × 17 loop-type PWRs. 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 MW(thermal). The resulting average linear power density is about half the AP1000 value. The improved thermal margin provides increased operational flexibility while enabling longer fuel cycles and increased overall plant capacity factors. The reference IRIS core will use UO_2 fuel, enriched to

4.95% in ^{235}U. (Additional fuel cycle options are discussed in Sec. V.)

Reactivity control is accomplished through advance 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. The core is designed for approximately a 3-yr cycle with half-core reload to optimize the overall fuel economics while maximizing the discharge burnup.

III.B.3. Steam Generators

The IRIS SGs are a once-through, helical coil tube bundle design with the primary fluid outside the tubes. Eight SG modules are located in the annular space between the core barrel and the RV. Each module consists of a central inner column that supports the tubes, the lower feedwater header, and the upper steam header. Each SG has several hundred tubes, and the tubes and headers are designed for the full external RCS pressure. The helical coil tube bundle design is capable of accommodating thermal expansion without excessive mechanical stress and has high resistance to flow-induced vibrations. This type of SG was successfully tested in Italy by Ansaldo in an extensive test campaign conducted on a 20 MW(thermal) full-diameter, partial height test section. The performance characteristics (thermal, vibration, pressure losses) were investigated, as was the operating domain for stable operation.

III.B.4. Reactor Coolant Pumps

The axial flow IRIS RCPs are of a spool type, which has been devised for marine applications and chemical plant processes requiring high flow rates and low developed head. The motor and pump consist of two concentric cylinders; the outer ring is the stator and the inner ring is the rotor that carries high specific speed pump impellers. The pump is located entirely within the RV, uses high-temperature motor windings and bearing materials, and requires only small penetrations for the electrical power cables. The spool pump geometric configuration maximizes the rotating inertia and provides a high runout flow capability; both attributes help mitigate the consequences of loss-of-flow accidents. Because of their low developed head, spool pumps have never before been considered for nuclear applications. However, the IRIS integral RV configuration and low primary coolant pressure drop can take full advantage of their unique characteristics.

III.B.5. Pressurizer

The IRIS pressurizer is integrated into the upper head of the RV in the region defined by an insulated inverted top-hat structure that divides the circulating reactor coolant flow path from the saturated pressurizer water. Using the upper head region of the RV provides a very large water and steam volume, and the pressurizer volume-to-power ratio is about five times larger in IRIS than in plants of loop design with a separate pressurizer vessel. This large ratio allows IRIS to eliminate pressurizer sprays, which are used in current PWRs to prevent the pressurizer safety valves from lifting for any design-basis heatup transients.

III.B.6. Control Rod Drive Mechanisms

The integral configuration is ideal for locating the CRDMs within the vessel, in the region above the core and surrounded by the SGs, yielding significant advantages. Safety-wise, the rod ejection accident (a Class IV accident) is eliminated because there is no potential for a large differential pressure (2250 psi or 15.25 MPa) to drive out the CRDM extensions shafts. Operations-wise, the absence of CRDM nozzle penetrations in the upper head eliminates the operational problems related to SCC of nozzle welds and seals that have intermittently plagued the industry and incurred heavy economic penalties. IRIS has no penetrations in the upper head (except for the automatic depressurization system safety valves piping), so the design and manufacturing of the upper head is also simpler and cheaper.

III.C. Containment

Complementing the integral primary system design is the patented containment design. The IRIS containment vessel (CV) (Fig. 4) is a spherical steel structure, 25 m in diameter, designed to sustain high pressure in transients, with a steam suppression system that combines the best characteristics of PWR and BWR containments. The greatly reduced containment footprint is due to the integral RV configuration, which eliminates the RCS loop piping and external SGs, pumps and pressurizer along with their individual vessels. This size reduction, combined with the spherical geometry, results in a capability of IRIS CV to sustain three to four times higher pressure than a typical PWR cylindrical containment, assuming the same metal thickness and stress level in the shell. IRIS CV also includes the pressure suppression pool that limits the containment peak pressure to well below the CV design pressure. Also shown is the RV flood-up cavity, which 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 indefinitely long period of time. It also provides sufficient heat removal from the external RV surface to prevent any vessel failure following beyond design-basis scenarios.

The most innovative feature of the IRIS containment and an excellent example of embodiment of the simplicity-driven design philosophy is how the CV and RV become coupled during a LOCA and intrinsically mitigate the transient. Although large LOCAs are eliminated in an

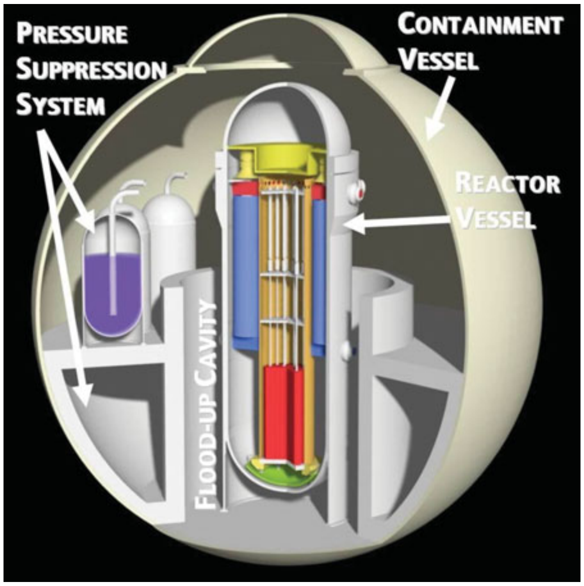

Fig. 4. IRIS spherical steel containment and its layout.

integral configuration, small/medium LOCAs can still occur since not all vessel penetrations can be eliminated (e.g., there is a 102-mm chemical volume control line below the pressurizer region). During a postulated small/medium LOCA, the large heat transfer surface of the SGs located inside the vessel is used to remove the heat produced in the core and condense the produced steam, thus depressurizing the vessel.

The sequence of events is illustrated in Fig. 5. During the initial phase of the transient, the pressure in the IRIS CV would be allowed to rise to levels substantially higher than possible for a loop PWR. The simultaneous pressure decrease inside the RV and pressure increase inside the containment would quickly decrease the pressure differential across the break, which is the driving force for the coolant loss. After 30 to 60 min, depending on the LOCA conditions, the break pressure differential would become zero and the coolant egress would stop automatically. The vessel and the containment would then be thermodynamically coupled through the break and act as a single system. The pressure suppression system keeps the containment pressure from rising further while outside cooling of the containment provides the controlling ultimate heat sink. Because of the very large coolant inventory, the core remains well covered throughout the entire transient, without any need for water makeup, by either active or passive means. This has been shown through analyses for a variety of postulated break sizes and locations.[18,19] Consequently, IRIS does not need and does not have a dedicated safety injection system for emergency core cooling; this system is eliminated together with all its auxiliary systems.

III.D. Integrated Building

The containment is located inside a cylindrical building (Fig. 6) approximately 55 m in diameter. Most of the vessel and containment is underground, and the height above ground of the concrete building housing the nuclear steam supply system (NSSS) is only 33 m. The main objective of the cylindrical configuration and low-profile building is to intrinsically boost security by significantly reducing the possibility, probability, and consequences

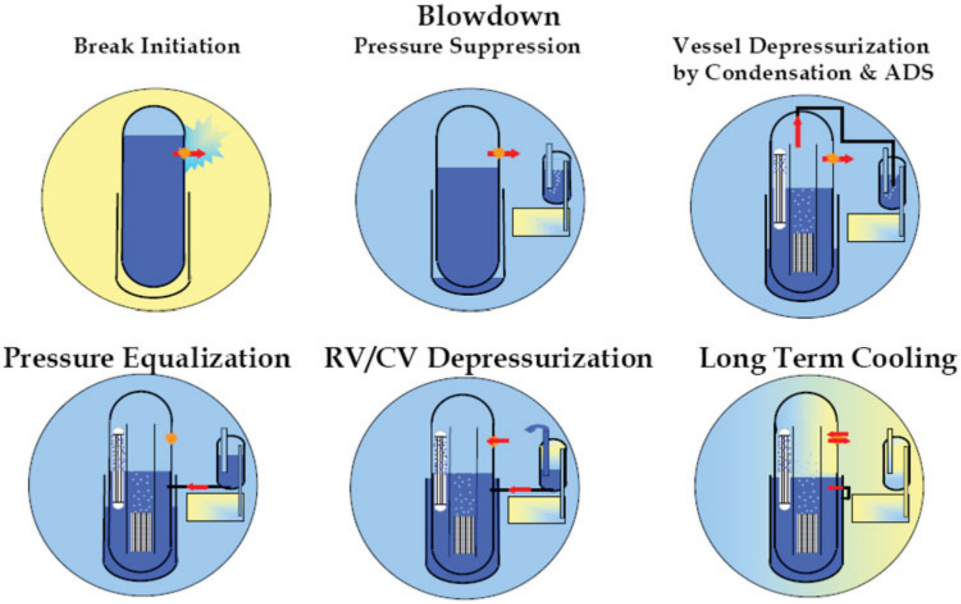

Fig. 5. Innovative thermodynamically coupled reactor-CV in IRIS.

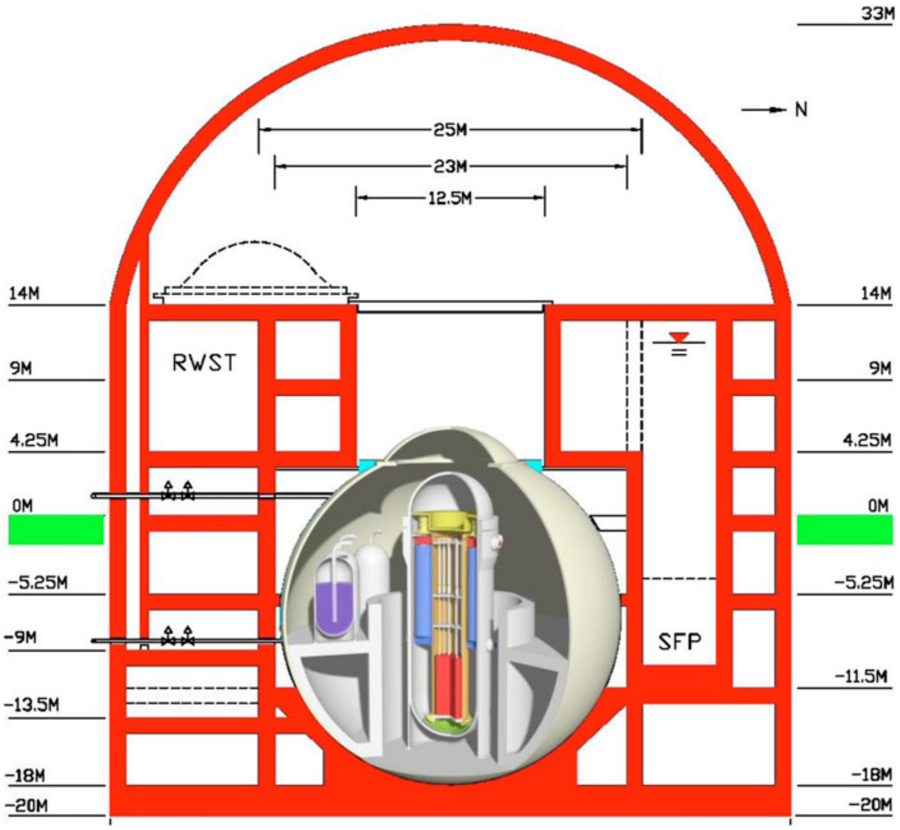

Fig. 6. IRIS containment and auxiliary building.

of a terrorist aircraft attack. Similarly, the spent fuel system, the most vulnerable part of the NSSS to an aircraft attack, is safely located underground and away from the outer wall.

The cost of putting the entire reactor and building underground was evaluated and judged to be prohibitive for a competitive entry to the power market. Although an IRIS underground location is not necessary, if it is so mandated or desired, IRIS can be located fully underground at a fraction of the corresponding cost for current and advanced loop-type LWRs.

III.E. Balance of Plant and Site Layout

The lower power of IRIS compared to large LWR plants [335 versus 1000 to 1600 MW(electric)] could impact the required land use per installed MW(electric). However, due to its simple design, it turns out that multiple IRIS units can provide the same total power as a larger monolithic LWR plant of present technology, using a similar or even smaller-size site. Preliminary results indicate that land use (without the switchyard and parking) ranges from ~0.1 km^2 per GW(electric) (for multiple twin units) to close to 0.2 km^2 per GW(electric) for a single unit. Specifically, site layouts have been developed[17] for IRIS reactor multiple single units and multiple twin units. Further optimization may increase the shared facilities and systems not only within a twin unit but also among single reactor units and twin units with the aim of reducing the plant overall footprint.

IV. A UNIQUE APPROACH TO SAFETY

In addition to the design improvements, the integral configuration offers very significant intrinsic safety advantages, which have led to the unique IRIS safety approach. This approach is represented by three tiers.

The first tier in the IRIS approach to safety is a significant step beyond passive safety and is called Safety-by-Design. The underlying principle is that potential accidents should be intrinsically eliminated by design, rather than coping with their consequences through safety systems, either passive or active. Thus, by eliminating some accidents, the corresponding safety systems (passive or active) become unnecessary as well, reinforcing the "safety-simplicity-economics" synergism.

The second tier is provided by simplified passive safety systems, which protect against the still remaining potential accidents and mitigate their consequences.

TABLE V

Implementation of Safety-by-Design in IRIS

IRIS Design Characteristic	Safety Implication	Positively Impacted Accidents and Events	Class IV DBEs	Safety-by-Design Impact on Class IV Events
Integral layout	No large primary piping	Large-break LOCAs	Large-break LOCA	Eliminated
Large, tall vessel	Increased water inventory Increased natural circulation	Other LOCAs Decrease in heat removal events		
	Accommodates internal CDRMs	Control rod ejection Head penetrations failure	Spectrum of control rod ejection accidents	Eliminated
Heat removal from inside the vessel	Depressurizes primary system by condensation and not by loss of mass	Other LOCAs		
	Effective heat removal by SG and emergency heat removal system	Other LOCAs All events requiring effective cooldown ATWS		
Reduced size, higher-pressure containment	Reduced driving force through primary opening	Other LOCAs		
Multiple, integral, shaftless coolant pumps	No shaft Decreased importance of single pump failure	Shaft seizure/break	RCP shaft break	Eliminated
		Locked rotor	RCP seizure	Downgraded
High-pressure SG system	No SG safety valves Primary system cannot overpressure secondary system Feedwater/steam piping designed for full RCS pressure reduces piping failure probability	SG tube rupture	Steam generator tube rupture	Downgraded
		Steam line break Feed-line break	Steam system piping failure	Downgraded
Once-through SGs	Limited water inventory	Feed-line break Steam line break	Feedwater system pipe break	Downgraded
Integral pressurizer	Large pressurizer volume/reactor power	Overheating events, including feed-line break ATWS		
Spent fuel pool underground	Security increased	Malicious external acts	Fuel handling accidents	Unaffected

The third tier is provided by active systems, which are not required to perform safety functions (i.e., are not safety grade) and are not considered in deterministic safety analyses, but do contribute to reducing the CDF. Their use and characteristics are optimized through a PRA-based design.

IV.A. First Tier: IRIS Safety-by-Design

The elimination by design of large-break LOCAs (no large pipes exist in IRIS) is a typical example of Safety-by-Design. The integral configuration offers the possibility of being able by design to (a) eliminate some of the accidents and (b) mitigate the consequences and/or decrease the probability of occurrence for the vast majority of the remaining accidents. In loop-type PWRs, there are typically eight accidents classified as Class IV, as a consequence of which radiation release to the environment may occur.

Table V summarizes the IRIS design characteristics and their safety implications, together with their impact on accidents, with particular emphasis on condition IV

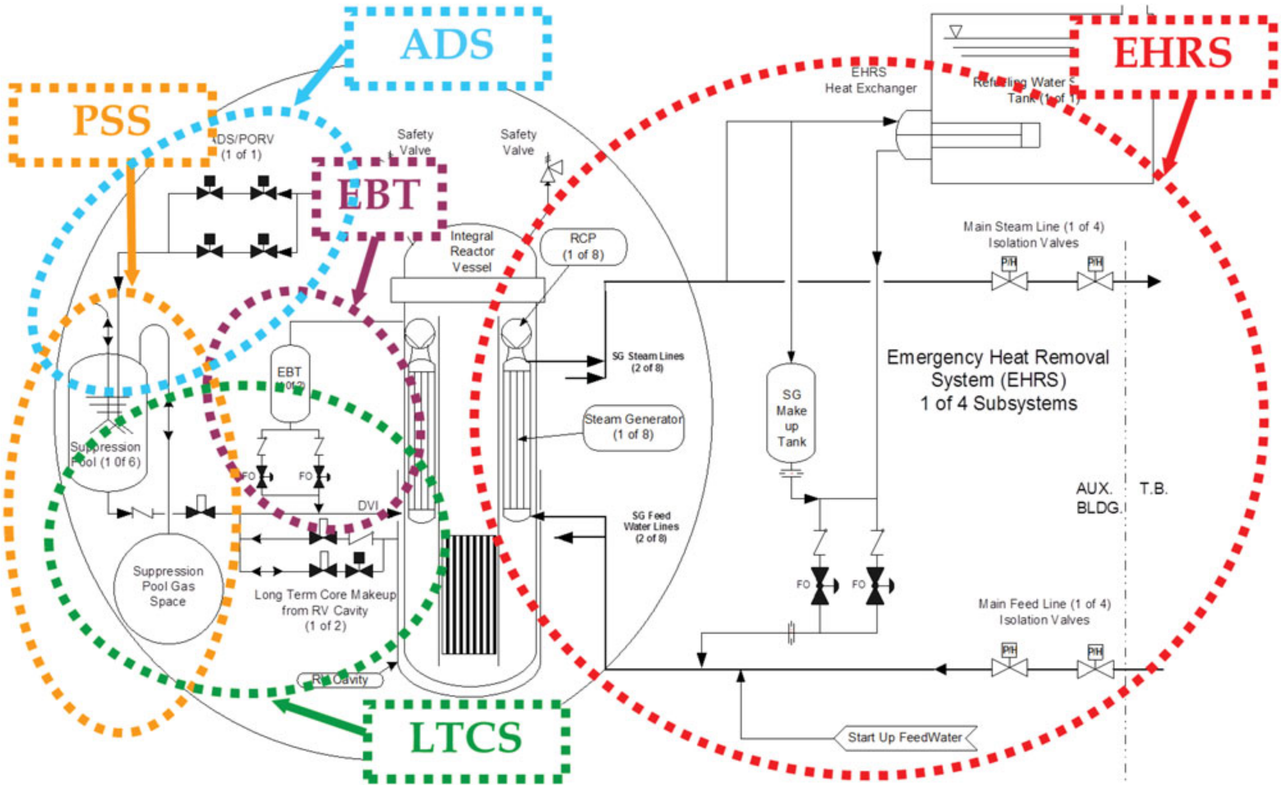

Fig. 7. IRIS safety systems.

events. Systematic implementation of the IRIS Safety-by-Design approach has enabled elimination of three out of eight design-basis events (DBEs) typically considered for LWRs, and for four of the accidents, the consequences are decreased, reclassifying them to a lower-severity class where radiation release will not occur. The only remaining Class IV accident is the fuel handling accident, because IRIS needs to be refueled periodically. Several traditional safety systems, such as the high-pressure injection emergency core cooling system, are no longer needed and are therefore eliminated. Of course, some safety systems are still needed, but they are fewer and simpler. IRIS has five passive and zero active safety systems. This yields a simpler design with lower cost and higher safety and reliability.

IV.B. Second Tier: IRIS Safety Systems

Complementing its Safety-by-Design, IRIS features a limited number of simple safety systems, i.e., only five safety-grade passive systems (shown in Fig. 7), and no active safety-grade systems.[16] 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.

A *passive emergency heat removal system (EHRS)* is made of four independent subsystems, each with a heat exchanger connected to a separate SG feed/steam line. These heat exchangers are immersed in the refueling water storage tank (RWSR) 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 operating in natural circulation can provide core decay heat removal in the case of a loss of secondary system heat removal capability. 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 RV. 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 (EBT)* provide a diverse means of reactor shutdown by delivering borated water to the RV through the direct vessel injection (DVI) lines. 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 RV when/if the RV coolant inventory drops below a specific level. This ADS function ensures that the RV 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 several water tanks and a common tank for noncondensable gas storage. 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 RV through the DVI lines in the event of a LOCA.

A *long-term cooling system (LTCS)* is implemented by 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 RV 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 RV through the DVI lines. This cavity also ensures that the lower outside portion of the RV surface is or can be wetted following postulated core damage events.

Extensive safety analyses were performed related to the second (deterministic) tier of IRIS safety performance. Main results can be found in Refs. 18 through 22.

IV.C. Third Tier: PRA-Based Design

The third tier of safety has been addressed within the PRA/PSA (probabilistic risk assessment/probabilistic safety assessment) framework.[23–26] By consistently applying the Safety-by-Design approach, IRIS has lowered the predicted CDF to below 10^{-7} events/reactor-yr and LERF to below 10^{-9} events/reactor-yr. However, this would not have been possible without the adoption of a PRA-guided design from the very beginning of the IRIS design process. PRA was used to iteratively guide and improve the design, as indicated in Fig. 8.

This process is conceptually straightforward but in practice involved tens of redesign iterations, as illustrated in Fig. 9. With the initial design, after reviewing dominant cut-sets, CDF was estimated to $\sim 2 \times 10^{-6}$, a respectable number but far from the IRIS target. In the next phase, marked in Fig. 9 as step 1, sensitivity cases on individual significant factors (test intervals, diversity, reassessment) were performed and the design was modified, reducing the CDF to $\sim 5 \times 10^{-7}$. That was a limit achievable by optimizing single parameters. In the next phase (step 2), more complex design changes were evaluated to understand and improve coupled processes by simultaneous optimization of several parameters, enabling reduction of CDF to $\sim 1.2 \times 10^{-8}$. Step 3 accounted for a higher level of design details, which increased the CDF to $\sim 2 \times 10^{-8}$. Step 4 evaluated IRIS specific auxiliary systems, anticipated transients without scram (ATWS), human reliability analysis, and further design details. Some weaknesses were identified that temporarily increased the estimated CDF, then the design was improved, restoring the low CDF value of $\sim 2 \times 10^{-8}$. Step 5 indicates initial evaluation of external events.

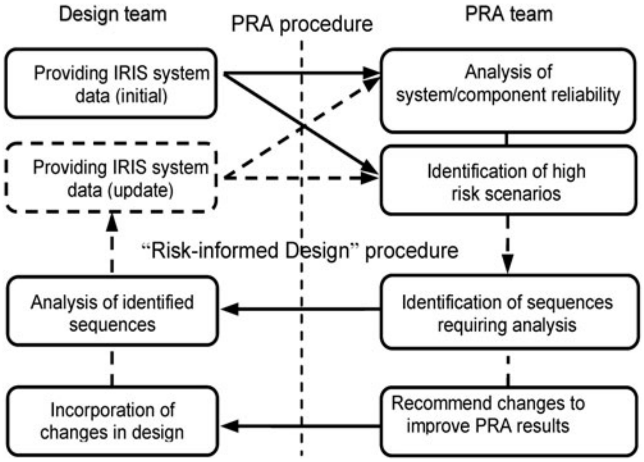

Fig. 8. IRIS PRA-guided design.

Thus, PRA has suggested modifications to the reactor system layout, resulting in reduction of the predicted CDF. After these modifications, the preliminary PRA level 1 analysis estimated the CDF due to internal events (including ATWS) to be about 2×10^{-8}, more than one order of magnitude lower than in current advanced LWRs.

IV.D. Safety Performance Characteristics

A subsequent evaluation[24] of the LERF also produced a very low value, $\sim 6 \times 10^{-10}$, which is again more than one order of magnitude lower than in advanced LWRs, and several orders of magnitude lower than in present LWRs. A comparison employing several top-level safety performance indicators is provided in Table VI. Although the present NPPs already demonstrate remarkable safety, further safety advances achieved in IRIS compared to advanced LWRs have the potential to provide a technical basis to enable plant licensing with a reduced or eliminated off-site emergency planning zone.[27] The approach developed and proposed by the IRIS team for such risk-informed licensing has been reviewed at IAEA technical meetings and incorporated into an IAEA Technical Document.[28] This feature not only should increase public acceptance but will produce a positive financial impact by reducing infrastructure cost, as well as enabling efficient cogeneration for district heating, process heat, and desalination.

We note that once the CDF due to internal events has been reduced, external events become a dominant contributor. To address this, the IRIS project has extended to the balance of plant (BOP) design the same approach that was so successful in dealing with internal events, i.e.,

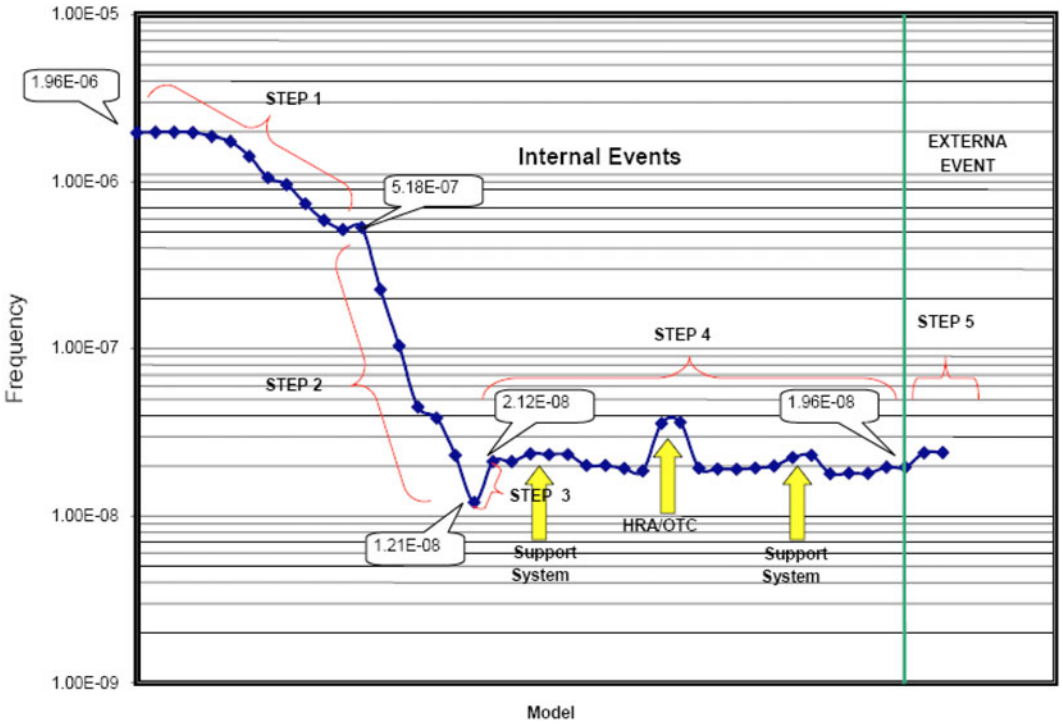

Fig. 9. CDF evolution in IRIS PRA-guided design.

TABLE VI

Indicators of IRIS Safety Performance

Criterion	Typical Advanced LWRs	IRIS
Defense-in-depth	Redundant and/or diverse active systems Passive systems	No active safety-grade systems Safety-by-Design with fewer passive safety systems
Class IV DBEs	8 typically considered	Only 1 remains Class IV (fuel handling accident)
CDF	$\sim 10^{-5}$ to 10^{-7} events/yr	$\sim 10^{-8}$ events/yr
LERF	$\sim 10^{-6}$ to 10^{-8} events/yr	$\sim 10^{-9}$ events/yr

implementing the Safety-by-Design combined with the PRA-guided BOP design. An initial evaluation revealed the inherent strength of the Safety-by-Design. In fact, even though it was developed for the NSSS, originally focusing only on internal events, it provides a robust safety response to loss of off-site power (LOOP) events. Since many external events challenge the plant primarily via LOOP, the IRIS response to external events is improved from the start, before other design considerations are introduced.

IV.E. External Events, Seismic Design, and Seismic PRA

Analysis of external events included evaluation of impact of seismic events and extreme weather (tornado, hurricane, flooding) as well as aircraft crash[29,30] with the PRA-based seismic margin analysis. To enable deployment of a single, standard IRIS design at different geographical locations, without the need to modify the structural design, redo analyses, and relicense the design each time, IRIS has devised the following approach. Its standard design covers typical locations with expected earthquakes of specified moderate magnitude. Additionally, seismic isolators will be deployed based on the site-specific seismic characteristics. Thus, only the isolators will be different for different locations.

Figure 10 illustrates the impact of isolators, indicating the model and results of a seismic analysis. Figure 10a shows the placement of horizontal isolators.

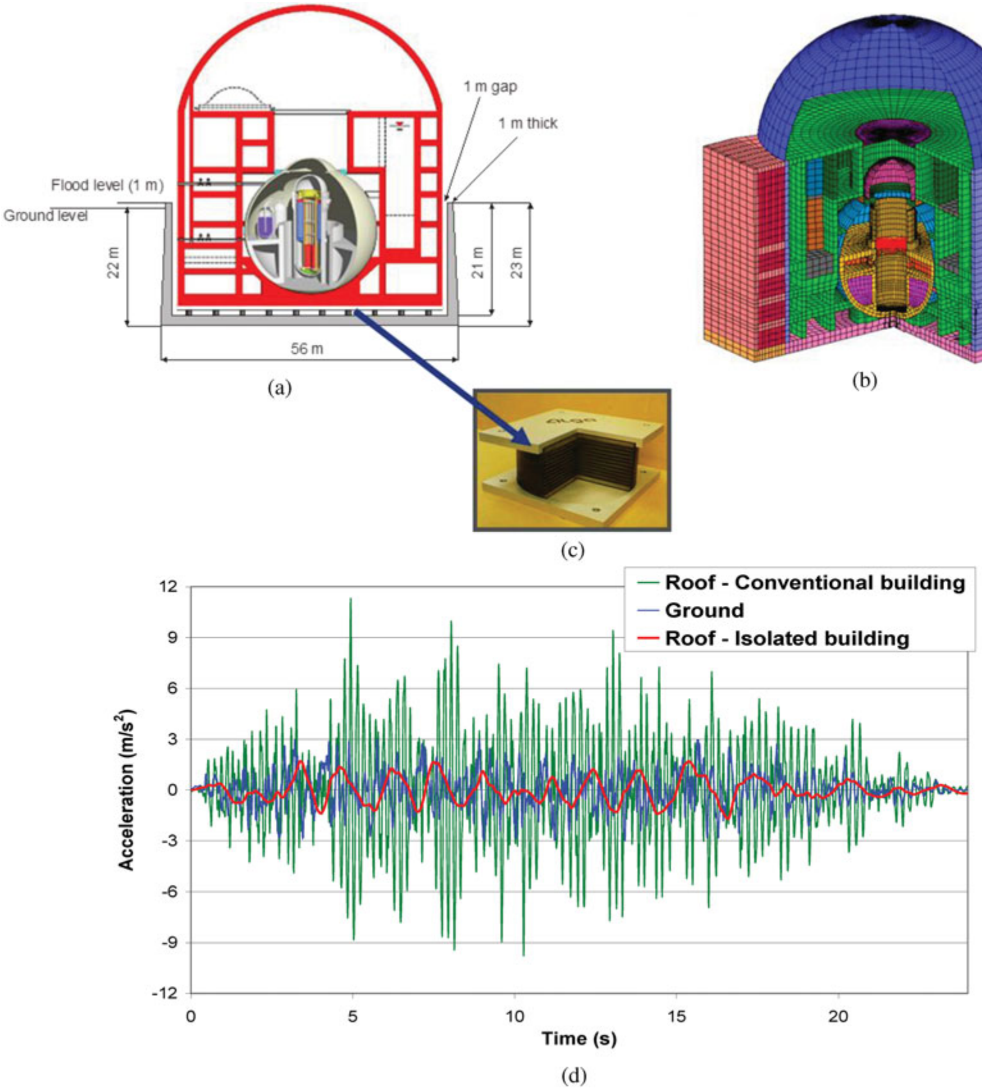

Fig. 10. IRIS design with seismic isolators.

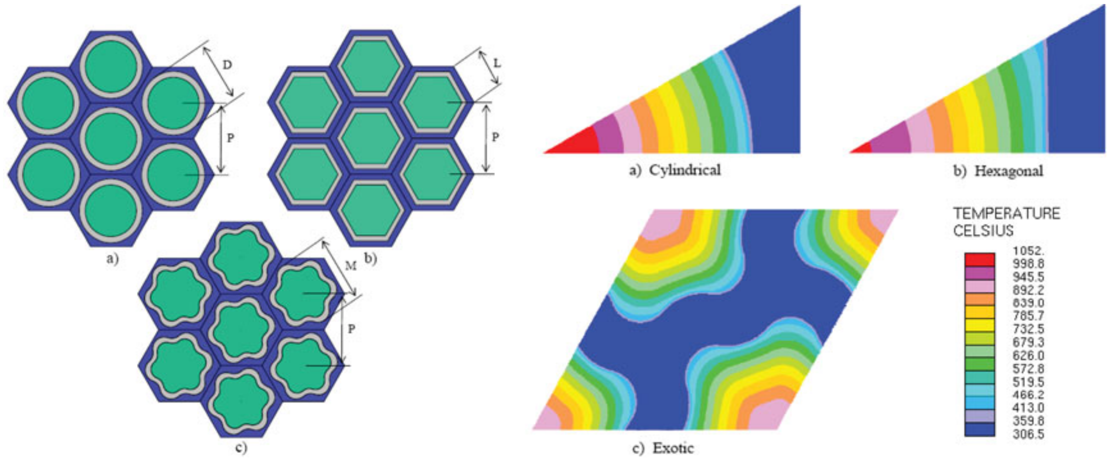

Fig. 11. Results of a CFD analysis for tight fuel lattices.

TABLE VII

Straight-Burn Extended–Cycle Length Options

	Reference Core	Future UO_2 Upgrade	Future MOX Upgrade
Fuel type	$UO_2 < 5\%$ fissile	$UO_2 > 5\%$ fissile	MOX $> 5\%$ fissile
Fissile content (%)	4.95	~7 to 8	~9 to 10
Core lifetime (straight burn) (yr)	~4	~8	~8
p/d	1.4	1.45	1.7
V_m/V_f	2.0	2.2	3.7

Figure 10b depicts the model. The isolators are illustrated in Fig. 10c. Figure 10d shows the ground acceleration (blue), acceleration at the roof location that would result without isolators (green), and the significantly reduced acceleration of a seismically isolated building (red). Similar results are evaluated for all major components, including the RV. For each location, the isolators would be designed to reduce the seismically induced CDF to approximately match the low CDF of internal events ($\sim 2 \times 10^{-8}$ events/reactor-yr). Because of the small IRIS footprint, this is not only a feasible but also an economically advantageous solution.[31] Evaluation of implementation of seismic isolators for IRIS has been performed.

V. FUEL CYCLE

Although IRIS is aiming for near-term deployment in the next decade, which mandates the use of current fuel technology, its longer-term objective is to further enhance its economic and proliferation resistance characteristics by extending the reloading interval to 4 years and beyond. Therefore, a multiprong approach was adopted including a range of fuel options[32]:

1. Rely on proven and licensed fuel technology to enable the near-term deployment objective.
2. Perform research on advanced core designs with higher discharge burnup and longer cycle for longer-term deployment.
3. Additionally, different needs and preferences of different countries should be addressed, such as emphasis on proliferation resistance, or use of MOX or thorium fuel.

A straight-burn (i.e., single-batch) core design was developed using fuel very similar to that of current PWRs (17×17 fuel assembly, UO_2, $<5\%$ enrichment), with a refueling interval of up to 4 years, albeit at a reduced discharge burnup. The IRIS design is such that the maintenance intervals can be extended up to 4 years, thus matching the longest fuel cycle. This makes a capacity factor $>96\%$ possible and decreases the O&M costs. A two- or three-batch refueling core design, on the other hand, improves the discharge burnup and fuel utilization. The two-batch reloading will yield the maximum burnup currently allowed by the NRC, with intervals between refueling of 30 to 40 months, still well in excess of current intervals.

For the reference two-batch near-term solution, several options were developed:

1. fuel with enhanced thermalization, i.e., slightly larger p/d (to increase discharge burnup and cycle length), as well as the completely standard PWR fuel (to avoid any development and licensing issues)
2. design with standard burnable absorbers such as integral fuel burnable absorbers (IFBA) and gadolinia
3. advanced burnable absorbers, including (a) erbium, (b) enriched erbium,[33] and (c) optimized combination of IFBA and erbium[34]
4. core design with load follow capability.[35]

Additionally, core design using 100% MOX fuel was devised.[36] For the longer term, use of nitride fuel was examined[37] to extend the fuel cycle, as well as use of fuel with fissile content $>5\%$ (Table VII).

Additionally, several issues related to epithermal spectrum design (tight lattices) were examined at MIT and Tokyo Institute of Technology, including evaluation of nonstandard fuel element geometries,[38] thermal-hydraulic issues related to tight lattices,[39] and economic evaluation of an alternative tight-lattice IRIS design.[40] Figure 11 shows representative results of a CFD analysis performed to address heat removal in several tight-lattice configurations.

VI. OPERATION, MAINTENANCE, AND RADIATION PROTECTION

One of IRIS design requirements was to optimize its O&M and thus reduce its costs. This is achieved by

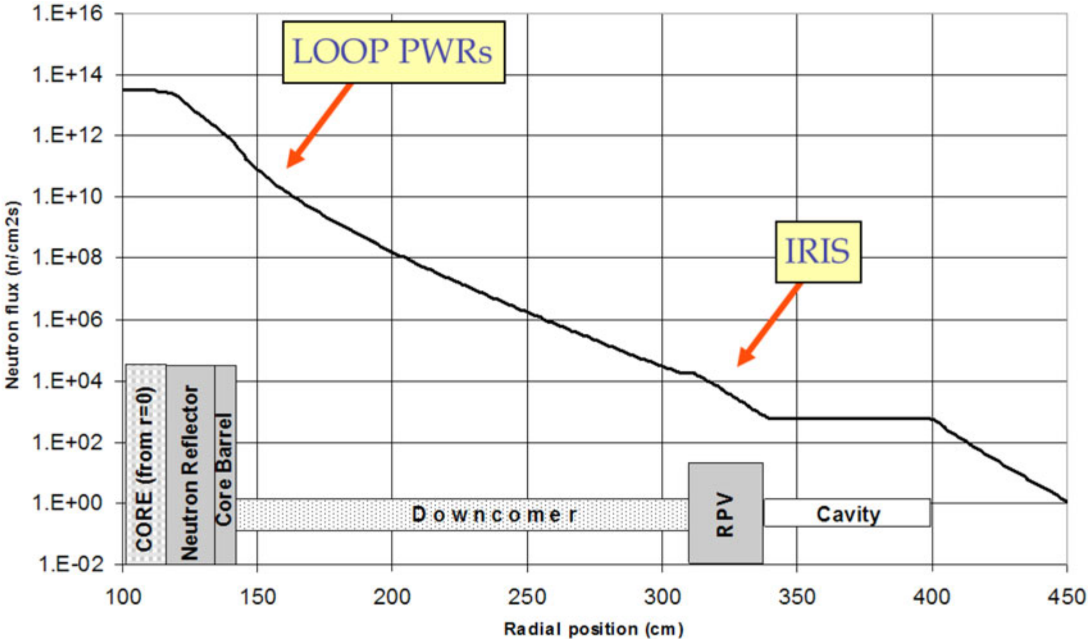

Fig. 12. Radial fast neutron flux profile in a loop-type PWR and integral layout IRIS.

1. fewer refueling outages (up to 4-yr refueling cycle)
2. fewer maintenance outages
3. higher capacity factors
4. fewer personnel due to the simple design
5. "cold" (essentially not activated) vessel
6. reduced dose to personnel
7. no vessel upper head problems (no CRDM penetrations)
8. no vessel lower head problems (no instrumentation penetrations).

A distinguishing characteristic of IRIS, enabling the first three items listed, is its capability of operating for up to 4 years without a need for refueling outage or maintenance outage. The core design able to operate without refueling for up to 4 years was discussed in the previous section. The basis for extending the maintenance cycle in IRIS to 48 months has been a study previously performed 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 online. The study identified a total of 3743 maintenance items, 2537 of them performed off-line and the remaining 1206 online. By evaluating each maintenance item from the standpoint of whether it was possible to extend its maintenance period to 48 months or whether to reclassify it from off-line to online, MIT was able to reduce the list of items that still needed to be performed off-line on a schedule shorter than 48 months to only 54 items. Starting from this study and factoring in the specific IRIS conditions (in particular, simplified design; for example, there is no need to change the reactor primary coolant pumps' oil lubricant, since the IRIS spool-type pumps are lubricated by the reactor coolant), only seven items were left as potential obstacles to a 48-month cycle.[41] These items were addressed and either were resolved or a plan for resolution was devised.[42]

Another feature of IRIS that increases the plant reliability and decreases the O&M costs is the radial water layer of 1.7 m between the edge of the core and the RV. This natural shielding decreases the fast neutron fluence on the RV by a factor of 10^5 compared to a loop-type PWR (Fig. 12), essentially eliminating vessel embrittlement and the need for surveillance coupons and for periodic in-service inspection of the reactor pressure vessel.[43] Also, the radiation field outside the vessel is so low that it allows unrestricted access for maintenance to many locations where the dose is otherwise high in present LWRs, fully supporting the ALARA principle. The end result is an increase in reliability and decrease in O&M costs.

Since there is practically no vessel embrittlement, which is currently the main reason for making the lifetime extension beyond 60 years unpractical or too costly, the lifetime of an IRIS plant can be extended substantially, up to 100 years, depending on the material condition of other systems and equipment. Overall, the following benefits and savings are achieved in IRIS:

1. significantly reduced fast neutron fluence to the vessel, no embrittlement, and elimination of the vessel surveillance program
2. reduced vessel activation, which reduces the dose in surrounding maintenance areas
3. reduced vessel activation, which simplifies ultimate D&D, with potential to dispose of significant portion of the vessel as nonradioactive materials
4. reduced activation of concrete forming the vessel cavity, with potential to keep it below the free release limit, which simplifies the ultimate D&D[44]
5. reduced activation of components within the containment and reduced dose in maintenance
6. reduced individual and collective dose.

The eliminated vessel embrittlement and reduced dose to personnel have immediate positive financial impact for the utility. The reduced D&D cost, although scheduled to occur in the future, also has an impact on present cost, since utilities are mandated to form a D&D "escrow" fund and set aside advance annual contribution to accumulate adequate funds for eventual D&D. Further details are available in Refs. 45, 46, and 47.

IRIS has set aggressive dose reduction targets, i.e., to have a negligible dose in accessible areas and small levels in maintenance areas. This implied attenuation factor over ten orders of magnitude and required challenging deep-penetration shielding calculations. To increase the reliability of results under these circumstances, analyses to confirm reaching the targets were simultaneously performed with deterministic discrete ordinates code TORT, Monte Carlo code MCNP with the direct statistical approach (DSA) method for variance reduction, and with MAVRIC sequence in SCALE6. The dose distribution throughout the IRIS building determined using MAVRIC is shown in Fig. 13. Figure 13a indicates the dose level throughout the building. In Fig. 13b, only those zones with dose levels higher than the natural background are shown; otherwise, the color is blanked out. All accessible areas except one room at the core level and above the vessel were found to be below the target level. The revised design (not shown) reduces the level in these areas as well.

VII. ECONOMICS AND COMPETITIVENESS

Although SMRs have many undisputed attractive features, one point of contention is the plausibility of their economic competitiveness. The main argument against the competitiveness of SMRs is based on the economy of

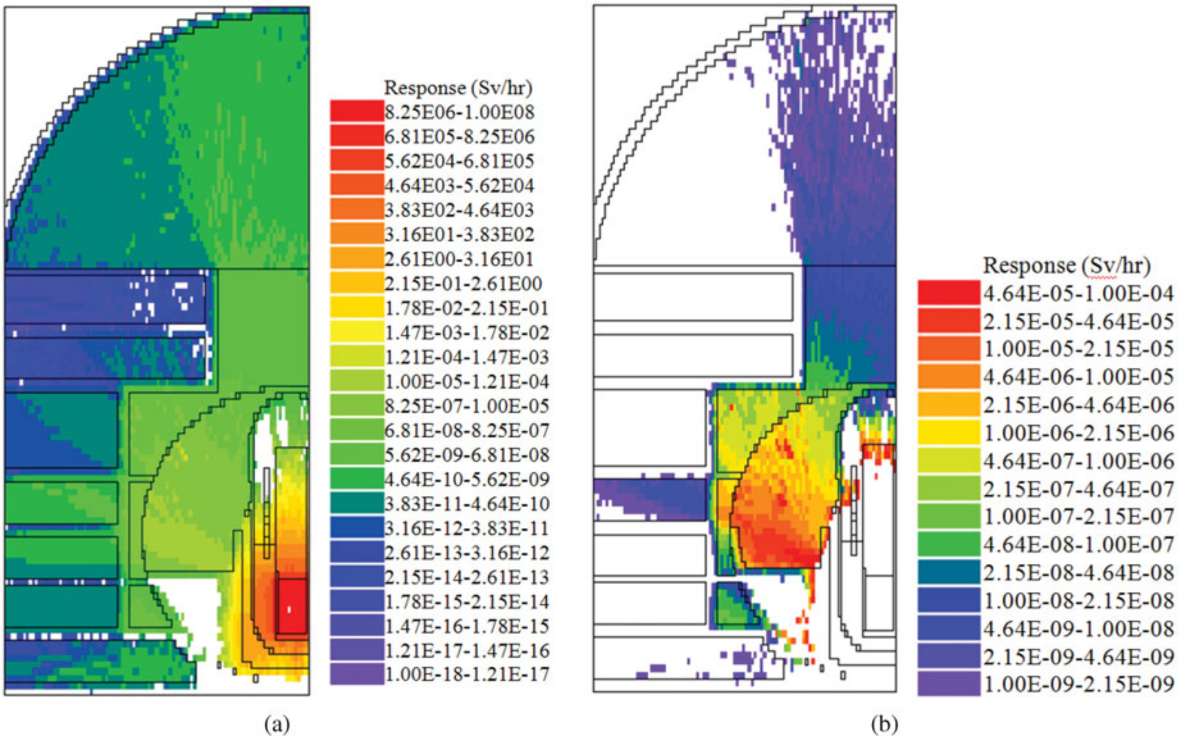

Fig. 13. Shielding analysis to determine dose throughout the IRIS building: (a) full range and (b) with dose comparable to background blanked out.

scale. Economy of scale is indeed well proven in praxis, but it is valid only when correctly interpreted and applied, which is not always the case when used to dispute potential competitiveness of SMRs.

First, the economy of scale applies to NPPs of *essentially identical* design that are scaled up or down in size, i.e., electric power. However, it does not necessarily apply to two *different* designs, one small and one large and with different characteristics. Smaller designs may be simpler (as is indeed the case with IRIS), and thus inherently cheaper per specific unit, but also may have inherent limitation preventing the scaling to very large power.

Second, the nominal construction unit cost [e.g., overnight cost per installed kW(electric)] does not capture the full financial picture. Maximum capital at risk and larger interest rate for larger projects, to name just a few, impact the effective cost, in most cases in favor of SMRs.

Third, even if the unit price [$ per installed kW(electric)] is somewhat cheaper for large units, the total cost may be out of reach for smaller utilities, emerging energy markets, and developing countries. Specifically, a large 1000 to 1600 MW(electric) unit may cost anywhere between $3 and $10 billion, whereas most SMRs would cost $1 billion or less. Experience shows that the latter amount is typically within reach, but the former amount presents significant funding challenges.

Fourth, in some cases there are technical reasons preventing deployment of large units. The limit may be imposed by the power grid size, i.e., its total installed capacity. A rule of thumb suggests that any single power-generating object should not be larger than 10% of the grid capacity, and preferably even not larger than 5%, which makes SMRs the only technically feasible choice in many developing countries and emerging energy markets, as well as in remote areas. Moreover, for a number of nonelectric applications (e.g., high-temperature process heat), the optimum power level is in the SMR range.

Fifth, societal considerations tend to favor SMRs. For example, they are more conducive to passive safety and have significantly smaller source term per reactor unit, and thus smaller consequences in case of a catastrophic single-unit failure. This will also enable a reduced size of the exclusion zone.

Such arguments and counterarguments related to competitiveness of SMRs have been known for a long time. However, the distinguishing significant contribution of the IRIS team is that it performed detailed and documented studies to identify major relevant positive as well as negative factors impacting the competitiveness of SMRs and to assign substantiated quantitative indicators to enable credible assessment of the overall relative cost of SMRs versus larger units.[48–50] Some of these studies were performed within IAEA-coordinated projects and reviewed by international experts, giving them further credibility.[51] When evaluating the competitiveness of SMRs, various factors were considered, as listed in Table VIII; the list is by no means exhaustive, and others factors might have been considered. Presented here are the ones judged to have higher priority for a quantitative evaluation. Six factors, identified by asterisks, are further discussed here.

The most important SMR-specific factor is its design-related characteristics. This factor varies from design to design, but many SMRs are characterized by simplicity and reduced type and number of components. Specifically for IRIS, Table IX summarizes its design simplification by listing the major components eliminated and reduced (positive impact) as well as those added or expanded (negative impact).

There is a clear positive overall effect. IRIS design is simpler (and consequently cheaper) that an equally sized typical large-loop-type PWR scaled to the same power. In other words, the economy of scale still applies, but for each design separately. IRIS is moving on a different curve than that of a traditional loop-type PWR (Fig. 14). Although the integral IRIS design does not allow scaling up in power of a single module to, for instance, 1000 MW(electric), it does allow IRIS to achieve the same unit price [$/kW(electric) installed] as a larger-power loop PWR.

TABLE VIII

SMR-Specific and Common Factors

SMR-Specific Factors	Common Factors
Design-related characteristics* Compactness Cogeneration Match of supply to demand* Reduction in planning margin Grid stability Economy of replication Bulk ordering Serial fabrication of components	Size* Modularization Factory fabrication Multiple units at a single site* Learning* Construction time* Required front end investment Progressive construction/operation of multiple modules

*Factors discussed in text.

TABLE IX

IRIS Design Characteristics Impacting Cost

Positive Impact on Cost	Negative Impact on Cost
Major components/systems eliminated in IRIS All large piping to/from the RV SG pressure vessels Canned motors and seals of primary pumps Pressurizer Pressurizer spray system Vessel head penetrations and seals due to external CRDMs Vessel bottom penetrations and seals due to in-core instrumentation All active safety systems High-pressure emergency cooling system **Major components/systems reduced in IRIS** Shielding Number and complexity of passive safety systems Number of valves Size of containment and nuclear building Number of NSSS buildings (from two or more to one) Number of large forged components (from a dozen or more to one)	**Major components/systems expanded in IRIS** None

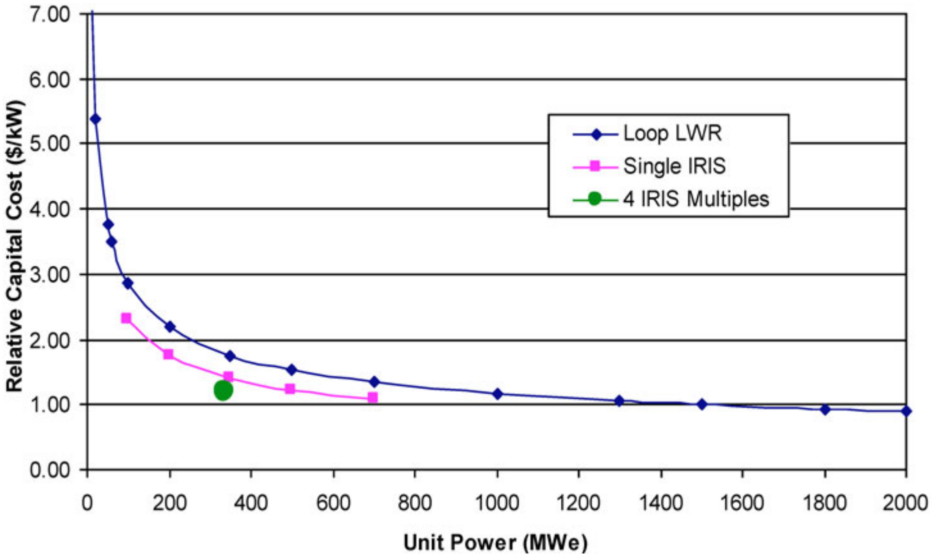

Fig. 14. Economy of scale curves for IRIS and a large loop PWR.

Overall, IRIS has reduced O&M costs due to its design characteristics. As already discussed, it requires less frequent maintenance outage and refueling outage (up to 4-yr maintenance intervals). Integral shielding dramatically decreases the personnel routine exposure and ALARA costs. Moreover, its simple design reduces the training costs.

Engineering additions required to enhance security are intrinsically less expensive in SMRs because of their smaller size and simpler design. For example, IRIS offers a much smaller target to a terrorist-driven aircraft. Its enhanced intrinsic safety and passive systems also decrease the chances (thus, costs of counteracting measures) of internal sabotage.

One other index considered in evaluating NPPs is the amount of required commodities (such as steel, concrete, and land use) per unit power. Because of its compactness, the "commodities index" for IRIS is approximately the same as or lower than that of large plants. Another effect of its compact design is that a cluster of several IRIS

SMRs, having the same total power as a large plant, generally requires less land.

SMRs are inherently better suited for cogeneration (production of potable water by desalination, of steam for district heating or industrial or agricultural application, and of process heat for chemical industry). Although electricity can be transported long distance, cogeneration products require proximity to the end user. Since NPPs are licensed with population restrictions (exclusion or low-population zone), either significant infrastructure or transportation costs are incurred or cogeneration is simply not possible. The safety characteristics of some SMRs (and IRIS in particular) may allow them to attain licensing without the need for off-site emergency response.[27] Representative analyses have been performed for IRIS deployed for desalination,[52–54] district heating,[55] process heat for chemical industry, and synthetic fuel production.

SMRs' size allows them a much closer match of supply to demand than possible with large plants. This of course reduces financing commitments and allows better planning, with reduction in planning margin. Also, insertion of smaller units reduces the challenge to grid stability. Although SMRs may be the only viable reactors for smaller electric grids, even in larger interconnected grids large power additions/subtractions (nuclear or conventional) can cause grid instabilities, as demonstrated by blackouts experienced in the northern U.S./Canada and Italy in 2003 and in Central Europe in 2006.

Rather than economy of scale of large plants, SMRs enable economy of multiples with bulk/serial component fabrication (e.g., many small SGs rather than several large, one-of-a-kind SGs), accelerated learning, and multiple units savings. Modular construction and multiple module deployment yield shorter construction schedule, module deployment tailored to demand (does not depress the market price with overcapacity), reduced requirement for purchase power (spin reserve), improved cash flow, and reduced capital at risk.

The last two factors have a significant financial impact, frequently not accounted for. Construction of a large plant takes a longer time, and there is no generated electricity or income until that unit is complete. A staggered deployment of SMRs enables "bootstrapping"; i.e., the first unit generates income that supports construction of the second unit, then the income of the first two units supports construction of the third one, and so on. As a result, the maximum cash outflow ("capital at risk") is significantly reduced, which has positive impact on financing (reduced interest rate). Figure 15 compares the cash flow of four 335 MW(electric) SMRs [1340 MW(electric) total] deployed in a staggered fashion (every 3 years) versus a single large PWR.

Quantification of the six selected factors affecting the comparison of SMRs versus large plants is described in Refs. 48 and 49 and is summarized in Table X. SMR refers again to one 335 MW(electric) IRIS plant, as part of four units, providing 1340 MW(electric), the same as one single 1340 MW(electric) large plant. SMR starts with a large penalty (factor 1.7) due to the economy of scale, but other factors are favorable, and the final cumulative factor is 1.05.That is, in this case the effective specific cost of multiple SMRs is estimated to be ~5% higher than that of a monolithic plant. Clearly, 5% is well below the uncertainty. Moreover, additional factors not accounted for are expected to be favorable to SMRs, which means that for all practical purposes the estimated cost is about the same, and SMRs do have the potential to be economically competitive.

TABLE X

Quantification of Factors Needed for SMRs versus Large Plant Comparison

Factor	SMR/Large Reactor Capital Cost Factor Ratio	
	Individual	Cumulative
(1) Economy of scale	1.7	1.7
(2) Multiple units	0.86	1.46
(3) Learning	0.92	1.34
(4) (5) Construction schedule and timing	0.94	1.26
(6) Design specific	0.83	1.05

Moreover, a novel approach to address and quantify societal and other nonfinancial factors has been devised and a corresponding model developed, integrated model for the competitiveness assessment of SMRs (INCAS) (Ref. 50).

VIII. TESTING AND LICENSING

VIII.A. Licensing Approach

IRIS had engaged in the preapplication review process with the NRC. This preapplication phase was intended to address long-lead items such as testing before the full-scale formal design certification process is started, thus allowing the latter to be completed expeditiously. Additionally, in its licensing IRIS may take advantage of the successfully completed design certification of passive PWRs (AP600 and AP1000) for those design features that are similar. Therefore, the scope of the preapplication review has been limited to those facets that are different or unique to IRIS, specifically the following:

1. *IRIS safety approach:* Preliminary safety analyses were conducted for the accidents where the IRIS response may be different from that of the loop-type passive PWR

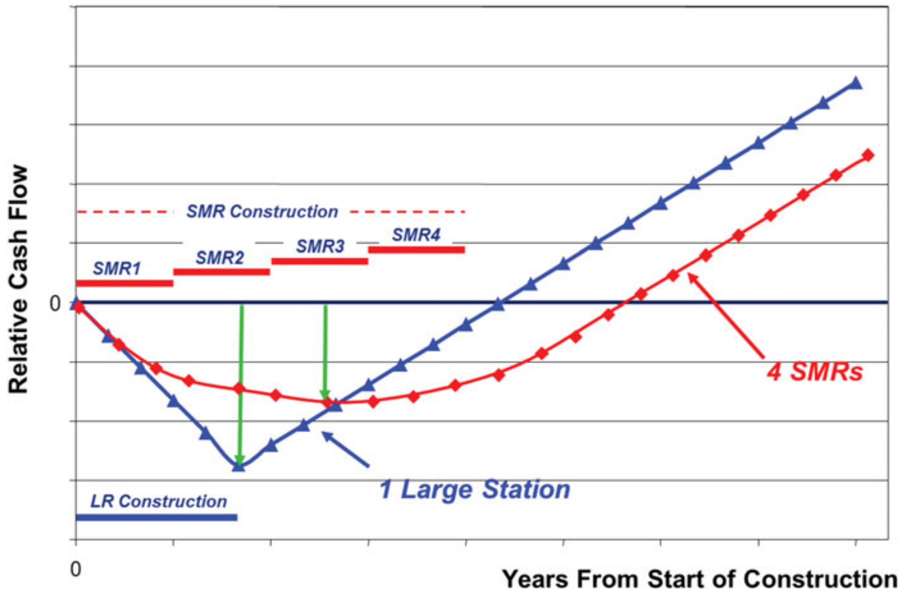

Fig. 15. Staggered modular build reduces maximum cash outlay and capital at risk.


Prototypic bundle, developed originally for a 20 MW thermal reactor and of the same diameter as the IRIS steam generator, was fabricated and tested

IETI (SIET Italy) Facility Thermal-Fluid-Dynamics experiments on a full-scale helical-coil tube of the IRIS reactor steam generator

SPES-3 at SIET (Piacenza, Italy) will be used to demonstrate IRIS integrated system performance and to support design approval (AP1000 testing was performed at SIET)

Fig. 16. IRIS test facilities.

(AP600 and AP1000). The results indicated an excellent performance, in many cases better than expected.

2. *Enhanced licensing:* Approach and methodology aimed at achieving licensing with eliminated, or at least significantly reduced, off-site emergency planning requirements has being developed, reviewed, and reported in the IAEA Technical Document (Ref. 28, Chap. 4).

3. *Adequacy of the testing program:* An IRIS prototype is not necessary because IRIS does not represent a new technology, but rather a new engineering.

However, a rigorous testing program is necessary to appropriately investigate all the new engineering aspects. Identification of the necessary testing program was completed[56] and reviewed by the NRC, and no apparent deficiencies were observed. More details on testing are provided below.

In summary, IRIS is licensable under the current NRC regulation, and no particular licensing show-stoppers were identified.

VIII.B. Testing in Support of Licensing

The testing that is being performed to support licensing of IRIS builds on extensive experience accumulated during the testing and licensing of advance passive PWRs (AP600/AP1000). However, further testing is necessary to address new IRIS design features and components, including the following:

1. integral RCS
2. passive safety features specific to IRIS
3. RV and containment interaction—demonstration of Safety-by-Design in eliminating consequences of small LOCAs.

To ensure adequacy of testing, IRIS test plan has been formulated in compliance with the NRC requirements of 10 CFR 52.47 and is a key part in the Evaluation Model Development and Assessment Procedure (EMDAP). The basic principles of evaluation model development and assessment that constitute an EMDAP and the associated plan have been developed utilizing the IRIS small-break LOCA PIRT (Ref. 57). The tests have been divided into three types according to their scope and primary purpose:

1. *Basic engineering development tests* are used to determine the feasibility of an engineering concept or verify the design of a particular component before proceeding to a larger-scale test or a full-scale prototype component development program. Generally, these engineering tests focus on materials and mechanical investigations.

2. *Component separate effects tests* are performed to provide specific information on the design, fabrication, and operation of large-scale or prototype components. Key components that will be tested include SGs, pumps, pressurizer, and CRDMs, both individually and as functional groups.

3. *Integral effects tests* examine the integrated performance of components through simulation of all important structures and interconnecting systems, components, and piping to provide thermal-hydraulic data for computer code validation, i.e., confirm that computer code models satisfactorily predict the appropriate individual component, system, and overall plant response. These tests are required for the NRC review and approval of the safety analysis and for plant certification.

The IRIS testing program started in 2006. A detailed design of testing facilities and definition of the testing matrix has been completed. Several test facilities are shown in Fig. 16.

A large part of the safety-related tests were planned to be conducted in Italy, at SIET, at the same site where testing of the passive systems for AP600 was conducted in the 1990s. Of particular importance is the new integral test facility[58] that will be used to perform integral system tests and evaluate behavior of the entire nuclear system (RV and containment) in response to postulated accidents.

Some tests have already been performed or are in progress, including, for example, experimental characterization of the IRIS passive EHRS (Ref. 59), experimental characterization of two-phase flow instability thresholds in IRIS SGs (Ref. 60), and testing of IRIS seismic isolators.[61]

IX. INTEGRATION OF ACADEMIA AND STUDENT RESEARCH INTO IRIS DEVELOPMENT

Universities have been involved since the very beginning in various aspects of the IRIS design development, and many innovative ideas came from the university members.[62] Under the guidance of the industrial team members, these ideas were subjected to strict review under criteria needed for real-life applications, and some were subsequently accepted and expanded into practical solutions and incorporated into the actual IRIS design. The project benefited significantly; without the students' talent and enthusiasm, it would not have been possible to generate such breadth of novel ideas. At the same time, this provided the students with the opportunity of working on real-life engineering challenges, becoming exposed to the industry environment, and in some cases being hired by one of the IRIS team industrial members. Students' involvement was organized in a variety of ways, including joint research, annual internship at industrial team members, student exchanges between IRIS universities, shorter summer internships, technical advising, preparation of joint papers, training in using industry programs and analytic tools, etc.

The extent of the university/student collaboration with and participation on the IRIS project is best demonstrated by the fact that by January 1, 2006, more than 70 doctorate and master's theses resulted from the IRIS-related research, as listed in Table XI. In addition, 40 undergraduate students participated in IRIS through design projects. Several tens of additional theses were prepared in 2006–2010. This true win-win collaboration established a new paradigm and enabled the project to move forward faster than under a traditional development model.

TABLE XI

Projects and Theses Resulting from IRIS-Related Research*

University	Undergraduate	Master's	Doctorate
Polytechnic of Milan	1	28	8
MIT	1	4	1
Tokyo Institute of Technology		6	6
University of Pisa	28	8	1
University of Zagreb	3	1	3
Polytechnic of Turin		1	
University of Rome		1	1
University of California at Berkeley		2	
University of Tennessee	1	4	
Ohio State University		4	1
University of Michigan	6	2	
Total	40	61	21
Cumulative total	122		

*As of January 1, 2006.

Some of the more prominent contributions by academia are as follows:

1. The Polytechnic of Milan is a coinventor with Westinghouse of the patent on the IRIS containment design and contributed to other design areas.

2. The University of Zagreb performed safety analyses that were the basis for the preapplication review with the NRC.

3. MIT made it possible to extend the scheduled maintenance outage intervals from the 12 to 24 months typical for present LWRs to 48 months for IRIS.

4. The University of Pisa and the University of Zagreb participated in evaluating various fuel management options for IRIS and in analyzing the reference core design; MIT examined epithermal core design; and Georgia Tech was involved in advanced core design (advanced burnable absorbers, nitride fuel).

5. The Tokyo institute of Technology made important contributions to the PRA/PSA analyses and the thermal hydraulics of tight-lattice cores.

6. The Polytechnic of Milan and MIT contributed to efforts to examine the possibility for licensing with reduced or eliminated off-site emergency response requirements.

7. The Georgia Institute of Technology led shielding analyses to evaluate/limit the dose to personnel and reduce activation of large structures (cavity concrete wall) below the free-release limit (for eventual decommissioning).

8. The Polytechnic of Milan developed an object-oriented fast simulation model for efficient simulation of the IRIS dynamic response.[63]

9. The Polytechnic of Milan and the University of Pisa performed seismic analyses and contributed to the evaluation of seismic isolators.

X. SUMMARY AND CONCLUSIONS

This paper aims to summarize main technical and programmatic achievements of the IRIS project, as well as to recognize the contributions of many individuals who made these achievements possible. During the past 10 years, IRIS has progressed from an SMR concept to a mature reactor and plant design. In the process it has introduced many new and innovative features that significantly improve its operational and safety performance as well as economics. Of particular interest is its Safety-by-Design approach and several related features that preclude or mitigate Fukushima-type events. IRIS has addressed in an integrated way all relevant design aspects. This was possible due to a large international expert team that effectively integrated academia, which enabled breadth and depth of investigation and analyses unparalleled before and not feasible in a "purely commercial" project. Detailed, realistic, and well-substantiated analyses of economics and the potential competitiveness of SMRs (and IRIS in particular) have provided credible arguments for feasibility of SMR deployment and achieved international recognition. It is the authors' belief that IRIS has played a leading role in the renewed interest in SMRs in the past decade and constitutes a milestone along the way to further development and deployment of advanced SMRs.

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