IRIS: A global approach to nuclear power renaissance

BY MARIO D. CARELLI

Although still at the preliminary design stage, the IRIS nuclear power plant design has moved rapidly from idea to viable commercial entry.

Fig. 1. IRIS logo

AMONG THE MANY new designs that have sprung to life in these recent years at the welcome sight of a possible nuclear power renaissance, IRIS (International Reactor Innovative and Secure) is the one that has moved most rapidly from an idea to a viable, albeit still at the preliminary design stage, commercial entry. IRIS is a modular pressurized water reactor with an integral configuration (all primary system components—pumps, steam generators, pressurizer, and control rod drive mechanisms—are inside the reactor vessel). It is offered in configurations of single or multiple modules, each having a power rating of 1000 MWt (about 335 MWe).

The IRIS program began in October 1999 as one of the winning proposals in the first Nuclear Energy Research Initiative (NERI) solicitation by the Department of Energy, and it has since progressed through the conceptual design and moved to a stage in the preliminary design, which has allowed initiation of the licensing process, with the first meeting with the Nuclear Regulatory Commission on pre-application licensing held in October 2002. IRIS is also one of the reactor designs considered in determining the envelope of the early site permit (ESP) by three U.S. power generation companies—Dominion, Entergy, and Exelon.

This early success of IRIS is attributable to two fundamental constituents of the IRIS approach:

- IRIS is a very innovative reactor design with many attractive new features, especially in the safety area, but at the same time its technology is grounded on well-proven and universally familiar water reactors experience.
- IRIS embodies a new paradigm with its development by an international partnership of industry, research organizations, academia, and power producers for potential future deployment in both developed and emerging markets. While most reactor programs have some international participation, such participation is of the contractor/supplier type and is not a qualifying characteristic; the internationality of IRIS is one of its very *raisons d'être.*

Why international?

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

Smaller, modular gas-cooled reactors had already been proposed: the Pebble Bed

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Table I. IRIS Consortium

INDUSTRY		
Westinghouse	USA	Overall coordination, core design, licensing
BNFL	UK	Fuel and fuel cycle
Ansaldo Energia	Italy	Steam generators design
Ansaldo Camozzi	Italy	Steam generators, CRDMs fabrication
ENSA	Spain	Pressure vessel and internals
NUCLEP	Brazil	Containment, pressurizer
Bechtel	USA	BOP, AE
OKBM	Russia	Testing, desalination
LABORATORIES		
ORNL	USA	I&C, PRA, core analyses, shielding, pressurizer
CNEN	Brazil	Transient and safety analyses, pressurizer, desalination
ININ	Mexico	PRA, neutronics support
UNIVERSITIES		
Polytechnic of Milan	Italy	Safety analyses, shielding, thermal hydraulics, steam generators design, advanced control system
MIT	USA	Advanced cores, maintenance
Tokyo Inst. of Technology	Japan	Advanced cores, PRA
University of Zagreb	Croatia	Neutronics, safety analyses
University of Pisa	Italy	Containment analyses
Polytechnic of Turin	Italy	Human factors, reliability/availability/maintainability support
University of Rome	Italy	Radwaste system, occupational doses
POWER PRODUCERS		
TVA	USA	Maintenance, utility perspective
Eletronuclear	Brazil	Developing country utility perspective
ASSOCIATED MEMBERS (NERI PROGRAMS)		
Univ. of California Berkeley	USA	Neutronics, advanced cores
Univ. of Tennessee	USA	Modularization, I&C
Ohio State	USA	In-core power monitor, advanced diagnostics
Iowa State (& Ames Lab)	USA	On-line monitoring
Univ. of Michigan (& Sandia Labs)	USA	Monitoring and control

Modular Reactor (PBMR) and the gas turbine-modular helium reactor (GT-MHR). For the PBMR, Exelon had made a strong case of the inherent advantage of small plants in introducing new power to the grid in limited increments, thus finely tailoring supply and demand and limiting the utilities' financial exposure. The same considerations apply to IRIS, as well as the consideration that in addition to being simpler to construct and operate, these smaller plants have to be fabricated in series—i.e., as American Nuclear Society past President Stan Hatcher once said, "We have to build aircrafts, not aircraft carriers." It was readily apparent that to fabricate and deploy an economically large enough number of multiple, identical modules, the market had to be one global, international arena.

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

The IRIS consortium

This approach immediately found a positive resonance, as the IRIS team kept growing over its short, three-year life from the initial four members and two countries to the present 20-plus members from nine countries (Fig. 1 and Table I). The original team of Westinghouse, two American universities (University of California Berkeley [UCB] and Massachusetts Institute of Technology [MIT]), and one Italian university (Polytechnic of Milan [POLIMI]) was joined by other reactor designers and component manufacturers, fuel and fuel cycle vendors, architect-engineers, power producers, universities, and laboratories. Table I provides a summary of the IRIS team partnership with the areas of responsibility of each team member. Associate members are U.S. universities and laboratories currently working on DOE-funded NERI projects, which, while of general interest, use IRIS

Table II. Students Contributing to IRIS Design

University	Undergraduate	Graduate	Doctorate
Polytechnic of Milan, Italy	-	16	4
MIT, USA	1	4	1
University of California Berkeley, USA	-	2	-
University of Pisa, Italy	10	4	1
Tokyo Institute of Technology, Japan	-	3	4
University of Tennessee, USA	1	2	-
Ohio State University, USA	-	2	1
University of Michigan, USA	6	2 (planned)	-
University of Zagreb, Croatia	3	1	3
Total	21	40	14

as the example application of the technology being investigated.

While associated members (and partially Westinghouse) were and/or are DOE-funded via NERI, the IRIS consortium members are self-funded and provide to the project both design effort and previous know-how. Currently, approximately 100 people across the IRIS consortium are contributing to the project.

The contribution of the universities to the IRIS program cannot be emphasized enough: a true win-win situation. Table II shows the number of students who around the world are or had been working on IRIS as of spring 2003. Innovative design solutions have been proposed and developed by the universities, and IRIS is perhaps the first and only commercial reactor project where academia and industry are in a partnership equally co-responsible for the design. The partnership with universities (and laboratories) also has a potentially very important long-term effect, in making IRIS a "living and contemporary" design. In fact, once the IRIS preliminary design is completed, its implementation will become essentially the responsibility of the industrial partners, while the universities and laboratories will shift to work on future improved designs incorporating the most recent technological advancements. As they are readied, industry can then implement them in a new series of IRIS modules. A key reason that this can conceivably be done and accepted by the market is that the size of an IRIS module is only about one-third to one-fourth of today's large light-water reactors, and thus the financial exposure is much more limited. As previously mentioned, with IRIS we are dealing with aircrafts, not aircraft carriers.

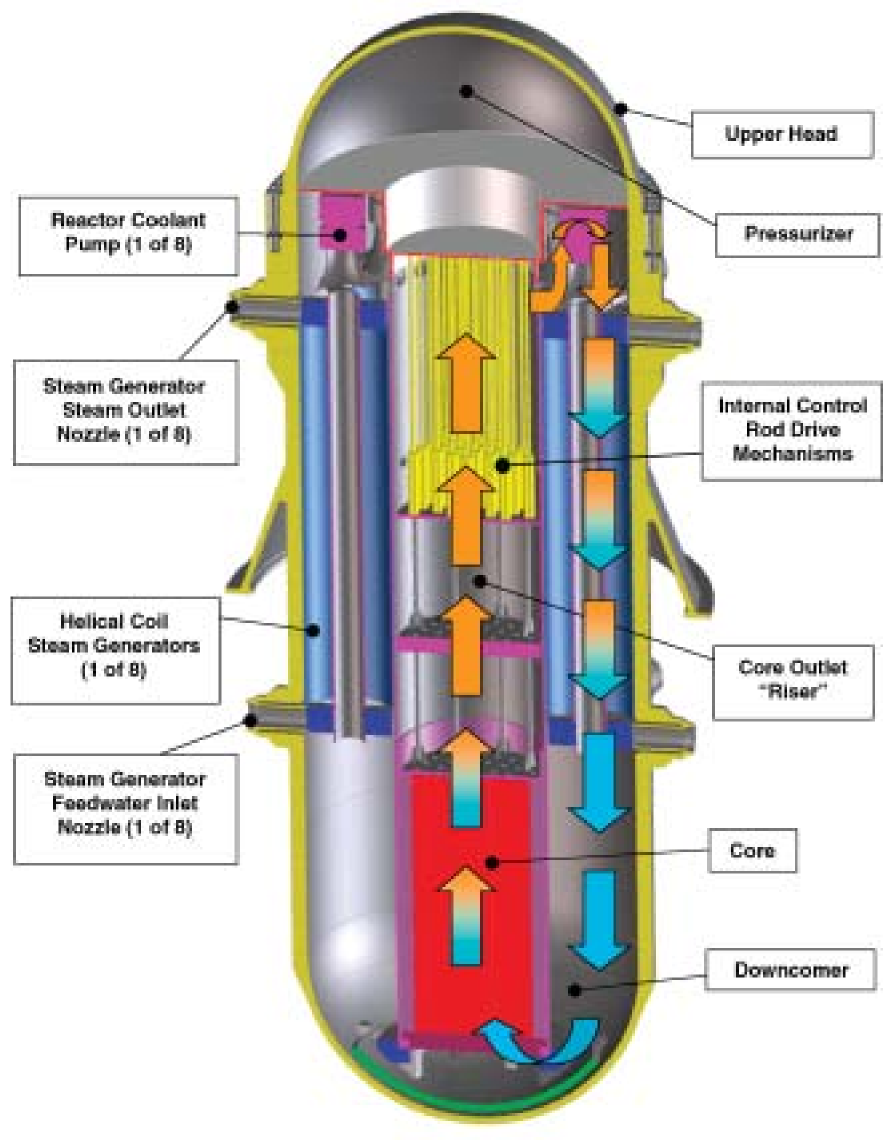

Fig. 2. IRIS integral layout

IRIS design characteristics

The IRIS design was conceived to satisfy the four objectives stated by the DOE for the new generation reactors: improved proliferation-resistance, enhanced safety, improved economics, and reduced waste. It is a pressurized water-cooled reactor, to take advantage of the extensive Westinghouse and worldwide technology base, and it is a small-to-medium power modular reactor, for the economic considerations previously discussed.

Distinguishing and defining characteristics of IRIS are:

- Integral configuration, which, to a greater or lesser degree, addresses all the four objectives.
- The capability of employing high burnup, long-life cores, which, together with the capability of operating four years without shutdown for maintenance, addresses the proliferation-resistance requirement, but, more important, increases the capacity factor and decreases the operation and maintenance (O&M) costs.
- Innovative containment design, which practically eliminates small-to-medium loss-of-coolant accidents (LOCAs) as a safety concern.
- The "Safety-by-Design" approach, where, rather than coping with their consequences, accidents are eliminated from occurring; alternatively, if this is not possible, their consequences are lessened by design or their probability of occurring is reduced.

The integral configuration

All the main primary system components (core with reflector/shield, pressurizer, reactor coolant pumps, steam generators, and control rod drive mechanisms) are located inside the reactor pressure vessel, as shown in Fig. 2. 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 annular plenum where the suction of the reactor coolant pumps is located. Eight pumps are employed, and the flow of each pump is directed downward through its associated helical coil steam generator module. The flow path continues downward through the annular downcomer region outside the core to the lower plenum and then back into the core, completing the circuit.

The major components of the reactor coolant system (RCS) housed in the IRIS reactor vessel (RV) are: the nuclear fuel and control rods (core); eight small, spool-type reactor coolant pumps (RCPs); eight modular, helical-coil, once-through steam generators (SGs); a pressurizer located in the RV upper head; the control rod drive mechanisms (CRDMs); and a steel reflector that surrounds the core in the RV downcomer to improve neutron economy. In addition, the reflector, together with the large water annulus and some additional shielding, very significantly reduces the neutron fluence on the RV and the radiation field outside the RV. The integral arrangement eliminates all the pressure vessels outside the reactor vessel, as well as the large connecting loop piping between them, resulting in a compact, more economical configuration and in the physical elimination of the LOCAs. Because the IRIS integral vessel contains all the RCS components, it is larger than a traditional RV, and has an inside diameter of 6.2 m and an overall height of 21.3 m, including the closure head. The internal configuration, however, yields a containment much smaller than those for conventional PWRs. IRIS employs a spherical containment, with a diameter of 25 m, slightly more than half the diameter of the cylindrical containment for a 600-MWe PWR (see Fig. 3). The compact containment has a positive impact on the safety approach, as it will be seen later.

Major design parameters of IRIS are summarized in Table III. The major in-vessel components are described below.

Reactor core

The IRIS core is composed of 89 fuel assemblies, and is discussed in detail in the next section.

Reactor coolant pumps

The IRIS pumps are of the spool type, which has been used in marine applications and designed for chemical plant applications requiring high flow rates and low developed head. The motor and pump consist of two concentric cylinders, where the outer ring is the stationary stator and the inner ring is the rotor that carries high specific speed pump impellers. The spool-type pump is located entirely within the reactor vessel; only small penetrations for the electrical power cables are required. High-temperature motor windings and bearing materials are being developed to eliminate the need for cooling water and the associated piping penetrations through the RV. This design is a significant improvement over the typical RCPs for PWRs, which have the pump/impeller protruding through a large opening in the pressure boundary where the motor cas-

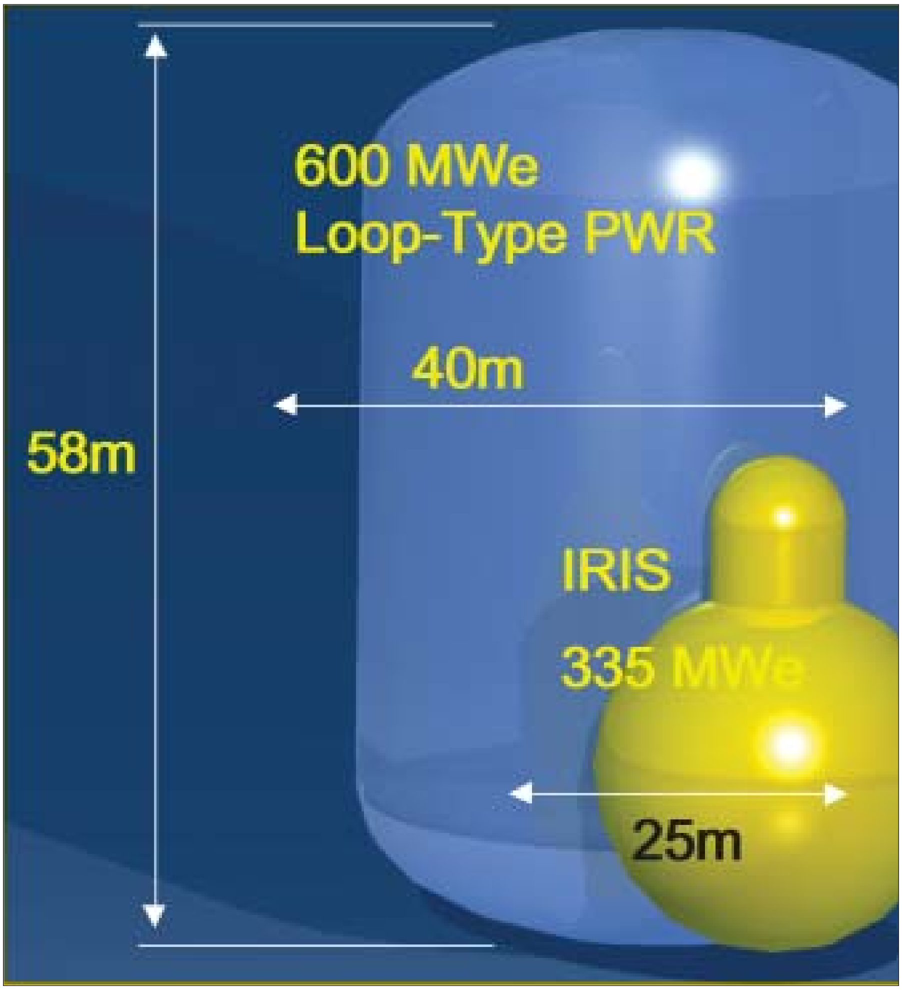

Fig. 3. Loop/integral configuration containment comparison

TABLE III. MAJOR IRIS DESIGN PARAMETERS

General Plant Data	
Power plant output, net	335 MWe
Core thermal power	1000 MWt
Nuclear Steam Supply System	
Number of coolant loops	Integral RCS
Steam temperature/pressure	317/5.8 °C/MPa
Feedwater temperature/pressure	224/6.4 °C/MPa
Reactor Coolant System	
Primary coolant flow rate	4700 kg/s
Reactor operating pressure	15.5 MPa
Core inlet temperature	292 °C
Core (riser) outlet temperature	330 °C
Reactor Core	
Fuel assembly total length	5.207 m
Active core height	4.267 m
Fuel inventory	48.5 tU
Average linear heat rate	10.0 kW/m
Average core power density (volumetric)	51.26 kW/l
Fuel material	Sintered UO$_2$
Rod array	Square, 17×17
Number of fuel assemblies	89
Number of fuel rods/assembly	264
Outer diameter of fuel rods	9.5 mm
Enrichment	4.95 Wt % U-235
Equilibrium cycle length	30-48 months
Average discharge burnup	60 000 MWd/tU
Reactor Pressure Vessel	
Cylindrical shell inner diameter	6.21 m
Wall thickness of cylindrical shell	285 mm
Total height	21.3 m
Steam Generators	
Type	Vertical, helical coil tube bundle, once-through, superheated
Number	8
Thermal capacity (each SG)	125 MWt
Number of heat exchanger tubes (each SG)	656
Reactor Coolant Pump	
Type	Spool type, fully immersed
Number	8
Pump head	19.8 m
Primary Containment	
Type	Pressure suppression, steel
Geometry	Spherical, 25 m diameter
Design pressure/temperature	1300/200 kPa/°C

ing is typically flanged and seal welded to the mating pressure boundary surface. In addition to the above advantages derived from its integral location, the spool pump geometric configuration provides high inertia/coastdown and high run-out flow capability that contributes to mitigating the consequences of loss-of-flow accidents (LOFAs). Because of their low developed head, spool pumps have not previously been considered for nuclear applications. The IRIS integral RV configuration and low coolant path pressure drop, however, are an ideal match for these pumps and can take full advantage of their unique characteristics.

Steam generators

The IRIS SGs are of a once-through, helical-coil tube bundle design, with the primary fluid outside the tubes. Eight steam generator modules are located in the annular space between the core barrel (outside diameter 2.85 m) and the reactor vessel (inside diameter 6.2 m). Each IRIS SG module consists of a central inner column that supports the tubes, the lower feedwater header and the upper steam header, and an outer wrapper. The enveloping outer diameter of the tube bundle is 1.64 m. Each SG has 656 tubes, and the tubes and headers are designed for the full external RCS pressure. The tubes are connected to the vertical sides of the lower feedwater header and the upper steam header. Each SG is supported from the RV wall and the headers are bolted to the vessel from the inside of the feed inlet and steam outlet pipes. Feedwater enters the SG through a nozzle in the reactor vessel wall, then flows to the lower feedwater header and to the SG tubing, where it is heated to saturation temperature, boiled, and superheated as it reaches the upper steam header. Steam then exits the SG through the nozzle in the reactor vessel wall. The helical SG tube bundle is contained within the outer wrapper, which acts as a flow shroud channeling the primary water flow from the top of the SG downward through the bundle and outside the tubes. The water exits the bottom of the bundle into the reactor vessel downcomer region. Each of the eight reactor coolant pumps is attached directly to the top of its corresponding SG flow shroud, so that its flow is entirely directed through the SG bundle region.

The helical-coil tube bundle design is capable of accommodating thermal expansion without excessive mechanical stress, and has high resistance to flow-induced vibrations. A prototype of this SG was successfully tested by IRIS team member Ansaldo Energia in an extensive test campaign conducted on a 20-MWt full-diameter, part-height test model (see Fig. 4). The performance characteristics (thermal, vibration, pressure losses) were investigated along with the determination of the operating characteristics domain for stable operation.

Fig. 4. Mock-up of IRIS helical coil steam generator

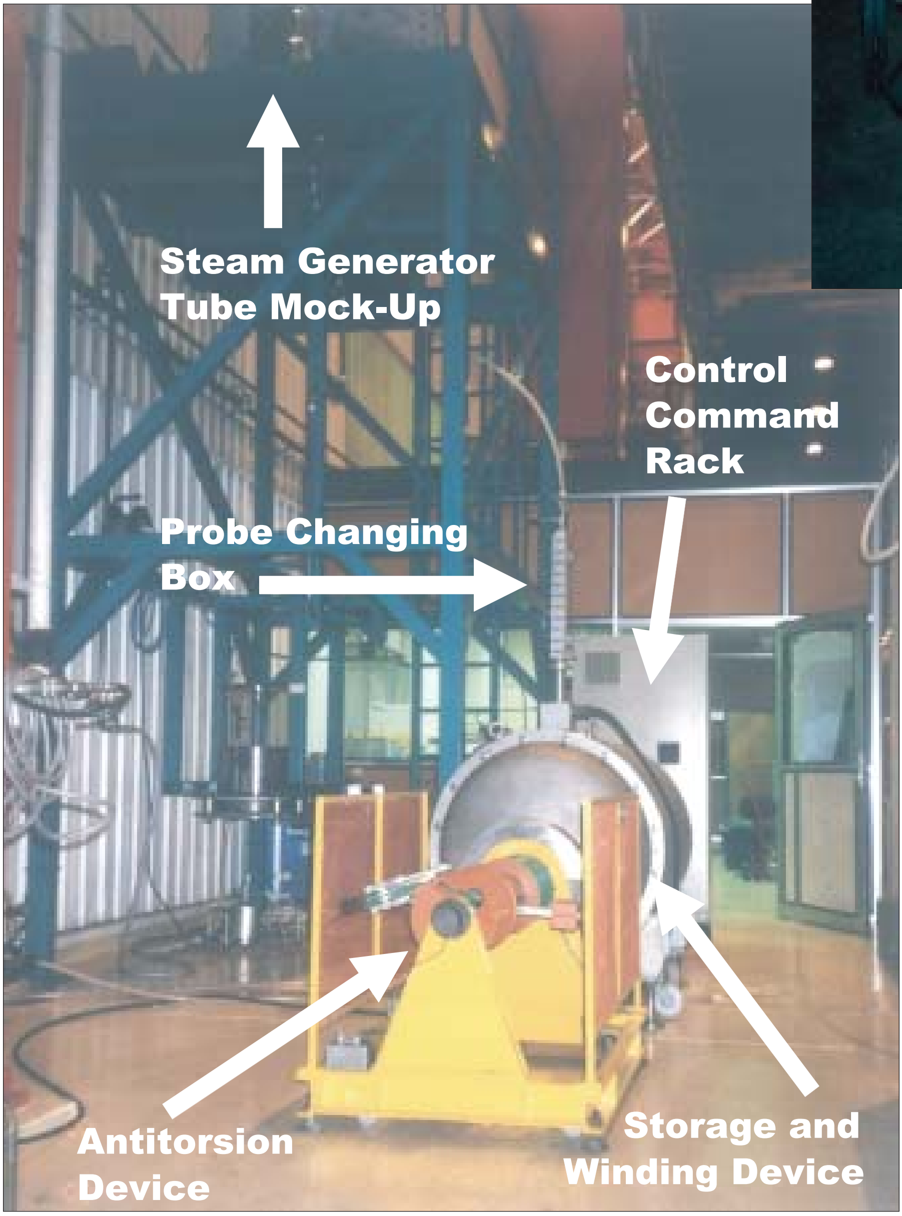

Fig. 5. Mock-up of steam generator inspection system

A unique aspect of the IRIS SG design is that the high-pressure primary coolant flows on the outside of the tubes. Thus, the IRIS SG tubes are in compression, and therefore, tensile stress corrosion cracking—which, according to EPRI data, has been responsible for more than 70 percent of all the SG tube failures—is automatically eliminated. Also, IRIS tubes are designed for full pressure (i.e., zero internal-secondary-pressure and full external-primary-pressure). Thus, the probability of tube failure is greatly reduced, and if it does occur, there is no plausible mechanism for failure propagation to other tubes. On the other hand, inspection and maintenance of integral steam generators require new tools and methodologies. Methods for inspection and cleaning of the tubes of the SuperPhénix steam generators had been established by Ansaldo Energia (the mock-up test apparatus is shown in Fig. 5). In addition, Iowa State University/Ames Laboratories and the University of Michigan, with Sandia National Laboratories, are investigating through two NERI grants new monitoring technologies for material degradation and loss of integrity, as well as prognostic methods for predicting failures and set up preventive maintenance. A promising monitoring technology is EMAT (electro magnetic acoustic transducer), which can detect changes in tube diameter (thinning by corrosion or thickening by deposit), thus alerting plant operators to possible impending failures.

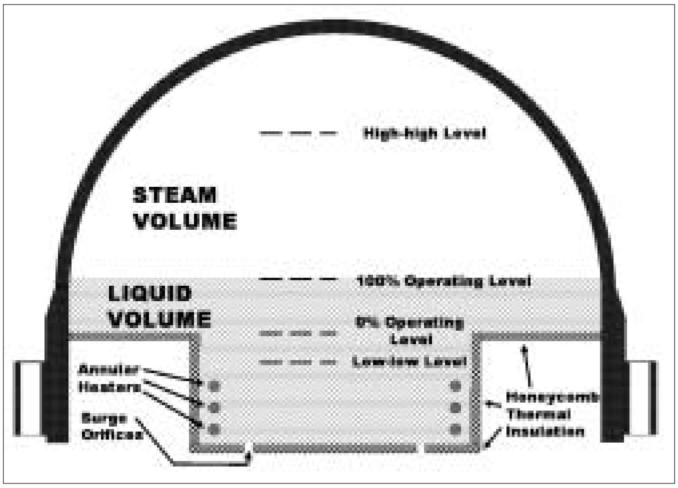

Fig. 6. Pressurizer

Pressurizer

The IRIS pressurizer is integrated into the upper head of the reactor vessel (see Fig. 6). The pressurizer region is defined by an insulated, inverted top-hat structure that separates the circulating reactor coolant flow path from the saturated pressurizer water. This structure includes a closed cell insulation to minimize the heat transfer between the hotter pressurizer fluid and the subcooled water in the primary water circulating flow path. Annular heaters are located in the bottom portion of the inverted top-hat, which contains holes to allow water insurge and outsurge to and from the pressurizer region. These surge holes are located just below the heaters so that the insurge fluid flows up across the heater elements.

By utilizing the upper head region of the reactor vessel, the IRIS pressurizer provides a very large water and steam volume, as compared to plants with a traditional, separate, pressurizer vessel. The IRIS pressurizer has a total volume of about 71 m^3, which includes a steam volume of about 49 m^3. This steam volume is about 1.6 times bigger than the pressurizer steam space for a large PWR, while IRIS has about ⅓ the core power. Because of this large steam volume-to-power ratio (about five times the value of a typical PWR), IRIS does not need a pressurizer spray function to prevent the pressurizer safety valves from lifting for any design basis heatup transients.

Adoption of an integral configuration has a very positive impact on the reactor's overall intrinsic safety, well beyond the obvious elimination of the large LOCAs. This has allowed IRIS to implement an extremely effective “safety-by-design” approach, which will be discussed in detail later.

Control rod drive mechanisms

The integral configuration is ideal for locating the CRDMs inside the vessel, in the region above the core and surrounded by the steam generators. Their advantages are in safety and operation.

Safety-wise, the uncontrolled rod ejection accident (a Class IV accident) is eliminated because there is no potential 2000-psi differential pressure to drive out the CRDM extension shafts. Operation-wise, the absence of CRDM nozzle penetrations in the upper head eliminates all the operational problems related with corrosion cracking of these nozzle welds and seals, which have intermittently plagued the industry, and most recently have extensively flared up (e.g., the Davis-Besse plant). The design and manufacturing of the upper head is also simpler and cheaper.

The project very recently adopted the internal CRDMs as reference (traditional CRDMs remaining as backup) because (1) they eliminate this corrosion problem, and (2) development of internal CRDMs has recently advanced significantly in regard to the electromagnetic drive concept in Japan, while internally to the IRIS project, Polytechnic of Milan has further advanced the hydraulic drive concept. IRIS is currently considering alternative concepts for the internal CRDMs, and will be proceeding soon to the preliminary design of the chosen one.

Reactor core and fuel design

A practical approach to promoting proliferation-resistance is to make the fuel significantly less accessible, by designing a core capable of operating in a straight burn mode for an extended number of years. A series of studies was performed early in the program aimed at achieving long core life. For that purpose, discharge burnup that can be achieved with different fuel lattice configurations was examined. Figure 7 presents results of the analysis for UO_2 fuel (left figure), as well as MOX fuel (right figure) for two fissile contents, about 10 percent and about 15 percent. Discharge burnup is shown as a function of p/d (lattice pitch to fuel diameter ratio). Current PWRs typically have a p/d value of approximately 1.3.

Open lattice (large p/d) provides long life for both fuel forms; therefore, it was selected as the preferred option. When using about 10 percent fissile content, it is possible to achieve an 8–10-year cycle; however, the corresponding burnup of about 80 000 megawatt-days per tonne

TABLE IV. REFUELING OPTIONS FOR CURRENT IRIS CORE DESIGN

	Emphasis on Proliferation Resistance	**Reference Option**	**High Burnup Option (When Licenseable)**
	Single Batch (Straight Burn)	**Two-Batch (Partial Reload)**	**Three-Batch (Partial Reload)**
FAs with 4.95% enrichment	69	40-44	28-36
FAs with 2.6% enrichment	20	--	--
Cycle Length (years)	4.0	3.0-3.5	2.5-3.0
Average discharge burnup (MWd/tU)	38-40 000	53-56 000	56-62 000
Lead rod burnup (MWd/tU)	<50 000	<62 000	<75 000

TABLE V. IRIS'S ACCOMMODATION OF CORE UPGRADES

	Initial Core	Future UO2 Upgrade	Future MOX Upgrade
Fuel Type	UO_2 <5% fissile	UO_2 >5% fissile	MOX >5% fissile
Fissile Content	4.95%	~8%	~10%
Core Lifetime	4–5 years	~8 years	~8 years
Pellet Diameter	0.366"	0.340"	0.296"
Clad OD	0.423"	0.395"	0.348"
Lattice Pitch	0.5922"	0.5922"	0.5922"
P/d	1.4	1.5	1.7
Vm/Vf	2.0	2.5	3.7

heavy metal (MWd/tHM) would require fuel irradiation testing. Also, currently only fuel enrichment up to 5 percent U-235 is licensed. An 8–10-year core with about 10 percent enrichment and high-discharge burnup would thus not be licensable for many more years to come, while the IRIS goal is to be deployable early in the next decade.

Therefore, it was decided that the IRIS first-of-a-kind plant would feature a four-year core fueled by a lower, standard-enrichment fuel (4.95 percent UO_2) in a fuel assembly that is practically identical to a Westinghouse PWR assembly. This fuel is licensable now and is thus consistent with the target deployment date. It can provide a 48-month straight-burn cycle, which is consistent with the 48-month maintenance interval discussed later. On the other hand, a straight-burn 48-month core has a relatively low-discharge burnup (about 40 000 MWd/tU) and feedback from utilities indicated that a high burnup was preferable to a longer single-core cycle length. Therefore, designs featuring two-batch and three-batch cores with partial refuelings were also developed (see Table IV).

The current reference design is the two-batch core, which has a cycle length in excess of three years and a lead rod burnup up to 62 000 MWd/tU, which is consistent with the currently licensable limit. Once that limit is raised to 75 000 MWd/tU, as currently envisioned, IRIS will immediately keep pace by going to a three-batch core. Actually, IRIS is designed to be able to accept interchangeable cores, as shown in Table V, which refers to the straight-burn option. This is accomplished by adopting the variable moderation approach, where the increase in fissile content is matched by an adequate increase in moderation ratio by adjusting the fuel rod diameter, while keeping the fuel assembly envelope unchanged. These advanced reloads can be envisioned to become available in the 2020s, as a higher burnup database becomes available and a higher fissile content becomes licensable. Finally, in line with the "living design" approach previously mentioned, some of the IRIS universities (UCB, MIT, and the Tokyo Institute of Technology) are already investigating advanced cores with: epithermal spectrum; tight p/d ratio, which for MOX fuel allows burnups well in excess of 100 000 MWd/tHM (see Fig. 7); and exotic fuel geometries (e.g., twisted hexagons), which offer adequate cooling even for very tight lattices.

The reference core design for the first-of-a-kind plant, which is the one presently going through the pre-application licensing process, is, as previously mentioned, similar to a conventional Westinghouse PWR design. Several features, however, have been modified to enhance performance as compared to conventional plants, while retaining existing technology. An IRIS fuel assembly consists of 264 fuel rods in a 17×17 square array. The central position is reserved for in-core instrumentation, while the remaining 24 positions have guide thimbles. The IRIS fuel assembly design is similar to the Westinghouse 17×17 XL Robust Fuel Assembly design. Low-power density is achieved by employing a core configuration consisting of 89 fuel assemblies (shown in Fig. 8) with a 14-ft (4267-mm) active fuel height, and a nominal thermal power of 1000 MWt. This results in the average linear power rating being approximately 60 percent of present PWRs. The improved thermal margin provides increased operational flexibility, while enabling longer fuel cycles and increased overall plant capacity factors.

Another feature that contributes to lowering cost and extending reactor life is the use of a stainless steel radial neutron reflector. This reflector reduces neutron leakage, thereby improving core neutron utilization. As a result, fuel utilization is improved as well, thus enabling extended fuel cycle and increased discharge burnup. The radial reflector has the added benefit that together with the water downcomer annulus and possibly some additional shielding, it does reduce the fast neutron fluence on the core barrel and reactor vessel and the dose outside the vessel to the extent of yielding, for any practical purposes, a "cold" vessel.

Reactivity control is achieved in a traditional manner by a combined use of soluble boron, integral absorbers, and control rods. Soluble boron concentration is reduced, however, as compared to conventional PWR cycles, to improve core response in transients (more negative reactivity coefficients) and reduce the amount of waste to be processed. Another advanced core design feature (common with the AP600 and AP1000 designs) is the use of reduced-worth control rods ("gray" rods) to achieve daily load follow while minimizing the required change in

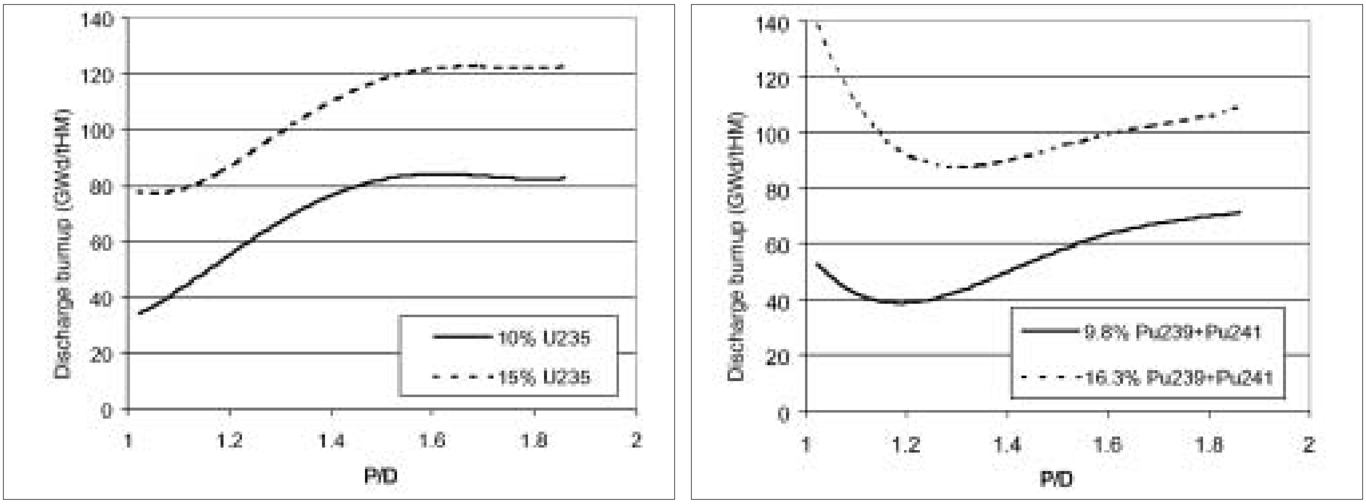

Fig. 7. Achievable discharge burnup as a function of p/d lattice parameter for UO_2 and MOX fuel

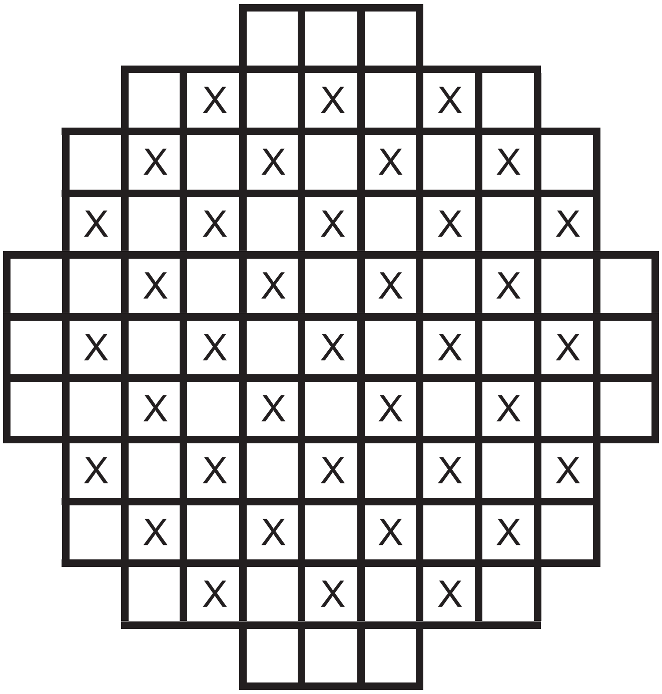

Fig. 8. IRIS core configuration and a typical control rod pattern

the soluble boron concentration. With the exception of the neutron absorber materials used, the design of the gray rod assembly is identical to that of a normal control rod assembly.

Optimized maintenance

As we have seen, a distinguishing characteristic of IRIS is its capability of operating with long cycles. Even though the reference design features a two-batch and a 3- to 3.5-year fuel cycle, selected on the basis of ease of licensing and U.S. utilities' preference, IRIS is capable of eventually operating in straight burn with a core lifetime of at least eight years. The significant advantages connected with a long refueling period in reducing operation and maintenance (O&M) costs, however, is lost if the reactor still has to be shut down on an 18- to 24-month interval for routine maintenance and inspection. Thus, first and foremost, the IRIS primary system components are designed to have very high reliability to decrease the incidence of equipment failures and reduce the frequency of required inspections or repairs. Next, IRIS has been designed to extend the need for scheduled maintenance outages to at least 48 months. The basis of the design has been a study performed earlier by MIT for an operating PWR to identify required actions for extending the maintenance period from 18 months to 48 months. The strategy was either to extend the maintenance/testing items to 48 months or to perform maintenance/testing online. MIT identified 3743 maintenance items, 2537 of them offline and the remaining 1206 online. It was also confirmed that 1858 of the offline items could be extended from 18 months to 48 months, while 625 could be recategorized from offline to online. Further, out of the 1858 items, there were 1499 that were electrical surveillances, and had a strong potential for also being performed online. This left only 54 items that still needed to be performed offline on a schedule shorter than 48 months. Starting from this MIT study and factoring in the specific IRIS conditions (for example, there is no need to change the RCP oil lubricant, since the spool-type pumps are lubricated by the reactor coolant), only seven items were left as obstacles to a 48-month cycle. Most of them are being resolved, under the direction of the Tennessee Valley Authority, an IRIS partner.

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

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

Safety-by-design approach

The current LWRs (identified by the DOE as Generation II reactors) cope and interfere with accident sequences through active means to assure that the consequences of the accident remain within specified acceptable limits. Advanced reactors now being considered for deployment (or Generation III and III+), like AP600/AP1000, adopt the same philosophy, but accomplish it with passive means to the maximum extent possible. The Generation IV reactors are supposed to demonstrate enhanced safety with respect to the passive designs. IRIS is not a Generation IV design since it will be available for deployment decades ahead of the 2020 to 2030 time frame projected for the six selected Generation IV systems. IRIS, however, has been the first to formulate and implement the philosophy that next-generation systems should leverage their design and operational characteristics to prevent accidents to the highest extent possible. This “safety-by-design” approach, which is gaining wide acceptance, is simply eliminating by design the possibility for an accident to occur. If it is not possible to eliminate the accident altogether, then the design should be such that it inherently reduces the accident’s consequences and/or decreases its probability of occurrence, without resorting to intervention of active or passive means. This approach is, of course, nothing more than good engineering; the key difference from past practice, however, is that the integral reactor design is intrinsically 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 obvious 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 the elimination of accident-initiating events. IRIS has striven to achieve that, and its implementation of the safety-by-design approach is summarized in Table VI, which shows that all the accidents are positively affected (either eliminated or consequences/probabilities reduced) by the IRIS design, except one: the feed line break in the once-through steam generator. The IRIS design, however, even in this case, amply compensates for the limited heat sink provided by the steam generators through the large thermal inertia in the primary system and the large steam volume in the pressurizer. Both the water inventory on a coolant-per-MWt basis and the steam volume-to-power ratio are more than five times larger in IRIS than in advanced passive PWRs.

TABLE VI. IMPLICATIONS OF SAFETY-BY-DESIGN APPROACH

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

The most telling consequences of the IRIS safety-by-design are shown in Table VII: Of the eight class IV accidents that must be considered in PWRs, only one remains unaffected in IRIS. All the others are either eliminated outright or are downgraded to a lower classification. This has very important implications on the IRIS approach to licensing as it will be seen later.

An example of the innovative thinking behind the IRIS safety-by-design approach is given by the handling of small-break LOCAs, which historically have been most plaguing to PWRs. The IRIS approach is to limit and eventually stop the loss of coolant from the vessel rather than to rely 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 large coolant inventory in the reactor vessel.
2. An emergency heat removal system (EHRS) employing the steam generators to remove 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 (see Fig. 9), which during the accident becomes thermodynamically coupled with the vessel and assists in limiting the blowdown from the

TABLE VII. IRIS RESPONSE TO PWR CLASS IV EVENTS

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

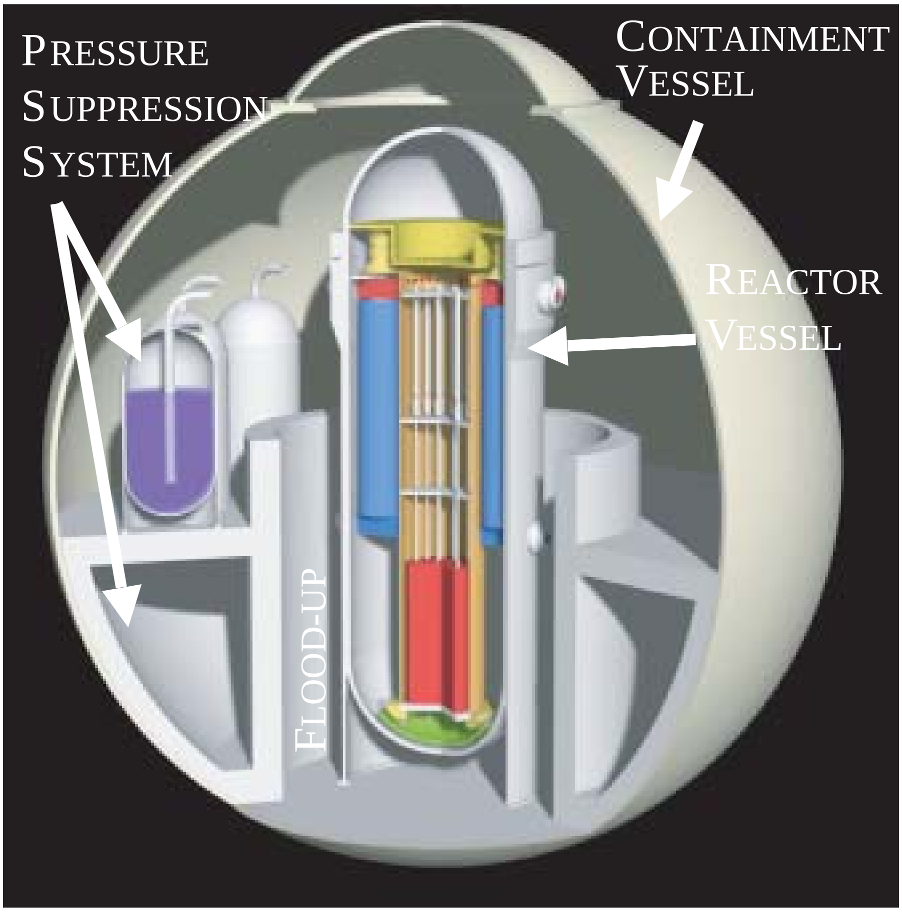

Fig. 9. IRIS containment

RV by rapidly equalizing the vessel and containment pressures. The IRIS small spherical containment has a design pressure more than three times the value typical of loop PWR containments, at the same shell thickness.

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 EHRS is actuated to depressurize the primary system by condensing steam on the steam generators (depressurization without loss of mass); and, finally, a small automatic depressurization system (ADS) is actuated to assist the EHRS in depressurizing the RV. A higher back pressure is allowed because of the higher containment design pressure. The pressure suppression system assures that the containment pressure remains safely below the design pressure. At the end of the blowdown phase, the RV and CV pressures become equal with a CV pressure peak less than 7 bar$_g$, and the break flow stops.

The coupled RV/CV system is then depressurized 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, and coolant actually enters back into the vessel (what jokingly has been referred to as temporarily transforming a LOCA into a GOCA—gain-of-coolant accident). The CV pressure is reduced as steam from the containment is condensed inside the pressure vessel, and consequently a portion of the 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 (RV and CV pressure reduced to less than 2 bar$_g$ in less than 12 hours), during which the gravity makeup of borated water from both the suppression pool and the 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 is in fact determined only by the containment heat loss.

> **The IRIS defense in depth, which is based on its safety-by-design approach, is so strong that the project believes that some of the current licensing requirements can be safely relaxed.**

Pre-application licensing

On October 3, 2002, the IRIS project had its first official pre-application licensing meeting with the NRC, quite an accomplishment for a program barely three years old. Since Westinghouse currently has the AP1000 going through its design certification phase, it was decided that IRIS will initiate formal design certification (DC) licensing once the AP1000 is finished, which is expected to occur in the 2005 time frame. In the meantime, IRIS is taking advantage of the NRC pre-application licensing process by undergoing a review focused on long-lead and novel items. The first item being addressed is a review of the IRIS testing program. No prototype is needed for design certification since IRIS does not represent a new technology, only new engineering. At the same time, the new engineering must be proven by appropriate tests, both of the individual and integrated effects type, to confirm the design and analytical predictions of novel IRIS items such as the integral components and safety by design. Design documents, such as plant design description, safety analyses (including RELAP model and prediction of the accident sequences), Phenomena Identification and Ranking Table (PIRT), scaling analyses, and proposed test program are being submitted to the NRC. Following the NRC review and comments on the IRIS proposed test program, actual testing will commence. Thus, testing of the IRIS novel features will be in progress by the start of the design certification. It will complement the completed AP600 test program, where common phenomena applicable to IRIS have already been demonstrated.

The IRIS defense in depth, which is based on its safety-by-design approach, is so strong that the project believes that some of the current licensing requirements can be safely relaxed. As shown in Table VII and discussed before, out of eight Class IV accidents of loop PWRs (the accidents that are responsible for a potential radioactive release), only one remains for IRIS. Because both the probability of occurrence and the consequences are much reduced for those accidents not being eliminated outright through the safety-by-design approach, a probabilistic-based riskinformed assessment could demonstrate that IRIS has no need for an offsite emergency response. This will be the second subject addressed during the pre-application licensing.

The advantages of IRIS not requiring emergency response are many and very significant: a concrete argument for increased public acceptance; reduced burden on utilities; and the possibility to site IRIS closer to population centers.

TABLE VIII. IRIS SCHEDULE OBJECTIVES

Objective	Scheduled For
Assess key technical & economic feasibility (completed)	End 2000
Perform conceptual design, preliminary cost estimate (completed)	End 2001
Submit licensing pre-application (completed)	Fall 2002
Develop licensing plan (completed)	Fall 2002
Outline path to commercialization (completed)	Early 2003
Perform preliminary design (in progress)	End 2003
Complete SAR	2006-2008
Obtain design certification	2008-2010
First-of-a-kind deployment	2012-2015

Plant layout

An early market recognition of the IRIS potential has been the decision by the three utilities—Dominion, Entergy, and Exelon—to include the IRIS parameters in the site characterization of the early site permit (ESP) program. The preferred IRIS plant arrangement offered for the ESP envelope is two twin units with a total output of 1340 MWe (see Fig. 10). Also offered were combinations of multiple identical modules, which allow increasing the installed capacity in 335-MWe increments.

The twin units arrangement is aimed at maximizing shared components between the two modules that make up one twin unit, yet it has the ability to initiate operation of a completed twin unit while construction of subsequent twin(s) proceeds in a "slide-along" manner. This means that multiple units are started up in sequence as construction, preoperational testing, fuel load, and startup testing are all completed for a unit. The first completed unit will be operated while construction of the subsequent unit(s) is still in progress, by establishing a temporary exclusion zone between the operating unit(s) and the unit(s) under construction. This arrangement and construction sequencing is aimed at minimizing the construction time of a unit and at providing the utility with generating capability as soon as possible. Another advantage of the slide-along construction method is the shorter construction time required for the subsequent units because of the experience of the work force. Each twin unit is completely independent from the subsequent twin(s) and each reactor within a twin has its own turbine generator (T/G), condenser, and feed and steam systems, contained in a single T/G building with their own nonsafety service water and main circulating water mechanical draft cooling towers. Within a twin unit, however, many systems, functions, and physical facilities are shared, including control room, fuel handling area with refueling machine and spent fuel pit and cask loading facility, radwaste treatment, support systems, and switchyard. Within the twin unit, separate safety-grade power supplies, protection cabinets and switchgear, and electrical systems are maintained.

Schedule and economics

The current top-level project schedule is shown in Table VIII. This schedule is for the first-of-a-kind IRIS module, and a construction period of three years has been assumed.

The economics of small-to-medium power modular reactors is quite uncertain since a database does not exist and the conventional economy-of-scale approach does not apply. Modular reactors offer the economy of identical multiples, lower financing requirements, and more responsiveness to market needs. These arguments have been already elaborated by the gas modular reactors (PBMR and GT-MHR), and they apply to IRIS as well. IRIS also has a relatively larger power rating per module, a simple configuration, and a small footprint.

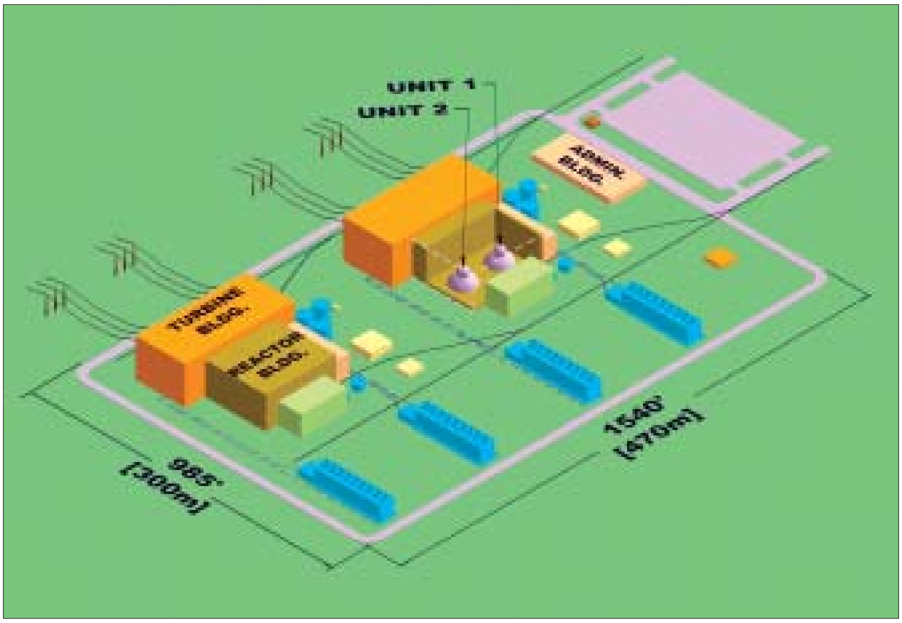

Fig. 10. IRIS two twin-unit plant layout arrangement

A top-down analysis was performed of the IRIS economics and market potential. The analysis started with an examination of global market projections for electricity demand out to 2030, segmented into eight key geographic regions of the world. A comprehensive financial modeling of reactor cash flows was used as the basis for comparing generation costs in $/MWh for IRIS and for conventional LWR designs. The analysis included a full sensitivity assessment of the key parameters in a high-level influence diagram, together with their supporting subset developed during financial modeling. A deterministic sensitivity analysis ranked all parameters in their order of importance, focusing attention on those vital to success. The final area of modeling completed a probabilistic analysis of the top 10 parameters (as identified by the deterministic sensitivity) to understand how changes in these parameters would affect overall net present value and generation costs.

The analysis indicated that market-clearing price construction costs and reactor power output are the key factors in driving value. While a commercially sized IRIS (335 MWe) is capable of competing in all world markets, much higher costs were evaluated for lower output (200–250-MWe) modules. The overnight capital cost of the Nth-of-a-kind unit was evaluated to be in the $1000–$1200/kWe range.

The analysis performed by BNFL/Westinghouse for IRIS employed the same procedures as for similar studies referring to PBMR and AP1000, and therefore is as reliable as a top-down analysis can be. While a bottom-up evaluation is currently being performed, up to this point, IRIS has given all indications that it is economically competitive with other nuclear and non-nuclear power generators, and is one of a few designs capable of global deployment.