Design of the Reactor Pressure Vessel and Internals of the IRIS Integrated Nuclear System

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Abstract - *IRIS (International Reactor Innovative and Secure) is a light water cooled, 1000 MWth power reactor which is being designed by an international consortium as part of the US DOE NERI Program. IRIS features an integral reactor vessel that contains all the major reactor coolant system components including the reactor fuel, the coolant pumps, the steam generators and the pressurizer. This integral design approach eliminates the large coolant loop piping, which eliminates large loss-of-coolant accidents (LOCAs) as well as the individual component pressure vessels and supports. In addition, IRIS is being designed with a long life core and has enhanced safety features to address the requirements defined by the US DOE for Generation IV reactors. The design of the integral reactor vessel (RV), the reactor vessel internals (RVI), and internally mounted reactor coolant pumps (RCPs) are a major design effort in the development of the integral IRIS concept. This paper will discuss the results of this design effort.*

I. INTRODUCTION

Today, partly due to the high capital costs of large power reactors, there is a move to develop smaller units. These may be built independently or as modules in a larger complex, with capacity added incrementally as required. The design objectives of IRIS are to provide greatly simplified nuclear plant design that meets or exceeds the latest regulatory requirements and safety goals, while still being economically competitive with fossil fuel power generation.

IRIS (International Reactor Innovative & Secure) is a new generation advanced light water reactor which addresses the Generation IV objectives of improved sustainability, safety and reliability, and economics. It is being developed by an international consortium led by Westinghouse/BNFL. The IRIS project, which was initiated at the end of 1999, has completed the conceptual design phase and is moving towards completion of the preliminary design, scheduled for the end of 2002.

Equipos Nucleares, S.A. (ENSA) has taken the responsibility to develop the design of the IRIS reactor vessel and reactor internals during the conceptual design phase. This paper describes the current configuration of both items, the key design uncertainties and the evaluations and considerations that support the current configuration.

II. REACTOR VESSEL

II.A. Description

The design of the IRIS reactor pressure vessel and internals is conceptually similar to the existing PWRs; it contains the pressurized primary coolant water and houses the reactor core and internals, and reactor control rods and drive lines and instrumentation. However, the IRIS vessel is longer and has a larger diameter than a typical PWR vessel in order to also house the eight (8) steam generators, eight (8) primary coolant pumps and pump diffusers, the pressurizer and radial shield plates. Figure 1 shows a longitudinal cross section view through the reactor pressure vessel.

As shown in Figure 1, the reactor vessel consists of a cylindrical shell made of several courses, a semispherically dished bottom head and a flanged and gasketed removable upper head. Stainless-steel cladding of 6 mm. minimum thickness covers the internal surface of the vessel. The reactor vessel size and configuration is dictated largely by the space required by the steam

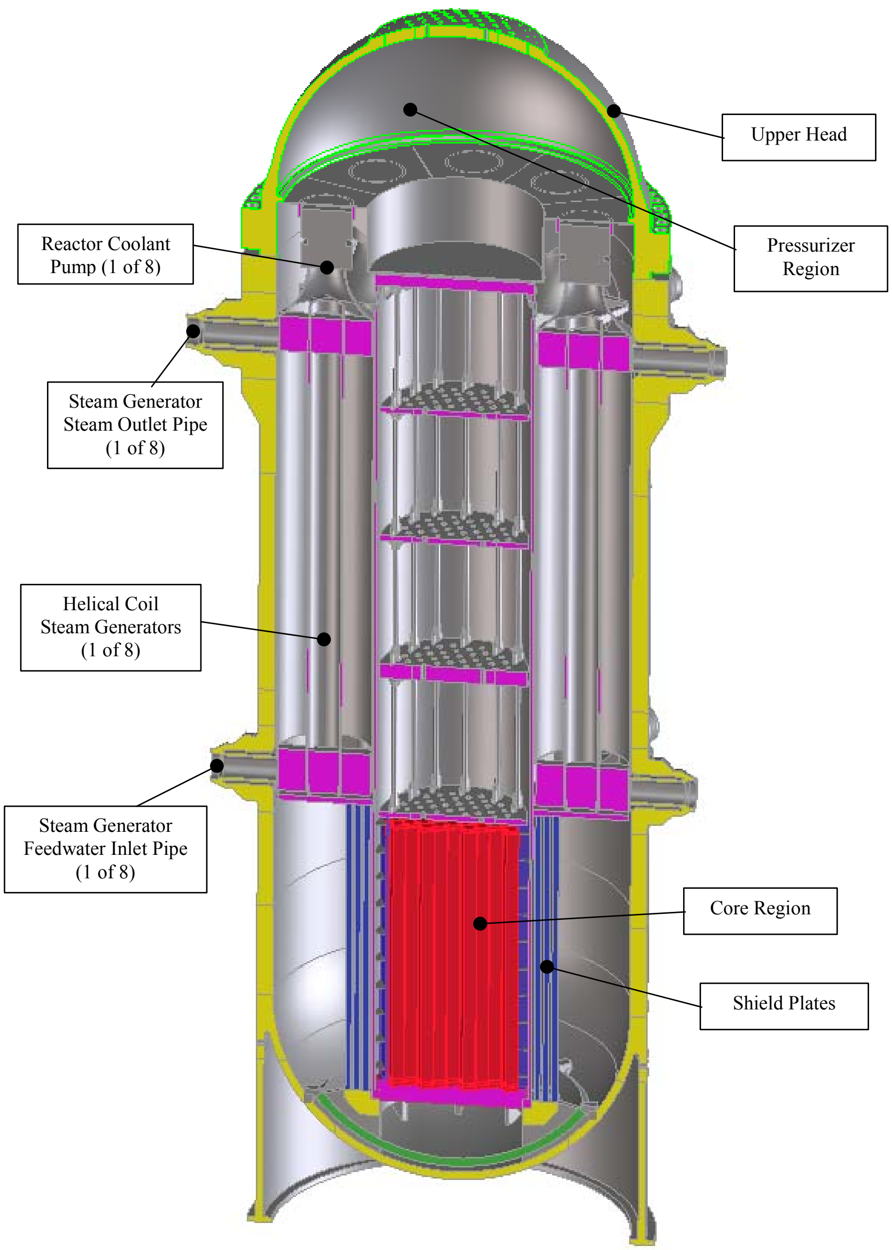

Figure 1 3D View of IRIS Reactor Pressure Vessel

Table 1 IRIS Reactor Vessel Parameters

Overall length of assembled vessel-closure head	23520 mm
Inside diameter of shell	6100 mm.
Nominal base metal thickness	280 mm.
Minimum cladding thickness	6 mm.
Design pressure	17.24 MPa (2500 psia)
Design temperature	343.3ºC (650ºF)
Vessel material	Carbon steel, SA 508, Gr.3, Cl.2
Cladding material	Stainless steel

generators and internally mounted reactor coolant pumps. The reactor vessel's design data is summarized in Table 1.

The removable upper head of the vessel contains a bolting flange with 72 8" studs and nuts. Hydraulic tensioning of the studs will permit uniform nut loading on the clusters. Two hollow, metallic O-rings form a pressure-tight seat in concentric grooves in the head flange. The closure head is penetrated by the control rod drive mechanisms (CRDMs), the pressurizer heater rods and other instrumentation mechanisms.

The reactor vessel cylindrical wall has 8 feedwater inlet nozzles located just above the core level and 8 steam outlet nozzles located below the vessel flange.

The reactor coolant is totally contained within the reactor vessel and is pumped in a closed circuit within the vessel (Fig. 1) with the exception of the makeup and purification systems. The coolant passes up through the core, turns radially outward at the top of the upper internals, flows up to the eight primary pumps, is pumped downward through the pumps and through the steam generators, passing over the tube bundle, down the annulus between the core barrel, shield plate assembly and inside reactor vessel wall, then upward through the core support assembly Steam generator feedwater passes through the feedwater nozzle into a feedwater header, enters the steam generator tubes and flows upward inside the tubes, first being heated to saturation then boiled, and then heated to dry superheated steam, which then flows into the upper steam discharge header and flows out through the steam outlet nozzles to the turbines.

The pressurizer in IRIS, Figure 2, is located in the reactor vessel upper head, and will be the subject of another presentation.

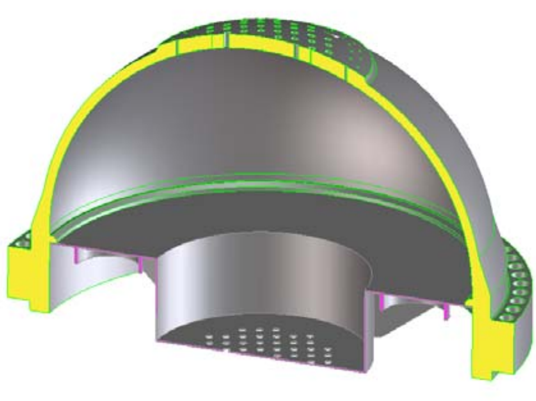

Figure 2 IRIS Pressurizer

Major challenges in the design of the reactor vessel of IRIS are the connections of the steam generators and recirculation pumps to the reactor vessel wall, both in terms of possible structural and resonance implications.

The reactor vessel and closure head are designed as a Class 1 vessel in accordance with the ASME Code, Section III. The design life for the reactor vessel is at least 60 years. In general, all attachments and pressure containing parts have full penetration welds.

II.B. Reactor Vessel Support

The reactor vessel shown in Figure 1 is supported vertically by means of a cylindrical skirt welded to a "Y" forging between the lower cylindrical shell and the semispherical lower shell. The possibility of using a conical skirt welded to the cylindrical shell between the steam generator inlet and outlet nozzles is being studied at this time, with the purpose of increasing the natural frequencies of the vessel and reducing the dynamic interaction of the different components. The support is designed to restrain lateral, vertical, and rotational movement of the reactor vessel and still allow for thermal growth.

The dynamic evaluation due to seismic effects is one of the most important considerations in the design of the reactor vessel supports and the internal supports. This input is currently not available; however, the natural frequency of the reactor vessel to identify possible resonant conditions due to known forcing frequencies has been determined for the lower and middle vessel skirt designs. Consequently, a dynamic analysis of the reactor vessel and the internals will be undertaken in order to determine the dynamic influence of the overall supporting scheme on the reactor and internals.

Another consideration in the design of the reactor vessel skirt is thermal stress due to the temperature gradient of the skirt at the attachment to the reactor vessel. Detailed thermal stress analysis of this area using finite-element techniques to determine primary plus secondary stresses of heatup and cooldown thermal transients will be accomplished. In addition, to provide good heat flow from the reactor vessel to the skirt a forged skirt attachment with full penetration welds and selective use of insulation in the crotch area will be used.

III. INTERNALS

The IRIS reactor vessel internals (RVI) are similar to current PWRs in that they support the core, core barrel, control rods, control rod drive lines and they also form the circulation path for the flow of coolant through the core. In IRIS, however, the RVIs provide the additional

The IRIS reactor vessel and internals are designed to permit the refueling operations to be conducted in the same manner as in the PWRs, providing access to the fuel assemblies after removal of the closure head and upper internals. Also, the support structures of the recirculation pumps and the steam generators are being designed to permit removal of these components for out-of-vessel inspection and replacement.

The reactor internals are shown in Figures 3 and 4. The components of the reactor internals are divided into two parts:

1) the lower core support structure (including the entire core barrel and thermal shields),
2) the upper core support assembly.

III.A. Lower Core Support Structure

The major restraining and support member of the reactor internals is the lower core support structure, shown in Figure 3. This support structure assembly

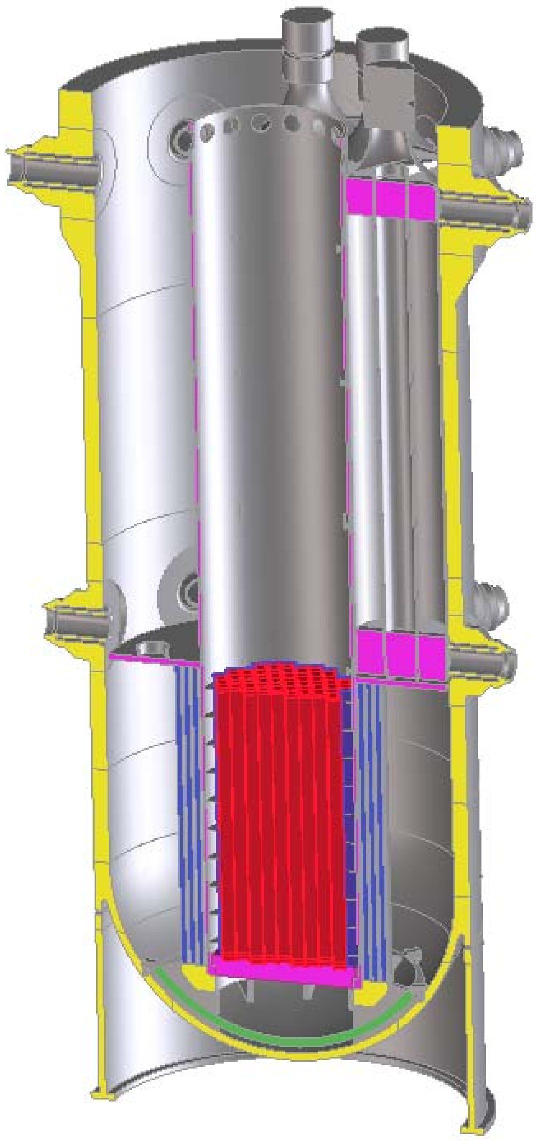

Figure 3 RPV and Lower Core Support Structure

functions of supporting the internally mounted steam generators, reactor coolant pumps and radial shield plates. In addition, the IRIS RVIs must provide support for the pressurizer heater rods, additional lateral support for the longer than normal control rod drive lines and provide an extended length upper core barrel to form the core flow path. The internals are designed to withstand the forces due to weight, preload of fuel assemblies, control rod dynamic loading, vibration and earthquake acceleration.

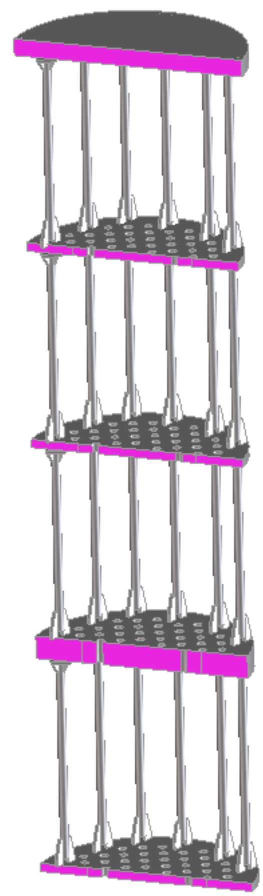

Figure 4 Upper Core Support Structure

consists mainly of the core barrel, the core baffle, the lower core plate, the thermal shield plates, the triangular shaped core support members which are welded to the bottom head, and the core support ring which also functions as neutron shielding for a portion of the lower head. Another intermediate shield plate will be placed below the lower core plate to complete the shielding of the vessel bottom head; it is supported by ledges welded to the bottom head. All the major components of this structure are supported at the bottom head; the lower end of the core barrel is restrained in its transverse movement by a bolted connection to the support ring which rests on the (triangular) support members. Within the core barrel are the axial baffles, which are attached to the core barrel wall and form the enclosure periphery of the assembled core. The lower core plate is positioned at the bottom level of the core below the baffle plates and provides support and orientation for the fuel assemblies. The lower core plate is perforated and contains the locating pins for the fuel assemblies.

The lower core support structure (principally the core barrel) also serves to define the passage-ways for the primary coolant flow through the core.

The cylindrical thermal shield plates are supported on horizontal ledges which are welded to the internal surface of the vessel and supported on the vertical members welded to the bottom head. This bottom support allows for differential axial growth of the shields with respect to the core barrel but restricts radial or horizontal movement of the bottom of the shields.

Vertically downward loads from weight, fuel assembly preload, control rod dynamic loading, and earthquake acceleration are carried out by the lower core plate partially through the support ring to the lower (triangular) support members and to the bottom head. Transverse loads from earthquake acceleration, coolant crossflow and vibration are carried by the core barrel shell to be shared by the horizontal ledges, support ring and the vessel shell. Transverse acceleration of the fuel assemblies is transmitted to the core barrel shell by direct connection of the lower core support plate to the barrel wall and by a radial support-type connection of the upper core plate to slab-sided pins pressed into the core barrel.

With this design, the internals are provided with a support at the furthest extremity, with the core barrel bolted to the column supports, and may be viewed as a beam simply supported at the bottom.

Radial and axial expansions of the core barrel are accommodated, but transverse movement of the core barrel is restricted by this design, keeping cyclic stresses in the internal structures within the ASME Section III limits, which essentially eliminates any possibility of failure of the core support.

III.B. Upper Core Support Assembly

The upper core support assembly, Figure 4, consists of the upper support plate, upper core plate, support columns, middle support plates and guide tube assemblies (not shown). The support columns establish the spacing between the upper support plate, middle support plates and the upper core plate and are fastened at top and bottom to these plates; the support columns transmit the mechanical loadings between the two plates and serve the supplementary function of supporting in-core and ex-core instrumentation conduits. The guide tube assemblies sheath and guide the control rod drive shafts and control rods, but provide no other mechanical functions; they are fastened to the lower middle support plate and are guided by pins in the upper core plate for proper orientation and support.

The main radial support system between the core barrel and the upper internals is accomplished by key and keyway joints. At equally spaced points around the circumference and coinciding with the level of each support plate, Inconel blocks are welded to the inside diameter of the core barrel. Each of these blocks has a keyway geometry; opposite each of these is a key which is attached to the internals. At assembly, as the internals are lowered into the vessel, the keys engage the keyways in the axial direction.

The upper core support assembly, which is removed as a unit during refueling operations, is positioned in its proper orientation with respect to the lower support structure by flatsided pins pressed into the core barrel which in turn engage in slots in the upper core plate. Slots are milled into the core plate at the same positions. As the upper support structure is lowered into the main internals, the slots in the plate engage the flat-sided pins in the axial direction. Lateral displacement of the plate and of the upper support assembly is restricted by this design. Fuel assembly locating pins protrude from the bottom of the upper core plate and engage the fuel assemblies as the upper assembly is lowered into place. Proper alignment of the lower core support structure, the upper core support assembly, the fuel assemblies, and control rods is thereby assured by this system of locating pins and guidance arrangement.

IV. MATERIALS AND CONSTRUCTION

Large integral type forgings for the construction of big primary components for nuclear power plants have been used from the standpoint of reducing the manufacturing period and in-service inspection.

Figure 5 shows a possible course layout for the reactor vessel design. With the application of the integral type forgings shown, the weld seams are extensively reduced and the following considerations are highlighted:

1. The use of integral type steel forgings for the fabrication of the IRIS reactor vessel enhances the structural integrity and makes easier fabrication and inspection, including ISI.

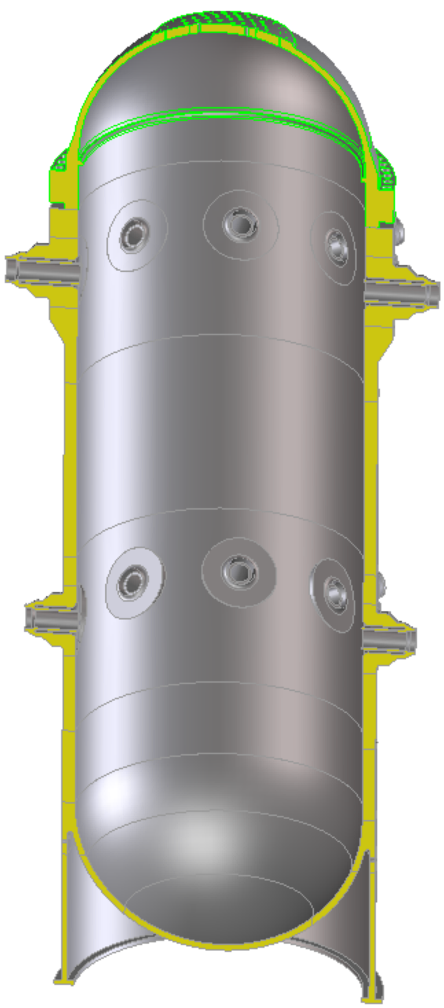

Figure 5 Layout of IRIS Vessel Courses

2. In order to decrease the overall weight, the high strength SA 508, Gr.3, Cl.2 is recommended for the reactor pressure vessel shell, flanges, and upper and lower heads. The resulting decrease in weight is beneficial from the standpoint of reducing loads resulting from earthquake. This material is used because of its strength properties, availability in the required sizes and thickness, satisfactory service in a neutron and gamma field, and the capability of producing high quality welds. The material is also compatible with the weld overlay cladding of stainless steel.
3. The present state-of-the-art of manufacturing technology makes possible the reliable fabrication of such pieces.

All surfaces of the reactor vessel in contact with reactor coolant are either clad with, or made from 300 series stainless steel and Inconel 690. Based on tensile and impact properties, Type SA 540, Class 3 is selected for closure studs, nuts, and washers.

The vessel shell material is protected from fast neutron flux and gamma heating effects by the assembly of shield plates made of stainless steel and located between the reactor core and the vessel wall. Studies are under way to identify the extent of shielding required.

A key design uncertainty deals with the adequacy of materials and suitable construction techniques. It is important to point out the challenges rising from the manipulation, construction and inspection of components of very large internal diameter and wall thickness; consequently, appropriate and safe fabrication procedures have to be carefully studied and implemented during the manufacturing stage. The transportation and installation of such a large and heavy piece of equipment to future sites might become an important concern.

V. CONCLUSIONS

This paper has presented the actual configurations of the IRIS reactor pressure vessel and internals. Although mainly existing and proven technology has been used in this design stage of the reactor vessel and internals for IRIS, the plant construction strategies incorporate changes that directly meet the challenge of shortening construction time. The first benefit of these designs, and probably the most obvious, is the large reduction of bulk quantities and components used in the plant design resulting from this integral reactor system configuration. Because there are no external cooling loops, steam generators, pressurizer or pumps, the containment building housing the reactor coolant system can be significantly reduced in diameter. This allows higher design pressures to be achieved with the same thickness containment shell, which can be translated to a reduction in the required containment volume. Fewer quantities and components mean less installation time with the obvious corollary that if there is less to install, there will be fewer installation mistakes and associated rework.

A second key to shortened construction schedules is the high level of modularization incorporated in the design of IRIS. This modularization is obvious in the use of multiple, small reactor components such as the steam generators and pumps, but also applies to the construction of multiple, smaller plants at a site rather than a large single unit. This can result in shortened construction times per unit, taking advantage of site personnel learning curves, but also minimize the time in which a plant operator begins to realize a return on investment.

These reductions not only simplify the plant design, thereby reducing capital costs, but also reduce maintenance and operations testing and their associated costs.

This conceptual design effort has of course identified some key design uncertainties and identified evaluations required to support the selected IRIS system configuration. Also the design of some internals and internal supports are strongly dependent on the design of key components like the stem generators, reactor coolant pumps and pressurizer. These design uncertainties will be addressed in future stages of the project as the design of these components is finalized. These future research and development programs are being identified for the project to reduce these uncertainties to acceptable levels.

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