INTERNAL SHIELD DESIGN IN THE IRIS REACTOR AND ITS IMPLICATIONS ON MAINTENANCE AND D&D ACTIVITIES

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ABSTRACT

IRIS (International Reactor Innovative and Secure) is a medium-power (~1,000 MWt) advanced light water reactor that is being developed by an international consortium led by Westinghouse. IRIS features an integral primary system configuration to enhance its safety performance. An annular region surrounding the core accommodates steam generators in its upper portion (above the core) and forms a thick downcomer (~1.7 m) next to the core. Compared to loop PWRs where the downcomer is only ~20 cm thick, IRIS configuration provides a neutron fluence reduction at the pressure vessel by several orders of magnitude. Additional internal shields consisting of steel plates may be placed in the downcomer region and in the lower plenum to provide further shielding and dose reduction at the pressure vessel outside surface. Transport theory (Monte Carlo and discrete ordinates) numerical simulations were performed to evaluate several alternatives of the internal shield design. The fast neutron fluence at the pressure vessel is sufficiently low that the pressure vessel surveillance program will not be required. The neutron and gamma dose (while the reactor is operating) are cut down to levels that may allow elimination of the external biological shield, whereas the reduced vessel activation lowers the cost and minimizes the personnel dose during the maintenance and D&D activities. This paper presents results of the analyses performed so far and describes studies currently under way.

1 INTRODUCTION

IRIS (International Reactor Innovative and Secure) is a modular light water reactor (LWR) of small-to-medium power (100-335 MWe/module). It is being developed by an international consortium which currently includes 18 organizations from eight countries. IRIS concept was developed under the DOE Nuclear Energy Research Initiative (NERI) for Generation IV reactors [Refs. 1, 2, 3]. Key requirements for Generation IV reactors include:

1. Proliferation resistance. In IRIS this was quantitatively translated in minimizing access to the fuel by the host country through a long life straight burn core without shuffling or refueling.
2. Improved economics. In IRIS the unfavorable economy of scale will be counterbalanced by substantial process simplification and mass production of the components.

3. Enhanced safety. IRIS approach is "safety by design", where by design most accidents either cannot occur or will not have serious consequences.

4. Waste reduction.

As it will be subsequently demonstrated, the internal shielding implemented in IRIS contributes to achieving several of these objectives. Namely, internal shielding leads to reduced dose which improves safety, to reduced activation which reduces waste, and to simplified maintenance and D&D which improves the overall economics.

Details related to the IRIS design are provided in a companion paper [Ref. 4] and elsewhere [Refs. 1, 2, 3], while in this section we summarize design features of importance to the internal shielding design and implementation. IRIS has an integral vessel which houses the reactor core and support structures, core barrel, upper internals, control rod guides and drive lines, steam generators, pressurizer located in the upper head, reactor coolant pumps and the biological shields (see Fig. 1). Such an arrangement eliminates separate steam generators and pressurizer, connecting pipes, and supports. The vessel has a height of ~22 m and an outside diameter of ~6.7 m, a size which is still within the state-of-the-art fabrication capabilities. Hot coolant rising from the reactor core to the top of the vessel is being pumped into the steam generator annulus by eight pumps.

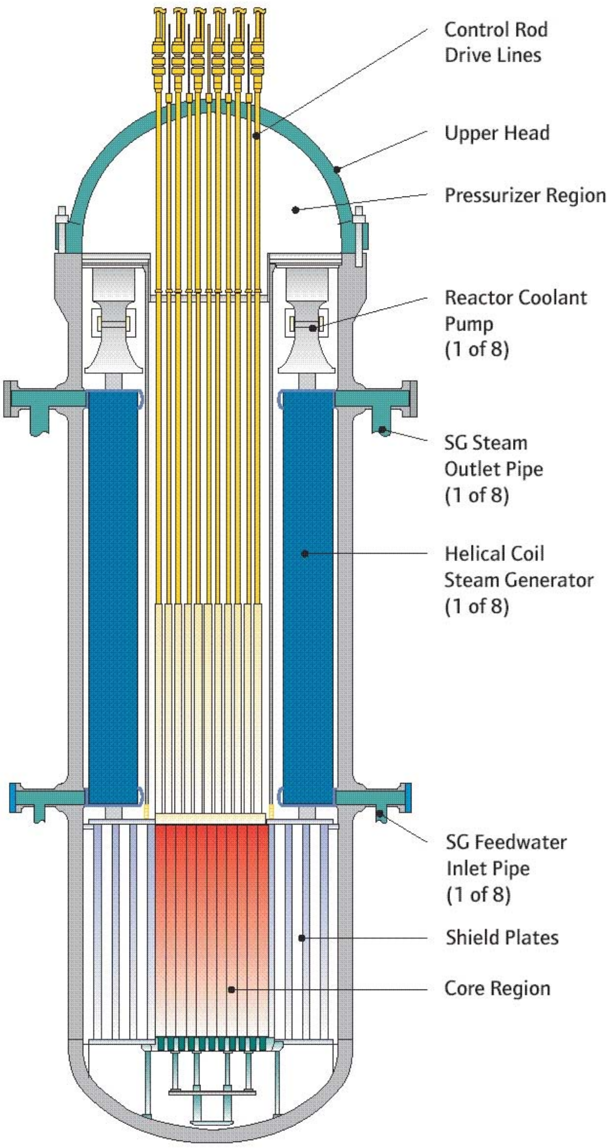


Figure 1. IRIS integral vessel layout

In the following sections we discuss the reasons for adopting internal shields, the pertinent simulations and the obtained results.

2 A DESIGN FEATURE: WIDE DOWNCOMER AND INTERNAL SHIELDS

As a consequence of the adoption of internal steam generators, it was necessary to design a vessel with a large diameter, at least in the part above the core. The vessel section corresponding to the core and lower plenum (approximately the lower quarter of the total height) could in principle have a reduced diameter. However, that wold require a transition region (with thicker vessel sides) and a more complex construction, that would largely offset the benefit. It was judged that a better solution is instead to maintain the same diameter over the whole height; and utilize the very wide downcomer for radiation attenuation. Since in the 1,000 MWt IRIS design the downcomer is 1.68 m thick, even the coolant (water) of such thickness with no extra shielding will reduce the fast neutron fluence by several orders of magnitude as compared to present loop-type PWRs. Such fluence reduction should eliminate concerns related to irradiation effects in RPV, moreover, with additional internal shielding, more ambitious objectives may become possible.

In this respects, possible targets include:

1) Eliminating the need for RPV surveillance program (required in present PWRs).
2) Providing sufficient gamma shielding to limit the dose outside the vessel from activated internals (barrel, lower support plate) to make it easier and more economical to perform:
    a) periodic in-service inspections (in temporary/periodic shut-down condition),
    b) decommissioning and disposal operations (after the permanent shut-down).
3) Keeping cumulative activation of materials outside the vessel (particularly the concrete of the cavity) below the regulatory clearance level, and limiting the activation of the vessel itself.
4) Eliminating the need for an external biological shield (while the reactor is operating).

The first target is the easiest one to meet, while the last one is the most demanding. Satisfying target 4) would likely also satisfy targets 2) and 3), since it requires that the dose level outside the vessel remains below exposure limits even during normal operation. The first target may be met in IRIS by default, i.e., with no special actions except for the wide downcomer. Achieving more demanding targets may require implementing additional internal shielding, e.g.. in the form of additional cylindrical steel plates located between the core barrel and pressure vessel (as depicted in Fig. 1).

3 PRELIMINARY 1-D FEASIBILITY STUDIES

Preliminary analyses were performed during the year 2001 at Politecnico di Milano (PoliMi), Milan, Italy, to assess potential benefits and limitations of the internal shielding. Focus was put on the lateral (i.e., radial) shielding. Radiation streaming downwards is inherently shielded by the concrete of the basement, hence, it was not considered in these initial studies. This approach has practical advantage that simulations can be performed in 1-D geometry.

Models were developed representing the core and reactor components as cylinders of infinite height employing a Monte Carlo code, MCNP [Ref. 5]. To validate MCNP models and results, analysis was also performed at Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, USA, using a deterministic 1-D code, ANISN [Ref. 6]. Both codes were applied to find the dose external to the vessel, for various shields. The relative standard deviation of MCNP simulations was below 10% in all cases, which was deemed sufficient for the purpose. The comparison between MCNP and ANISN results is satisfactory; differences are within 10%-30%.

The flux impinging on the vessel is many orders of magnitude lower than in standard PWRs. The fast neutron fluence (E>1 MeV) at the vessel inner surface at the end of lifetime, even without any internal shielding, is estimated to be $\ll 1\times10^{17}$ n/cm^2 (at least two orders of magnitude lower). For comparison, fluence can approach the regulatory limit of 2×10^{19} n/cm^2 in present loop PWRs. At the low IRIS fluence level , there is absolutely no irradiation damage (embrittlement) to be expected. In fact, 10 CFR App. H which defines requirements for Reactor Vessel Material Surveillance Program, specifies that such a program is not necessary if the vessel fluence is conservatively estimated not to exceed $1x10^{17}$ n/cm^2. Hence, target 1) is achieved, and a substantial O&M saving will result from eliminating the need for surveillance program.

A series of calculations was performed for several internal shielding configurations implementing different amount and placement of shield plates. Results of these 1-D calculations are summarized in Table 1. The first case represents a configuration with the thick IRIS downcomer, but no extra internal shielding, i.e., downcomer is 100% coolant, as a reference starting point. Case 2 represents the downcomer as a homogeneous mixture of 30% low-carbon steel and 70% water. (Note that in practical implementation, low-carbon steel will probably be clad with stainless steel.) The homogenized case is an acceptable approximation (for preliminary evaluations), as demonstrated by comparing this result to Case 3, a more realistic representation of individual shield plates, that produces results within ~10% of the homogeneous case. Case 4 optimizes the distribution of the steel shielding, by placing thicker plates next to the core. Case 5 further increases the steel content, from 30% to 33%.

Comparing Cases 2 and 3 vs. Case 1, we observe that a dose reduction of ~2,000 times may be achieved by introducing internal steel shielding, equivalent to ~30% by volume. Additional reduction may be obtained by optimizing its distribution (Case 4 vs. Case 3), or further increasing steel content (Case 5 vs. Case 4), but these changes lead to much more limited effects, within a factor of 2 or so. This means that a generic internal shield design may be assumed in current evaluations, and refinements and a detailed design may be carried out later.

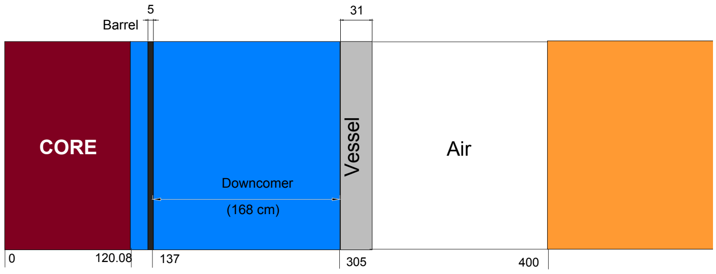
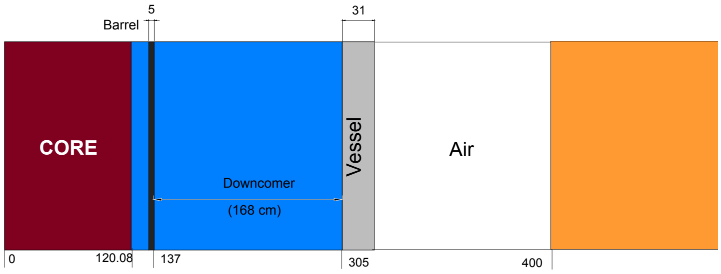
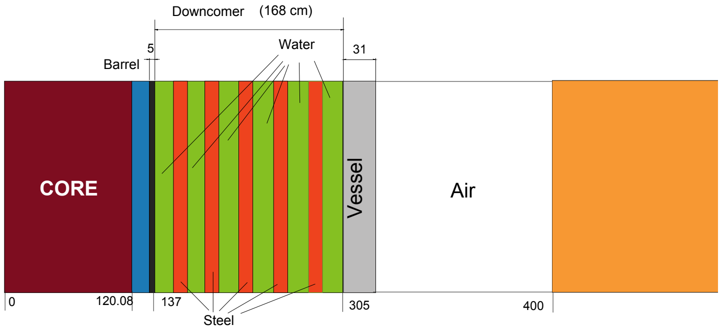
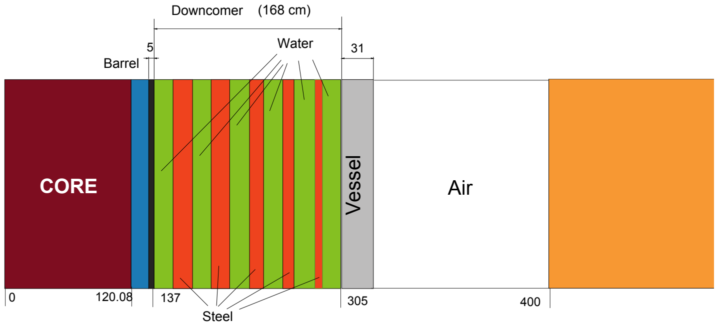
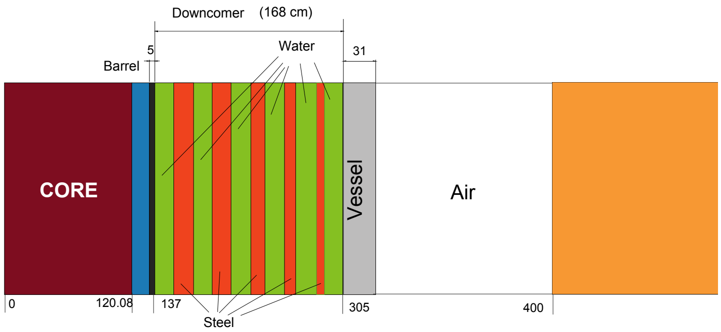
Looking at the absolute dose values, we may conclude that an internal shielding able to satisfy target 4 (elimination of biological shield) is feasible. In fact, our evaluation is conservative, since the reactor cavity (and whole containment building) will have an inert atmosphere and thus will not be accessible during operation. Moreover, concrete cavity walls will be present in any case and provide further shielding. However, a large amount of steel is necessary to achieve target 4, and the joint fulfillment of targets 2 and 3 may represent the basic desirable design feature of the internal shielding. Regarding the target 2, it is clear that target 2b is less demanding than 2a, because in this case the cooling time may be extended to several years (or more) after the shut-down, and before the final D&D operations start.

During the year 2002, further studies were performed to evaluate the second and third target. These studies were more detailed and carried out in 2-D (r,z) geometry. Some of the uncertainties and issues still remaining with these analyses include:

- Material selection for all IRIS internals and external components has not been finalized, therefore, the content of cobalt and other impurities e.g. in carbon and stainless steel is not completely defined.
- It has not been fully specified yet how long the inspections will last, what operations will be done during decommissioning and disposal, and then which are the acceptable levels of dose rates and material activation.
- The computational procedures to determine doses due to activated materials are complex, lengthy, and not yet fully implemented in an automated manner.

In the following sections, the studies performed during the year 2002 are reported. These studies were again performed in parallel by PoliMi and ORNL. Working in parallel and independently has the advantage of reducing the total required time and permits a validation of the results, as it was done in the 1D analysis. However, in some cases the results were not directly comparable, mainly due to the fact that IRIS project has evolved rapidly in that period. In particular, the design of many components relevant to shielding and the shields themselves were significantly affected (modified), and different IRIS geometry was sometimes assumed. Despite of these inconsistencies, comparison of results of these studies remained within an acceptable range of differences.

Table 1. Dose on lateral vessel surface; 1D calculations

Sketch	Case	Description	Dose µSv / h
	1	100% water (for comparison)	MCNP: 390,000 ANISN: 291,000
	2	Homogeneous mixture of steel and water (30% - 70% vol) (valid approximation)	MCNP: 190 ANISN: --
	3	Heterogeneous (30% - 70%), constant steel plates thickness (realistic)	MCNP: 175 ANISN: 160
	4	Heterogeneous (30% - 70%), decreasing steel plates thickness (realistic, more efficient)	MCNP: 145 ANISN: 127
	5	Heterogeneous (33% - 67%), decreasing steel plates thickness (realistic, heavier shield)	MCNP: 95 ANISN: 86

4 INTERNAL SHIELDS: DORT 2D STUDY (ORNL)

The assumed reactor design is the same as that depicted in Fig. 1. Beyond the vessel, the vault and the thick concrete of the cavity were described as well. The analyses were performed in 2D geometry, by the DORT computer program [Ref. 7] with BUGLE-96 cross section library [Ref. 8], in S_{12}-P_3 approximation. The resulting neutron and gamma dose distributions are shown in Fig. 2. The lateral dose level is higher (about double) than the one resulting from 1D analysis, due to the radiation streaming above and below the lateral steel plates. It is also evident that the bottom part of the vessel is much less shielded than the lateral one. However, this is largely due to the assumed simplified shield configuration, whereas the actual design will provide improved shielding in critical directions as well.

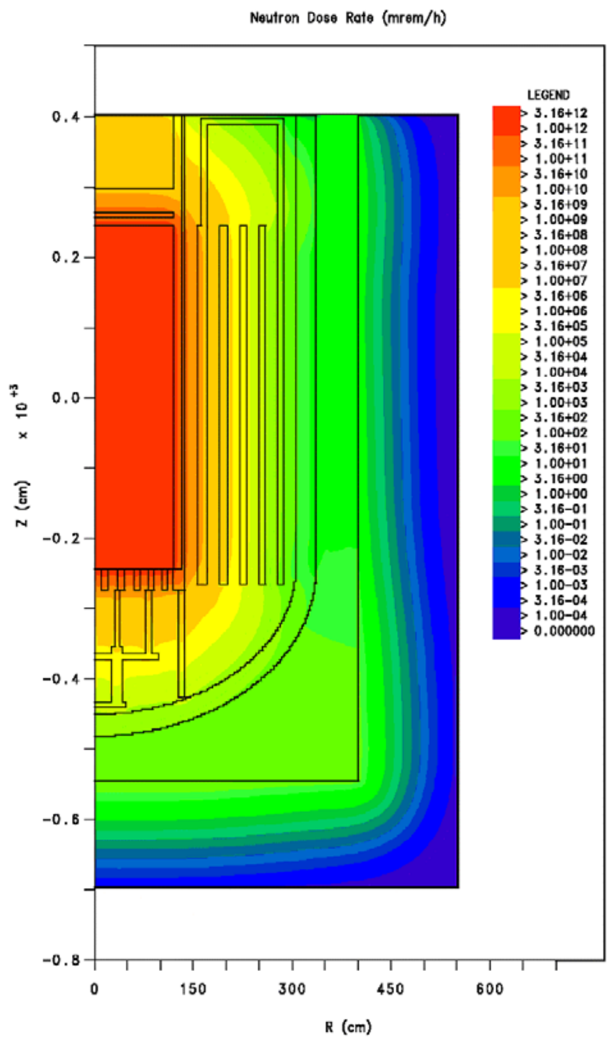


Figure 2.a Neutron dose rate in operation

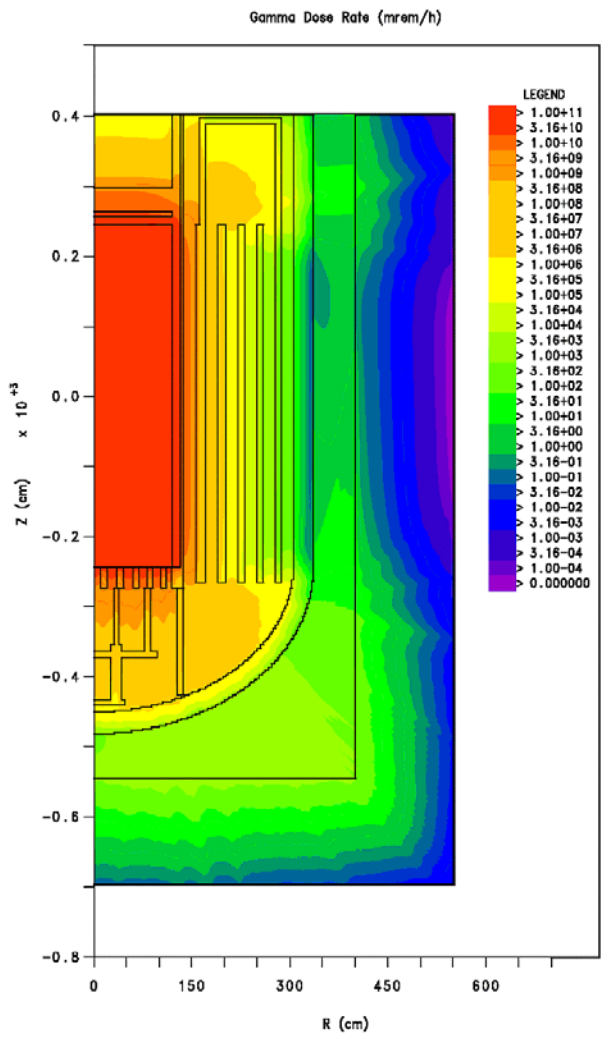


Figure 2.b Gamma dose rate in operation

The evaluation of the dose rate in the cavity due to the activated steel of the vessel and of the internal shields is a lengthy procedure which involves:

- Getting cross sections for 12 basic nuclear reaction rates (in carbon steel) from MCNP and group-averaging into BUGLE structure, then placing in a post-processor code (ACTIVATE).
- For each mesh interval made by carbon steel (5077 in vessel and 4733 in shield plates) the post-processor will:
  - read the 47-group fluxes from DORT flux file, fold with cross sections, do irradiation / decay analysis (T_{irr}=30 yrs, T_{decay}=7 days), and compute decay gamma source terms

  - write out source terms for each mesh interval in a DORT-ready format to be used by next DORT calculation.
- DORT then performs a follow-up radiation transport calculation to obtain resulting dose rates.

One limitation of the present implementation of interface codes is that they are set up to evaluate steel activation only for carbon steel; however, the extension to stainless steel will be made in the future.

If only the vessel activation is considered, the dose rate is ~0.12 μSv/h. This value rises to ~0.26 μSv/h and to 40.5 μSv/h, respectively, in the lateral and bottom region of the cavity, if the internal shield plates are left inside the vessel.

The lateral vessel activation, evaluated at the internal vessel surface, is about 2 orders of magnitude lower than the U.S. regulatory limit for waste disposal, which is assumed to be 18.5 Bq/g, as reported in 10 CFR, Part 30.70. Even the peak value of the vessel activation (~12 Bq/g), located at the internal surface of the bottom part, is within that limit. Keeping the whole RPV below the regulatory limit for waste disposal should lead to significant savings in the total D&D cost.

However, there are several further issues to be addressed. E.g., regulatory limits on all nuclides should be checked. Also, a limit on the total activity may be imposed by regulations, in addition to specific activity per weight. Finally, plate-out source term may become the limiting factor and needs to be evaluated.

5 INTERNAL SHIELDS: MCNP 2D STUDY (POLIMI)

IRIS design was modified during March 2002. It was decided to enlarge the region between the core baffle and the barrel by 5 cm, and to introduce in this volume a high fraction of steel, which is an efficient neutron reflector (improves fuel economy) and a good shielding material. The vessel diameter was increased accordingly, and its bottom part is now hemispherical, adjacent to the support skirt. The main consequence of these changes is that the vessel, particularly in the bottom part, is more shielded than in previous designs. Both lateral and lower internal shields were designed, having in mind the following requirements:

- Exclude any possibility, even hypothetical, of coolant flow blockage, e.g. as the result of the collapse of some component inside the vessel.
- Obtain a rather homogeneous distribution of activated materials outside the vessel, namely of the cavity's stainless steel liner.

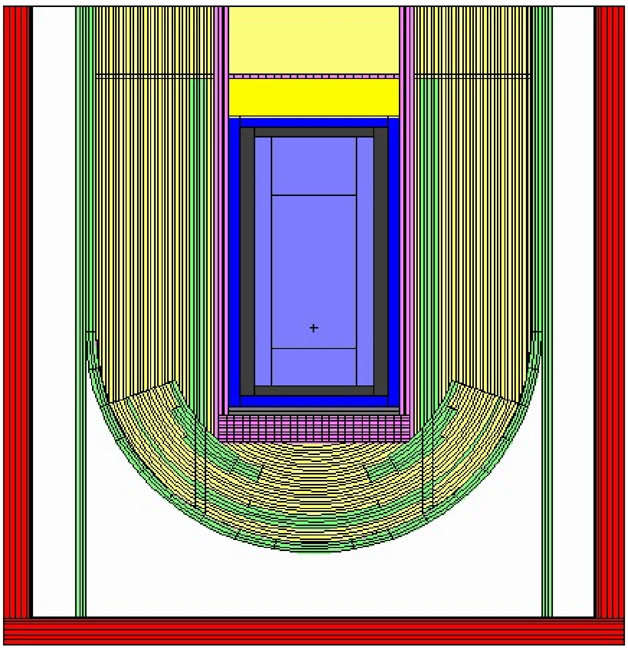


Figure 3.a The input geometry for MCNP runs

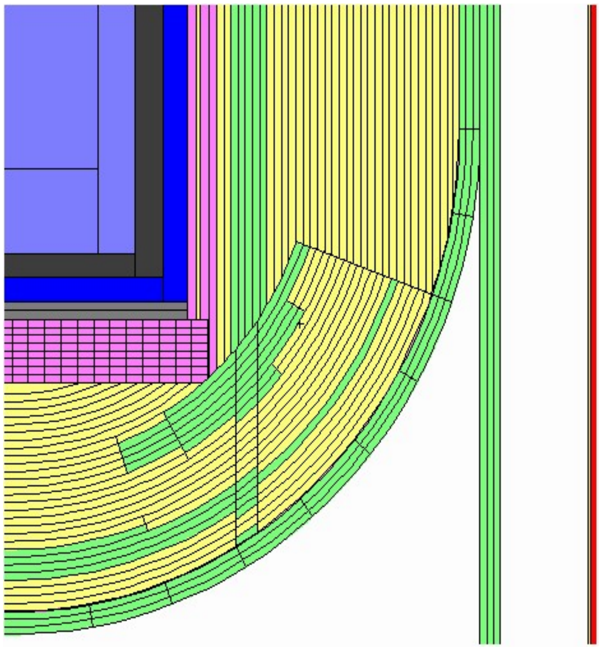


Figure 3.b A detail of the geometry

Simulations were performed with the code MCNP-4C. To maintain the computing time of Monte Carlo runs within reasonable levels, i.e. about half a day on an up-to-date PC, many simplifications were adopted:

- Only neutron mode, no photons.
- Only the core periphery emitted neutrons: the source was described as a 15—17 cm thick layer of the lateral, upper and lower core periphery.
- Neutrons below 1 eV were terminated, from the source and up to 10—15 cm from the internal vessel surface.
- The lateral steel shield was collapsed in a single very thick plate, while the effective shape will more likely have a "sandwich" structure of steel and water layers.
- In addition, cells had to be suitably shaped, to allow an efficient cell weight definition.

The shielding study, performed with a trial-and-error procedure, ended with the definition of a conceptual shield design, which is shown in Figure 3. The lateral shielding, which is now greatly reduced from the previous design, was extended and made thicker downwards, to suitably shield the part close to the skirt of the hemispherical bottom vessel, while an additional spherical plate was implemented to provide adequate shielding of the lower head.

To assess activation of materials, the following material composition was assumed:

- For the stainless steel liner, the main activated isotope is ^{60}Co, and its parent nuclide has a concentration of 200 ppm by weight.
- For concrete, the main activated isotopes are ^{152}Eu and ^{60}Co, and the parent nuclides (^{151}Eu and ^{nat}Co=^{59}Co) are present with a concentration of ~1-8 ppm and ~10 ppm, respectively [Refs. 9 and 10].

The regulatory clearance level varies from country to country, and the set of applicable regulations may change depending on circumstances. However a value in the range 0.1—1 Bq/g can be assumed to represent reasonably well the threshold value.

Table 2 summarizes the results of the runs with and without internal shields (steel plates between barrel, lower support grid and vessel, lesser thickness than in previous studies), and with two different assumed Eu concentrations. The most activated material is the liner, always in the clearance range, while concrete activation is much lower.

Table 2. Summary table of activation outside vessel

Max neutron flux on outer vessel surface	n cm^{-2} s^{-1}	Where
With shields	2,000	Bottom, 70°— 80° (close to skirt)
Without shields	70,000	bottom, 50°— 60°
Max activation of liner, Co 200 ppm	Bq g^{-1}	Where
With shields	0.02	lateral, core midplane
Without shields	0.6	bottom, close to skirt
Max activation of concrete, ^{151}Eu 8 ppm	Bq g^{-1}	Where
With shields	0.008	Bottom, flat distribution
without shields	0.3	bottom, close to skirt
Max activation of concrete, ^{151}Eu 1 ppm	Bq g^{-1}	Where
with shields	0.001	bottom, flat distribution
without shields	0.04	bottom, close to skirt

6 CONCLUSIONS

The integral IRIS primary circuit provides a wide downcomer. The thick layer of water which extends from the core barrel and lower support grid to lateral and bottom vessel reduces by many orders of magnitude the intensity of the radiation streaming from the core. This eliminates the need for RPV surveillance program and reduces O&M costs. Moreover, reduced vessel activation significantly reduces the D&D cost. A further shielding improvement, which would enable reaching the clearance level for the liner of the cavity and is beneficial to ease periodic inspection and decommissioning operations, can be obtained inserting steel plates close to the barrel and the lower support grid. The present study also suggests that a chance exists to accomplish this objective by simply making some internals thicker, namely the core barrel and support grid. In summary, intrinsic features of the IRIS design enable notable improvements in its O&M and D&D procedures and cost.

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