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A MONTE CARLO SIMULATIONS APPROACH FOR IRIS INTERNAL SHIELDS OPTIMIZATION

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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 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.

Key Words: Monte Carlo, variance reduction, shields

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 nine countries. IRIS concept was developed under the DOE Nuclear Energy Research Initiative (NERI) for Next Generation reactors [Refs. 1, 2, 3]. Key requirements for these 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 the modular approach with 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. In IRIS this goal is accomplished by eliminating several components (thanks to the integral primary circuit design), and avoiding a significant activation of any material outside the vessel.

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

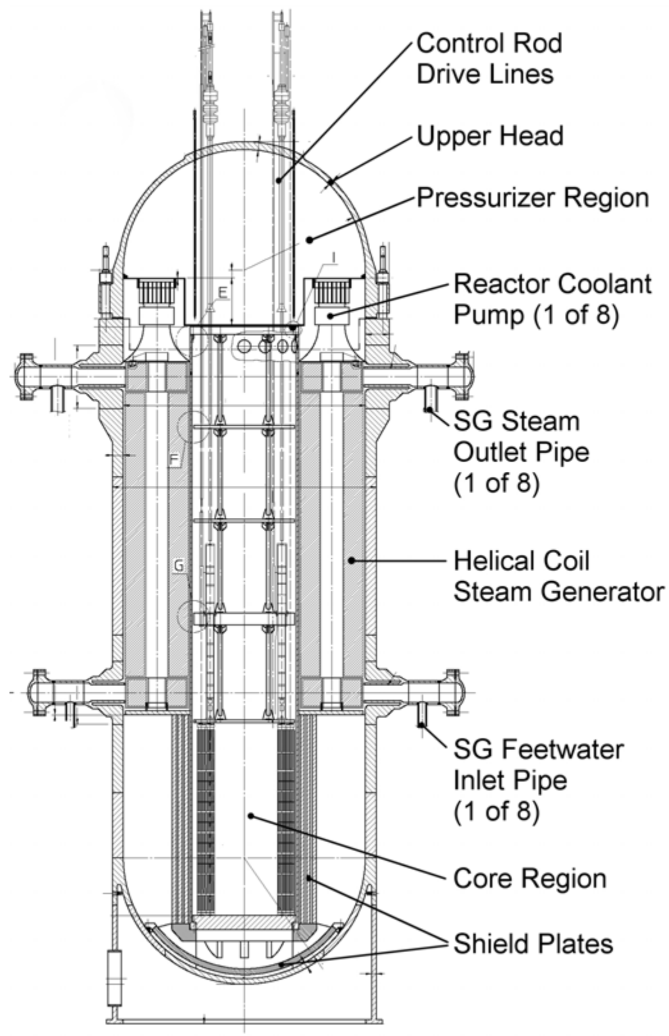


Figure 1. IRIS integral vessel layout.

Details related to the IRIS design are provided in previous papers [Refs. 1, 2, 3, 4], 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 internal shields (see Figure 1). Such an arrangement eliminates separate steam generators and pressurizer, connecting pipes, and supports. Hot coolant rising from the reactor core to the top of the vessel is being pumped into the steam generator annulus by eight pumps. 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 resulted to have 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. 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 would 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, attaining more ambitious objectives may become possible.

2. TARGETS OF INTERNAL SHIELDING

Possible targets to be met by internal shielding are:

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 steel liner and the concrete of the cavity) below the regulatory clearance level, and limiting the activation of the vessel itself.
4. Moving entirely/partially the biological shielding function inside the vessel, with the aim of:
   a. eliminating the need for an external biological shield (while the reactor is operating)
   b. limiting the need for an external biological shield to the amount which is in any case necessary for structural requirements.

The first target is the easiest one to meet, while target 4a is the most demanding. Satisfying target 4a 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, but such an extreme performance is not really needed. The first target may be met in IRIS by default, i.e., with no special design provisions 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 Figure 1).

In the present study we focus our attention essentially on target 3, and in part also on the dose (in operation) outside the vessel. We used the Monte Carlo code MCNP-4C [Ref. 5] to perform the analysis. Note that we assign to the word “dose” the meaning of flux weighted by the dose-equivalent conversion factors for external irradiation by a parallel broad beam; then radiation quality factors for human body are implicitly accounted for.

3. COMPUTATIONAL ISSUES

Neutrons are responsible for material activation; going from the core periphery to the reactor cavity their intensity is attenuated by many orders of magnitude, thus the adoption of some variance reduction technique is mandatory. But a difficulty immediately arises: run optimization can be performed for a single tally, while we are interested in the activation of the vessel, the liner and concrete of the cavity, and also in the neutron and gamma dose outside the vessel. Moreover, knowing the shield’s activation level and the dose at different radii inside the vessel can be useful too, as insight can be gained on the attenuation process. However, the most important values to be obtained pertain to the same location, i.e. outside the vessel; then it can be expected that the optimal variance reduction parameters turn out to be similar for the major part of the radiation path, i.e. in most of the cells inside the vessel.

In principle the assignment, cell by cell, of suitable weight windows promises to be a very efficient technique, maybe the best one among various variance reduction techniques. However, defining weight windows values is not simple: the automatic weight window generation option of MCNP most times does not give satisfying results, while an adjoint calculation with the aid of a deterministic code adds complexity to the procedure. Thus the simplest choice is just to assign a suitable importance to each cell. Worth noting is the fact that in our case a suitable subdivision of the geometry in cells, that is in parts with constant importance, can be reduced to a trivial task if the reactor geometry can be approximated by cylindrical shells of infinite height, that is, in 1-D geometry. The determination of the importance values was performed by a trial and error procedure, trying to maintain cell populations more or less constant and avoiding large importance ratios between adjacent cells.

However, the runs still required too much time; and had to be modified. Initially we used the code in coupled neutron-photon mode with the “kcode” option, that is with iteration of the fission source. Afterwards, we successively tried:

1. Changing the calculation option, by imposing a uniform fission neutron source in the core periphery, and no longer iterating the neutron source. This simplification is justified by the argument that it is known that almost 90% of the radiation escaping the core is originated in the most external layer, about 15-20 cm thick.
2. Often performing the calculation only in neutron mode, as we are mainly interested in obtaining the activation of the vessel and of the materials outside it. We only performed a couple of coupled neutron-photon calculations, to get the total dose.
3. Imposing, in a neutron mode calculation, an energy cutoff: neutrons falling below a given threshold (of the order of 0.1-1 eV) were terminated. It is well known that, inside water, the

average square distance reached by neutrons during slowing down (Fermi age) is significantly larger than the average square distance traveled by thermal neutrons (diffusion area). Therefore, thermal neutrons found after a thick layer of water are hardly originated by thermal neutrons which have traveled a long path, on the contrary, they are likely to come from fast neutrons which traveled most of the thick layer of water and slowed down in the nearby. As a thermal neutron collides during its life many more times than a fast or epithermal neutron, it is reasonable to expect a sensible shortening of the run times if thermal neutrons are disregarded. Of course, it should be a catastrophic error cutting them everywhere, as they are the main contributors to activation. As first of all we are interested in vessel and liner activation, thermal neutrons should not be cutoff in those cells, as well as in a suitable layer of water (of the order of ~20 cm) close to the vessel. We emphasize, however, that cutting off thermal neutrons was just an option investigated, but not used in the final calculations. The reason is that it was judged interesting obtaining correct answers through all the downcomer region as well.

Each of the above described variance reduction approaches allowed to roughly double the efficiency (compared to the cell importance approach alone) of the calculations for the cases at hand. Furthermore, the correlation between results of runs starting from the same random number is retained, while it would be quickly lost in kcode runs.

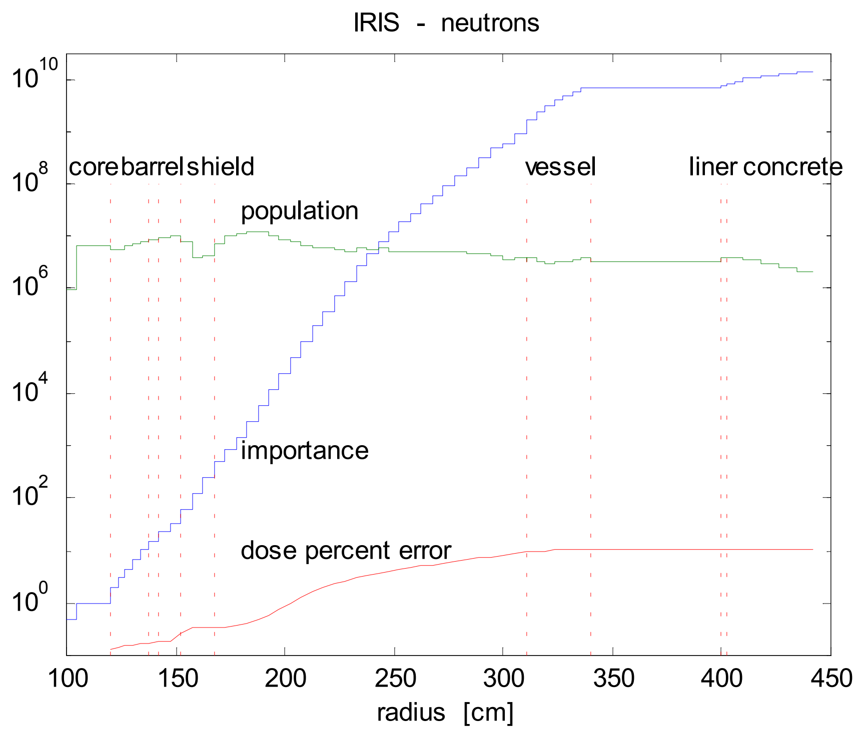


Figure 2. Importance, population and dose relative error for neutrons.

Figure 3. Importance, population and dose relative error for photons.

Figures 2 and 3 show the importance assigned to cells and the resulting population, relative to neutrons and photons, respectively. The run lasted more than 2 days on a 500 MHz PC. Also shown is the relative statistical error for the dose, as reported in MCNP output.

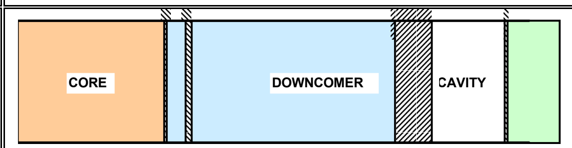
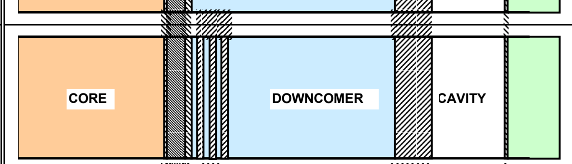
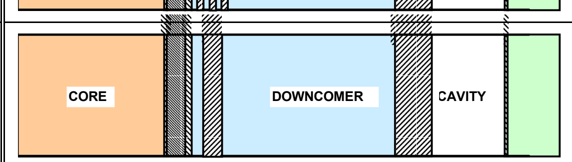
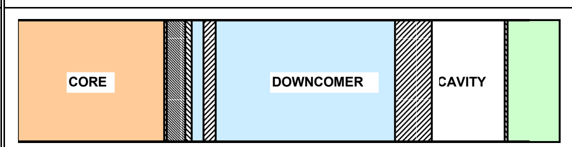
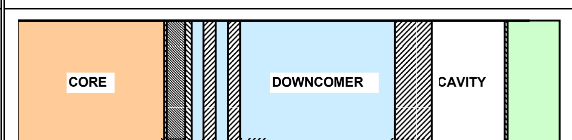
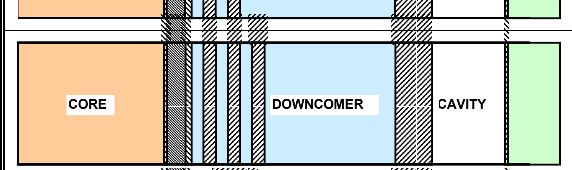
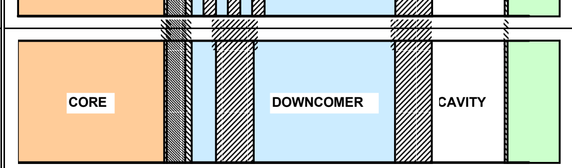
The two figures illustrate some of the well-known practical difficulties of deep-penetration Monte Carlo simulations. Even with the aggressive variance reduction approach, it was difficult to reduce the relative error in the reactor cavity and beyond below 10% within a day of PC CPU time. On the other hand, the presence of very high importance values (in outward cells) increase the probability that importance assignment were poorly made, which, in turn, could cause the reported relative error to be underestimated.

4. CASES EXAMINED AND RESULTS

4.1. 1-D Cases

Table I summarizes simulations in which the reactor geometry is approximated by concentric cylindrical shells of infinite height; then results are meaningful for lateral streaming only. A sketch (vertical section) for each case is also provided. The space between core baffle and barrel (former region) could be filled with water or with steel. The latter option is more convenient for core neutronics: the added steel acts as a better reflector than the replaced water, and core life can be extended by several percent. Moreover, it is more effective for shielding purposes too, as can be seen by comparing Cases 1 and 2. Case 1 is the only one with “water reflector”, i.e. with water filling the gap between baffle and barrel, in fact it is very likely that the “steel reflector” will be adopted in the final design. The activation values have to be compared with the clearance limit, which varies from country to country within the range 0.1-1 Bq/g.

Table I. Liner activation and dose outside vessel for the examined cases

Case	Sketch	Description	liner activ. Bq/g	n (γ) dose μSv/h
1		water reflector, no shielding	0.14	10,000. (510,000)
2		steel reflector, no shielding	0.05	3,000. (300,000)
3		steel reflector, 3 plates x5 cm	0.01	700. --
4		steel reflector, 1 plate x15 cm	0.01	700. (27,000)
5		steel reflector, 1 plate x10 cm	0.02	1,500. --
6		steel reflector, 2 plates x10 cm	0.006	400. --
7		steel reflector, 3 plates x10 cm	0.003	200. --
8		steel reflector, 1 plate x30 cm	0.003	200. (1,500)

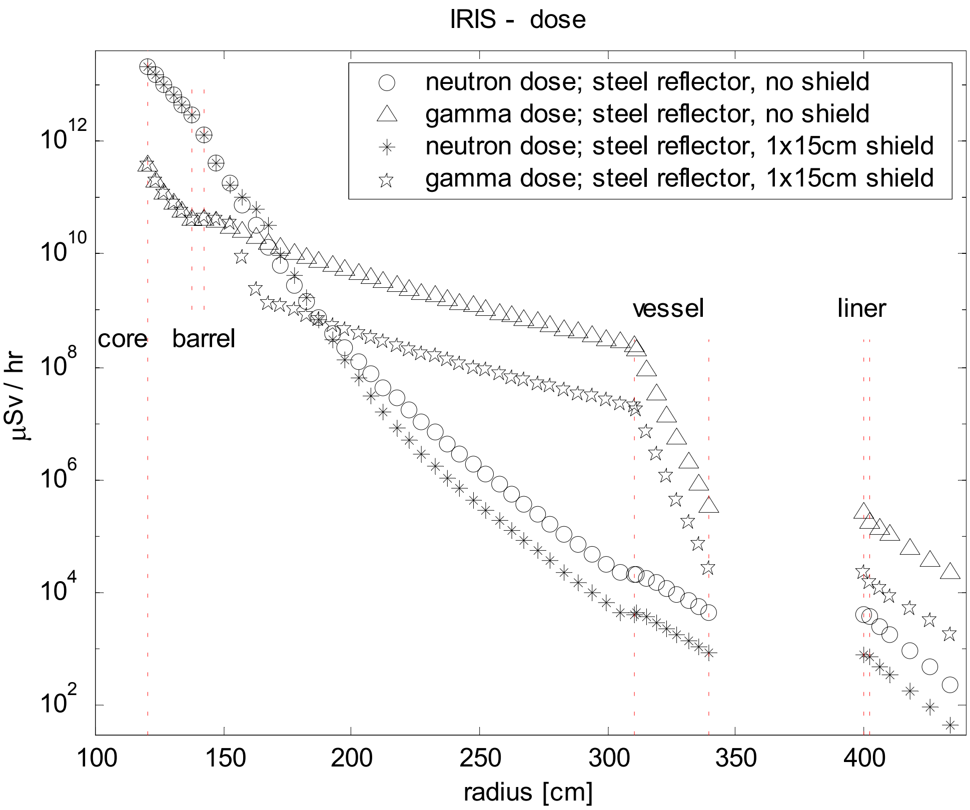


Figure 4. Neutron and gamma doses for Cases 2 and 4.

In Figure 4 the effect of inserting a steel plate 15 cm thick in the downcomer (Case 4) can be appreciated by comparing the behavior of the relative neutron and gamma doses. The steel shield acts locally and sharply on the gamma dose, while neutrons are affected in a different manner: inserting the steel shield leads to a slight increase in term of neutron dose within the whole shield itself (15 cm) as well as the subsequent 20 cm of water; only afterwards the shield brings you an advantage. This is the effect of the different neutronic characteristics of the two materials: water has a small cross section for fast neutrons, but, provided the first collision has occurred, it is very efficient in slowing down and absorbing them; steel has a larger cross section for fast neutrons, but is not very effective in thermalizing them. At the shield exit, more neutrons have survived, but also more have collided, that is, have been removed from the high energy tail of the spectrum; the subsequent layers of water will do the job of slowing them down and absorbing them.

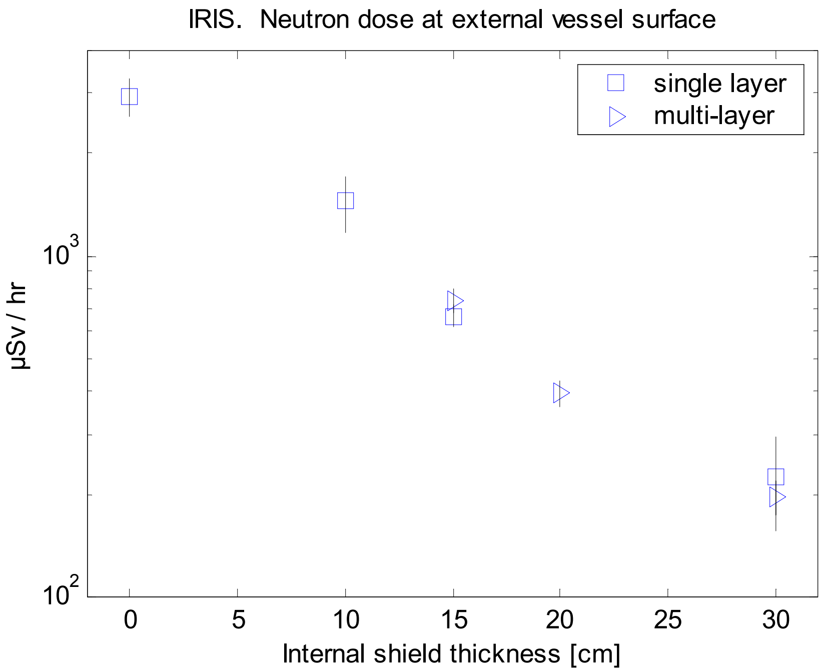


Figure 5. Neutron dose outside vessel vs. steel shield thickness.

The improvement in neutron attenuation when adding internal shields of different thickness is also shown in Figure 5. It is interesting to note that the neutron dose outside the vessel depends primarily on the total shield thickness, and not significantly on the actual distribution, e.g. one thick (squares) or several thin plates (triangles). For example, Cases 3 and 4, as well as Cases 7 and 8 lead to a similar dose estimate. Of course, fine tuning is still possible. Moreover, gamma dose rate is expected to be more sensitive to the actual shield placement. This will be checked in subsequent shield optimization studies. However, a difficulty will arise, namely, obtaining reliable differential results when simulating several alternative shield configurations. We intend to address this issue by employing the MCNP perturbation option in future studies.

4.2. 2-D Case

In Figure 6 a vertical section of the modeled 2-D geometry is shown. The vessel with internals, the support skirt, the liner and concrete of the cavity are described with axial-symmetric cells, i.e. cylinders of finite height and spherical shell segments. The design target was to flat the level of liner activation all around the reactor. In the figure a possible shield plates position (distribution) which fulfills this target is shown. The maximum liner activation for this configuration is ~0.01 Bq/g, well below the clearance limit, both for the lateral and the bottom liner. The adopted variance reduction technique, the problems and the variance reduction approaches used in the simulation are the same as the ones used in 1-D cases. Results of lateral radiation streaming are similar to the corresponding ones obtained in 1-D geometry, so confirming the adequacy of such a drastic approximation.

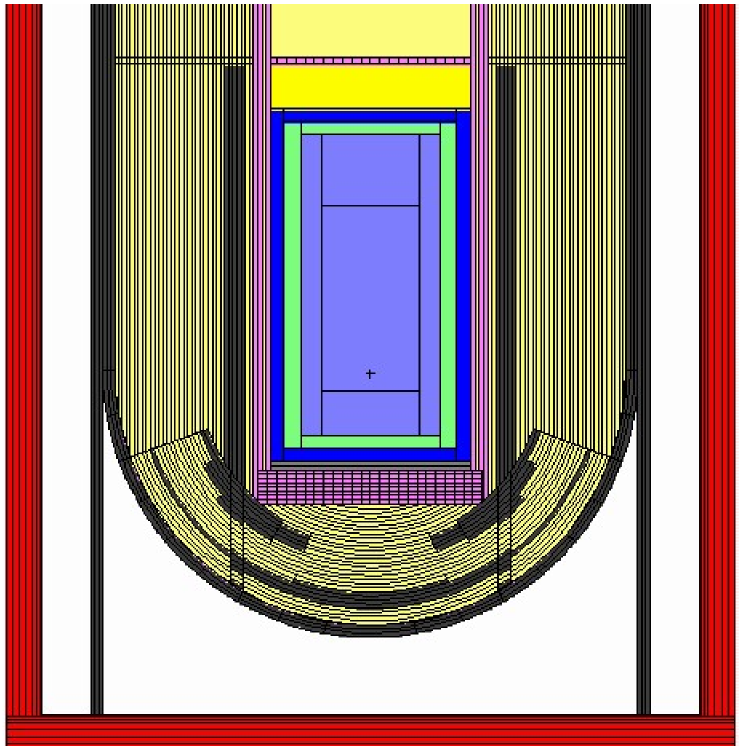


Figure 6. Vertical section of the geometry adopted for 2-D simulations.

5. 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 can be obtained inserting steel plates close to the barrel and the lower support grid; this would enable reaching the clearance level for the liner of the cavity or even for the vessel itself, and is beneficial to reduce the thickness of biological shielding and to ease periodic inspection and decommissioning operations. A final decision on whether to implement internal shielding, and of what thickness, will be made based on the pending more detailed cost-benefit analysis.

Monte Carlo simulations were performed to evaluate different shield configurations and assess the feasibility of achieving several design targets. This deep-penetration problem required heavy reliance on a combination of variance reduction techniques. Assignment of cell importances to keep cell population nearly-constant was used as the basic approach, supplemented by several additional model simplifications or assumptions (e.g., fixed source, limiting source region, energy cut-off) that further increased the obtained speed-up. In spite of the aggressive variance reduction strategy, it was difficult to reduce relative errors in neutron dose outside the reactor vessel below ~10% in less than a day of PC simulations. This is not surprising since the dose attenuation in IRIS (from core to cavity) is 10 orders of magnitude or more. However, the obtained level of statistical errors and reliability of results is deemed adequate for the current purposes and a higher accuracy is not necessarily needed at the present design stage. Improvement in accuracy will be needed to further optimize the shield configuration. We intend to address this issue by employing the MCNP perturbation option in future sensitivity studies.

ACKNOWLEDGMENTS

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