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RICERCA DI SISTEMA ELETTRICO

Continuing Analysis with Monte Carlo Techniques of the Impact of the Heavy Reflector of a Typical Large Size Gen II+ Reactor Design on Some Safety Features: Completion of the Ex-Core Detector Calculations from PAR2010 and Examination of the Impact on the Phenomenon of Flux Tilt

Ken William Burn

Report RdS/2012/003

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Ken William Burn (ENEA)

Settembre 2012

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Titolo

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Sommario

This report is a continuation of that submitted last year (PAR2010) regarding the collaboration between ENEA and IRSN (Institut de Radioprotection et de Sûreté Nucléaire) dealing with safety issues related to the thick steel reflector of a typical large size GEN III+ reactor design. Concerning the impact of the steel reflector on the signal in the ex-core detectors, issues left open from the previous report (moving the 252Cf primary source assemblies from their outer core positions one assembly position inwards towards the core centre; generation of results for the Sb-Be secondary source assemblies) are addressed. All the results for the ex-core detectors were summarized in a paper at the TopSafe-2012 meeting in April, 2012, which is appended to this report.

In current operating plants with large cores, flux tilt can be a problem. Although it may be due to a variety of factors and also involve positive feedback effects, one possible contributory cause that may be simply modelled is a variation in the coolant density. It is known that relatively small azimuthal variations in the coolant density in the external assemblies can induce a proportionately high power asymmetry throughout the core (especially at low power) with a conventional baffle-water configuration as reflector. To understand what impact the thick steel reflector has on this effect, results have been generated with a 2-dimensional model of the reactor core at HZP and at 30% NP.

Note

Autori: K. W. Burn

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Index

1. Introduction

This work has been performed within the framework of an agreement between ENEA and IRSN (Institut de Radioprotection et de Sûreté Nucléaire). The particular area of the activity deals with safety issues concerning the thick steel reflector of a typical large size GEN III+ reactor design and in particular the differences caused by this reflector compared with current PWR designs.
This report is a continuation of the report: "Analysis of the Impact of the Heavy Reflector of a Typical Large Size GEN III+ Reactor Design on the Ex-Core Detector Signals with Monte Carlo Techniques (Employing MCNP-5)", submitted under PAR-2010.
As much of the data employed was confidential, this report is by necessity in a condensed form. Corresponding more detailed confidential documents are also being issued (in presentation form).

2. Completing the Activity on Ex-Core Detectors from PAR-2010

Left over from PAR-2010 were an evaluation of the change in signal in the ex-core detectors when the primary source assemblies are moved one assembly position towards the core centre and an analysis of the signal in the ex-core detectors from the secondary source assemblies.
Moving the ^{252}Cf primary source assemblies from their outer position one assembly position towards the core centre reduces the signal in the ex-core detectors by approximately one order of magnitude when fissions are turned off. This becomes a factor of roughly 2 when fissions are included. These results hold both for the heavy steel reflector and the conventional one (baffle + water).
As far as the Sb-Be secondary sources are concerned, firstly the ^{123}Sb(n,γ) rate in each of the 16 secondary source pins in each of the 3 secondary source assemblies in 4 axial segments was evaluated under conditions of criticality, then the neutron source was formed assuming it to be proportional to the amount of ^{124}Sb ($T_{1/2}$ = 60.2 d) present, then, under conditions of 0.95 criticality, these neutrons were transported outside the core, through the reflector to the detector. Excluding fissions, the signal in the ex-core detectors with the steel reflector is around 3 orders of magnitude higher than with the water reflector. (These signals are completely negligible compared with when fission is switched on.) Including fissions, the ratio of the signal in the ex-core detectors with conventional reflector and with steel reflector varies between 4.1 and 3.7, depending on which detector is considered.
All the results for the ex-core detectors were presented to the TopSafe-2012 meeting at Helsinki in April, 2012. The paper is shown in Appendix 1 and gives a complete summary of the ex-core detector results, including the above issues of change-of-position of the primary source assemblies and the secondary source assemblies. The summary poster presented at the TopSafe-2012 meeting is shown in Appendix 2 (which also contains a short introduction to the Flux Tilt problem).

3. Flux Tilt

The flux tilt may be due to a variety of factors and also involve positive feedback effects. One possible contributing cause that can be modelled relatively simply is a variation in the coolant density. Thus the coolant water density in the outer assemblies of opposite core quadrants was changed slightly – see Fig. 1 where an increase in the water density in the SE quadrant is shown with a corresponding decrease in the NW quadrant.

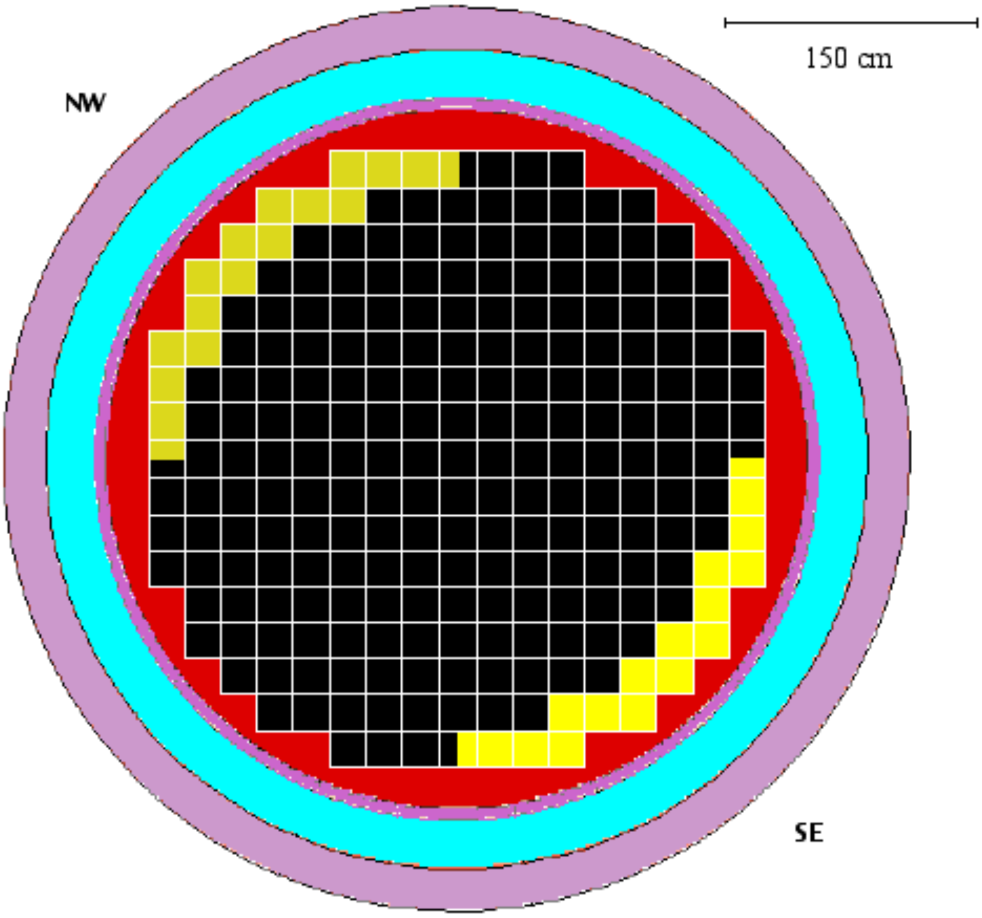

Fig. 1: Assemblies defining the change in water density that may be a factor in inducing the flux tilt.

The tilt is then defined by the increase in power in the whole SE quadrant compared with the mean and the decrease in power in the NW quadrant compared with the mean (see Fig. 2). (Note that the increase and decrease are not necessarily the same.)

In these calculations a 2-dimensional model of the reactor core was employed. This was for reasons of simplicity, speed and ease of comparison with deterministic approaches. However it should be borne in mind that 3-D effects, due for example to the axial variation in the temperature field of the core, exist and are important in current models that represent flux tilt.

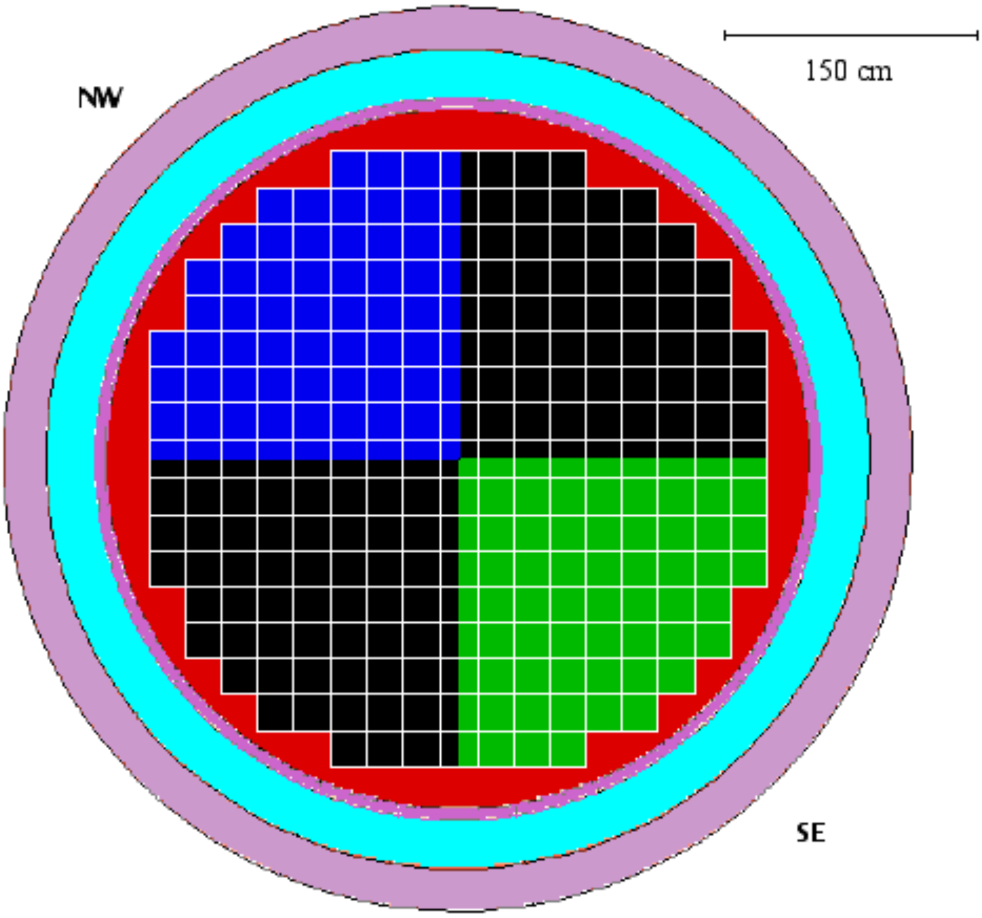

Fig. 2: Assemblies defining the flux tilt

The various stages in the activity are listed as follows:

1. A 2-dimensional model of the reactor core was created based on the 3-dimensional model used to evaluate the ex-core detector signal at HZP, firstly with a heavy steel reflector and secondly with a conventional 1 inch thick steel baffle with water outside. Both models extended out to the pressure vessel. The model with the heavy steel reflector included a natural boron concentration of 884 ppm in the coolant water (that gives approximate criticality at HZP for the 3-dimensional model with the neutron cross-sections employed).

2. For the case of the 1 inch thick steel baffle with water outside, a search was made for the boron concentration that gives approximately the same k_{eff} as for the heavy steel reflector with 884 ppm. The result was found to be 825 ppm boron.

3. For the model developed in item 2, a search was made of the amount of increase in water density in the outer assemblies of the SE core quadrant (15 whole assemblies + 2 half assemblies) (and with the same amount of decrease in water density in the outer assemblies of the NW core quadrant), that provided an increase of approximately 5% of power in the whole of the SE core quadrant (52 whole assemblies + 16 half assemblies + 1 quarter

assembly) (and a decrease of approximately 5% in the NW core quadrant). The result was found to be ±1.50%. [Note that in all the calculations of the differential energy deposition in the core, even with a relatively gross spatial division such as a core quadrant, well-known methodological problems were encountered that are discussed in Appendix 3.]

4. For the model of the heavy steel reflector with 884 ppm water and with the variation of water density in the relevant assemblies of ±1.50% from item 3, the variation in power in the core quadrants was found. This turned out to be substantially higher than the approximately ±5% variation in power for the case of the 1 inch thick steel baffle with water outside.

5. A 2-dimensional model of the core was created for the two cases: heavy steel reflector and steel baffle + water, at 30% nominal power, each case with the same respective boron concentration as at HZP. Note that differences between the model at HZP and that at 30%NP were in the geometry (thermal dilations), water density and the fuel temperature with the cross-sections Doppler-broadened to near the required temperature, according to the available data. (Note that the difference in evaluated temperature of the fuel cross-sections between HZP and 30%NP was 73°K whilst the difference in the models supplied by IRSN was 85.5°K.)

6. Employing the variation of water density in the relevant assemblies of ±1.50% found in item 3, for the two models at 30% nominal power: heavy steel reflector and steel baffle + water, each with their respective boron concentrations, the variation in power in the core quadrants was found. Note that at the time of issue of this report, this work is still underway.

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7. Items 5 and 6 will be repeated at another power state to be defined.

8. Item 3 may be repeated, but varying the water density in the outer assemblies of the core quadrants in the N-S direction, observing the variations in power in the N and S quadrants.

4. Concluding remarks

The activity dealing with the effect of the heavy steel reflector on the ex-core neutron detectors has been concluded. That concerning the effect of the heavy steel reflector on the phenomenon of flux tilt is still underway. Comparisons with other approaches (*viz.* deterministic) are indicated.

Acknowledgements

G. Bruna (IRSN) coordinated this activity.
B. Normand (IRSN) provided the data for the ex-core detector calculations.
A. Sargeni (IRSN) provided the definition of the core at 30%NP for the flux tilt calculations.
O. Dubois (IRSN) provided the standard definition of the flux tilt.
G. Glinatsis (ENEA) generated all the locally-processed cross-sections with NJOY.

Appendix 1: Paper submitted to TopSafe-2012

IMPACT OF THE HEAVY STEEL REFLECTOR OF A CURRENT LARGE PWR DESIGN ON SOME SAFETY FEATURES

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ABSTRACT

At low power levels, the ex-core neutron detectors, placed outside the pressure vessel of a PWR, are the only tools available to monitor the neutron flux in the reactor core. The introduction of a heavy steel reflector in some current PWR designs means that the neutron attenuation between core and detectors is substantially different (and higher) compared with that in existing operating PWR's. Monte Carlo methods have been employed to evaluate these differences under various circumstances:

- hot zero power at criticality (with the fundamental mode neutron source);
- hot zero power at 0.95 criticality with the ^{252}Cf primary sources;
- hot zero power at 0.95 criticality with the Sb-Be secondary sources.

Furthermore it is expected that the heavy steel reflector will also have an effect on the phenomenon of flux tilting. Studies (employing Monte Carlo) are underway to evaluate its impact on flux tilting at low power levels.

1) Introduction

In some modern large PWR designs, a thick steel reflector is employed between the active zone and the barrel. This reflector substitutes the much thinner baffle (with water outside) of current operating PWR plants. Advantages of such a thick steel reflector are of course to flatten the power profile in the active zone and also to reduce the displacement rate in the pressure vessel (PV). Here we look at a potential disadvantage, that of reducing the response in the ex-core neutron detectors, placed in the well outside the PV. (The response is reduced because the fast neutrons that carry the signal from the fission event to the outside of the PV are attenuated more by steel than water.) As at low power levels the ex-core neutron detectors are the only tools available to monitor the neutron flux in the reactor core, a verification of their capability of detecting such power levels through the steel reflector is deemed appropriate.
A quarter core horizontal section with the steel reflector is shown in Fig. 1 whilst the conventional baffle scheme is shown in Fig. 2. Whilst the baffle is typically 1 inch (2.54 cm) thick, this may vary. Therefore in the calculations the baffle was assumed to be water. This introduced a conservative element in the results.
As the ex-core detector signal at start-up and at low power is of particular interest, three distinct situations are analysed:

- hot zero power at criticality (with the fundamental mode neutron source);
- hot zero power at 0.95 criticality with the ^{252}Cf primary sources;
- hot zero power at 0.95 criticality with the Sb-Be secondary sources.

2) Methodology

Monte Carlo was employed with the MCNP5 code (versions 1.30 and 1.40) [1].

Cross-section libraries from a number of sources were employed, with some processed locally into ACE format and others already processed:

- ^{1}H, ^{2}H, ^{16}O, ^{235}U, ^{238}U from JEFF3.1 (processed locally to 600°K);
- ^{10}B, ^{11}B, ^{nat}C, ^{nat}Zr, ^{55}Mn, all isotopes of: Cr, Fe, Ni, Gd (apart from ^{152}Gd), from ENDF-B/VI (Rel. 1 and 2) (processed locally to 560°K);
- All other nuclides from public ACE format data distributed with MCNP5 based on ENDF-B/VI (Rel. 6 and 8) (apart from ^{nat}Sn from ENDL-92). All processed at 293°K.

For the thermal treatment:

- All materials within the PV: elastic scattering cross-section and velocity of the target nucleus in the free gas model adjusted to 576°K. $S(\alpha,\beta)$ data for hydrogen attached to the water molecule from JEFF3.1 (processed locally to 574°K);
- All materials outside the PV: elastic scattering cross-section and velocity of the target nucleus in the free gas model adjusted to 294°K. $S(\alpha,\beta)$ data for hydrogen attached to the water molecule from the public “SAB2002” file (based on ENDF/B-VI Rel. 5) (processed to 294°K); $S(\alpha,\beta)$ data for hydrogen attached to the polyethylene molecule from the public “SAB2002” file (processed to 294°K).

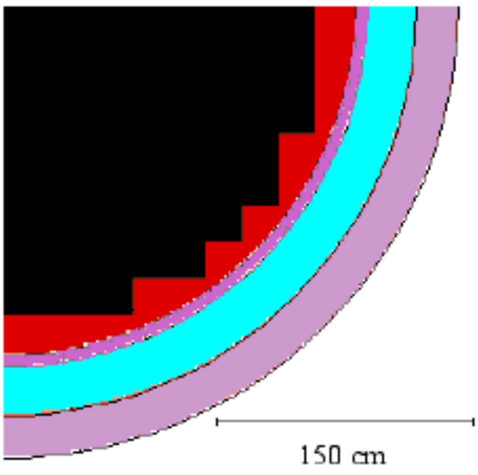

Fig. 1. 1/4 Section of Core with Thick Steel Reflector

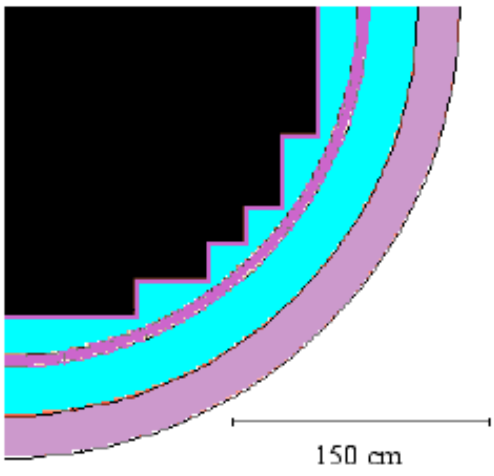

Fig. 2. 1/4 Section of Core with 1 inch Thick Baffle

A pin-by-pin representation was made of the fuel assemblies (Fig. 3). The thick steel reflector contained a number of coolant water channels (Fig. 4). It was verified that homogenizing this water with the steel was an excellent approximation.
Rather than score the fast neutron flux leaking through the PV as a measure of the ex-core detector response, the detector was modelled explicitly (Fig. 5), scoring the $^{10}B(n,\alpha)$ reaction rate on the inner (cylindrical) surface. Two possible positions of the detectors were considered: attached to the outer surface of the PV or to the inner surface of the concrete in the PV well (Fig. 6). In nearly all the calculations, the position was that attached to the PV.

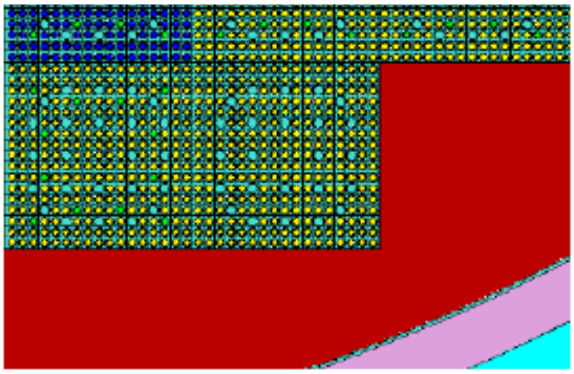

Fig. 3. Segment of Outer Core Assemblies showing Pin-by-Pin Model

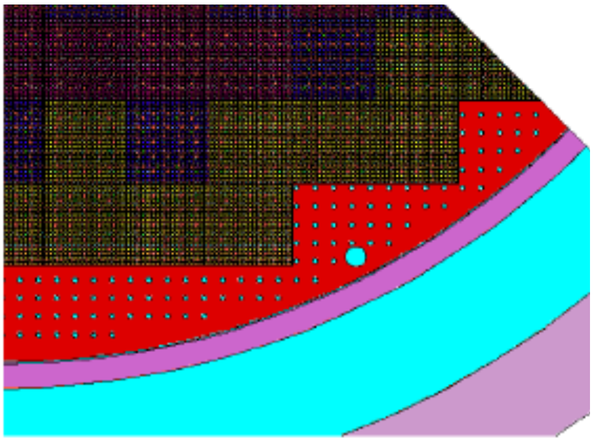

Fig. 4. 1/8 segment of the Core showing the Water Lattice in the Steel Reflector

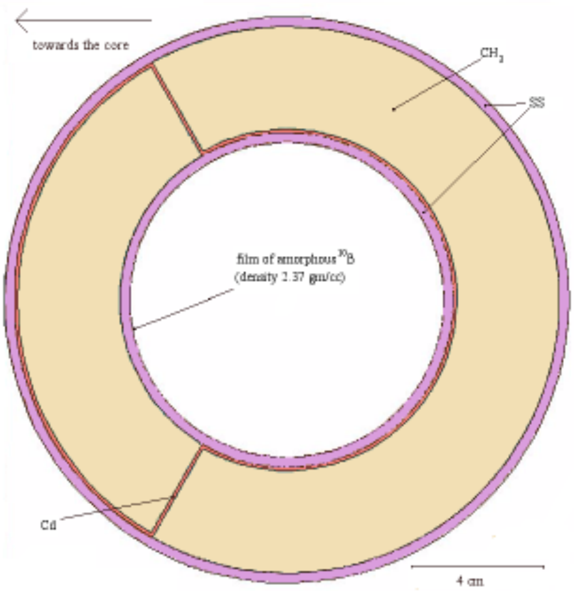

Fig. 5. Model of Ex-Core Neutron Detector (horizontal section of cylinder)

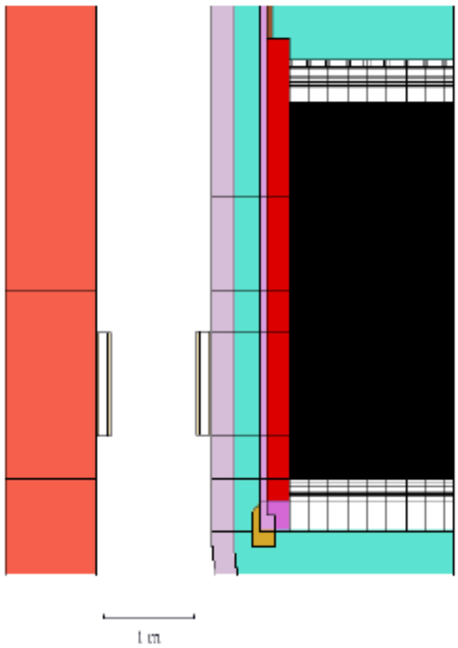

Fig. 6. Vertical Section showing 2 Possible Positions of Neutron Detectors

2.1 The Fundamental Mode Calculations

Having searched for the boron concentration in the coolant water that provides criticality, the standard approach was adopted for coupling the fundamental mode calculations to the ex-core evaluations. That is, the fission neutron production rate in each pin of each assembly from the eigenvalue calculation with an appropriate axial discretization (21 axial bins) was converted to a fixed source. MCNP5 was patched to sample this source from a direct access file, written with an interface program that read the results of the eigenvalue calculation. Because of the employment of a 1/8 azimuthal segment with reflection surfaces for this calculation, a further patching of the

code was required to sample the source correctly in the case of rejection (when a pin intersects one of the reflection surfaces and the sampled position is on the wrong side of the surface).
The transport from the core to the ex-core detector required variance reduction and the DSA technique was employed [2].
The results are given in terms of number of reactions of $^{10}B(n,\alpha)/cm^3/sec$ per watt of reactor power in the thin amorphous film of ^{10}B coated on the inner surface of the detector.

2.2 The Calculations with the Start-Up Sources

The positions of the assemblies containing the ^{252}Cf primary and the Sb-Be secondary start-up sources are shown in Figs. 7 and 8 respectively. As implied by these figures, a full 360° azimuthal model was employed. For both types of start-up sources, the boron concentration in the coolant water was increased until 0.95 criticality was achieved. Results were then generated, again employing variance reduction with the DSA for two cases: with fissions "switched off" and with fissions allowed. (In the latter case 160 fission generations were found to be a sufficient number at 0.95 criticality.) For the primary start-up sources, results were also generated when the primary source assemblies were moved one assembly position inwards compared with the positions shown in Fig. 7.
The intensity of the primary start-up sources is known, thus the results are given in terms of the number of reactions of $^{10}B(n,\alpha)/cm^3/sec$. Instead the intensity of the secondary start-up sources is not known as it depends on the activation history and on the length of decay time of ^{124}Sb ($T_{1/2}$ = 60.2 d) [whose decay gamma's are the predominant contributors to the (γ,n) rate in ^{9}Be]. Therefore only the correct proportionality of the neutron sources in each of the 16 Sb-Be pins and in each of the 3 secondary source assemblies could be maintained by calculating the $^{123}Sb(n,\gamma)$ rate in each pin under conditions of criticality (i.e. operation) with the fundamental mode neutron distribution. Then the neutron source in the Be was assumed to be proportional to the amount of ^{124}Sb present. The neutron energy spectrum from $^{9}Be(\gamma,n)$, in the case that the gamma's are from the decay of ^{124}Sb, was taken from [3].

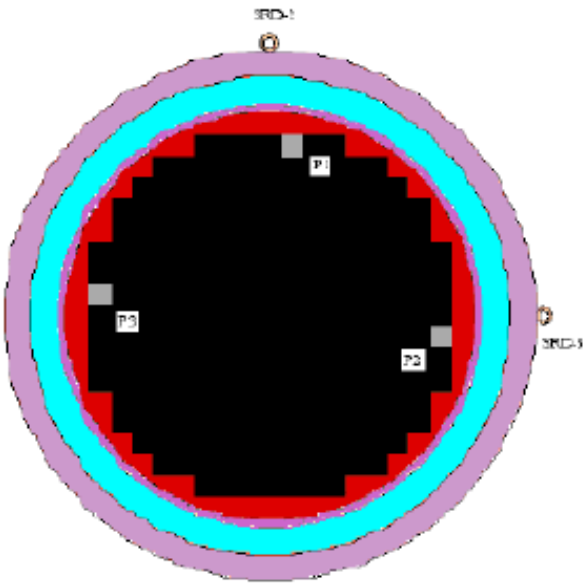

Fig. 7. Positions of the Assemblies with the 252-Cf Start-Up Sources

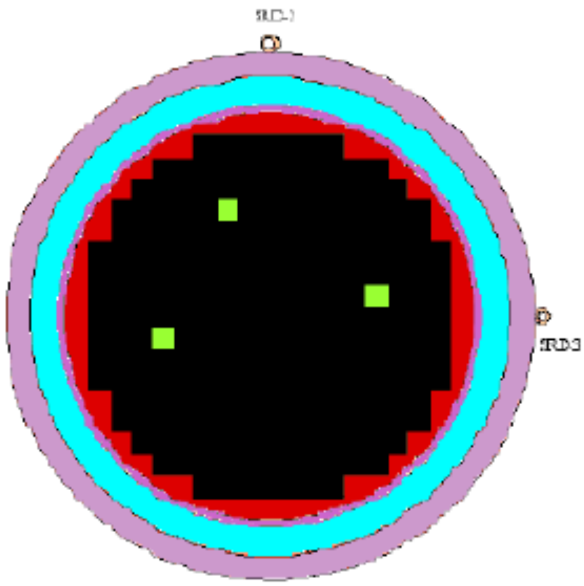
Fig. 8. Positions of the Assemblies with the Sb-Be Start-Up Sources

3) Results

Unless otherwise stated, the results are for the detector position adjacent to the PV (Fig. 6).

At 0.95 criticality:

Moving the primary source assemblies from their outer position, one position inwards, reduces the signal in the ex-core detectors by approximately one order of magnitude when fissions are turned off. This becomes a factor of roughly 2 when fissions are included. These results hold both for the heavy steel reflector and the conventional one.

At 0.95 criticality and with the ^{252}Cf primary sources (only) in their outer assembly positions:

Excluding fissions, the ratio of the signal in the ex-core detectors with water and with steel reflectors is 5.4 (6.4 when the primary source assemblies are moved one position inwards).
Including fissions, for the water reflector, fissions account for 91% of the total signal in the ex-core detectors. For the steel reflector, this is 94%. (Around 99% for both reflectors when the primary source assemblies are moved one position inwards.)
Including fissions, the ratio of the signal in the ex-core detectors with water reflector and with steel reflector is 3.8. (Identical when the primary source assemblies are moved one position inwards.) Compare 5.4 (6.4) without fissions, and 2.7 for the fundamental mode fission distribution at k_{eff}=1 (see below).

At criticality (for the fundamental mode fission distribution):

The ratio of the signal in the ex-core detectors with water reflector and with steel reflector is 2.7. [For the detector placed adjacent to the concrete in the PV well (see Fig. 6), this ratio is instead 2.2.]

Thus for the ^{252}Cf primary sources (only) in the outer assembly position:

If $k_{eff} < 0.95$, 5.4 > ratio (water/steel reflector) > 3.8
If $1 > k_{eff} > 0.95$, 3.8 > ratio (water/steel reflector) > 2.7

At 0.95 criticality and with the Sb-Be secondary sources (only):

Excluding fissions, the signal in the ex-core detectors with the steel reflector is around 3 orders of magnitude higher than with the water reflector. (These signals are completely negligible compared with when fission is switched on.)
Including fissions, the ratio of the signal in the ex-core detectors with water reflector and with steel reflector varies between 4.1 and 3.7, depending on which detector is considered (see Fig. 8). Compare 3.8 for the primary sources.

Comparing the signal in the detectors with the primary sources in their outer assembly positions at 0.95 criticality with that from the fundamental mode at criticality:

Starting from the shut-down state at 0.95 criticality with the detector signal coming (directly and indirectly) from the primary start-up sources, there is a continuous range of states ending with criticality and the fundamental mode source. It is of interest to compare the results from the initial and end states: at criticality, the part of the signal in the ex-core detectors from the fundamental mode becomes comparable to that from the primary sources at the starting point at 0.95 criticality when the reactor power reaches 0.50 W for the thick steel reflector and 0.69 W for the conventional reflector.

4) Conclusion

These results are conservative (baffle made water, detectors in position adjacent to PV which gives a higher factor compared with adjacent to concrete). Given that the sensitivity of the ex-core neutron detectors should be an order of magnitude higher in current designs compared with present-day operating plants, this work indicates that there should be sufficient margin to detect the neutron signal. Nevertheless this investigation is not comprehensive and care is to be recommended at reactor start-up and shut-down until sufficient operating experience has been accumulated.

5) Ongoing Work

In the current context of employing Monte Carlo neutron transport methods to verify some safety aspects of PWR designs with heavy steel reflectors, work is ongoing on verifying the effect of the steel reflector on the phenomenon of flux tilting.

6) References

1. X-5 Monte Carlo Team, “MCNP – A General N-Particle Transport Code, Version 5”, LA-UR-03-1987, LA-CP-03-0245, LA-CP-03-0284 (2003) [ver. 1.3: LA-UR-04-8086, LA-UR-04-5921 (2004); ver. 1.4: LA-UR-05-8617 (2005)].
2. K. W. Burn, “Optimizing Monte Carlo to Multiple Responses: the Direct Statistical Approach, 10 Years On”, Nucl. Technol. **175-1** 138-145 (2011)
3. H. Tagziria, N. Roberts, A. Bennett and D. J. Thomas, “Calibration and Monte Carlo Modelling of the NPL Long Counters at 22.8 keV”, NPL-CIRM48 (Oct. 2001)

Appendix 2: Poster presented at TopSafe-2012

Italian National Agency for New Technologies, Energy and Sustainable Economic Development
http://www.enea.it/

IRSN Institut de Radioprotection et de Sûreté Nucléaire
Institute for Radioprotection and Nuclear Safety
http://www.irsn.fr/FR/Pages/Home.aspx

TopSafe 2012
Safety in Reactor Operations
Helsinki, April 22-26, 2012

IMPACT OF THE HEAVY STEEL REFLECTOR OF A CURRENT LARGE PWR DESIGN ON SOME SAFETY FEATURES

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INTRODUCTION

In some modern large PWR designs, a thick steel reflector is employed between the active zone and the barrel, that substitutes the much thinner baffle (with water outside) of current operating PWR's. Advantages of the steel reflector are to flatten the power profile and to reduce the damage to the pressure vessel (PV). One disadvantage is to reduce the response in the ex-core neutron detectors placed in the PV well. As at low power levels these detectors are the only tools available to monitor the neutron flux in the reactor core, a verification of their capability to detect such power levels with the steel reflector is needed. Results are presented at HZP at criticality and at 0.95 sub-criticality with the ^{252}Cf primary sources and the Sb-Be secondary start-up sources. Furthermore studies are underway to evaluate the impact of the thick steel reflector on the phenomenon of flux tilting.

METHODOLOGY

Monte Carlo was employed with the MCNP5 code [1]. Cross-sections were from a number of sources (^{235}U and ^{238}U were from JEFF3.1), some processed locally and others already in ACE format. The transport from the core to the ex-core detector required variance reduction. For this, the DSA technique was employed [2].

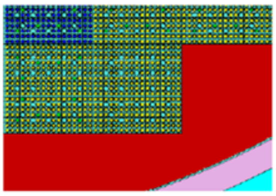
To calculate the response in the ex-core neutron detectors, the "classic" approach was adopted, decoupling the in-core eigenvalue calculation from the ex-core fixed source calculation. MCNP5 was patched to sample the (fixed) fission source from a direct access file, written with an interface program that read the results of the eigenvalue calculation. Some further code patching was required to sample the source correctly in the case of rejection.

[1] X-5 Monte Carlo Team, MCNP – A General N-Particle Transport Code, Version 5, LA-UR-03-1987 (2003).
[2] Burn, K.W. Optimizing Monte Carlo to Multiple Responses: the Direct Statistical Approach, 10 Years On, Nucl. Technol. **175-1** *138-145 (2011).*

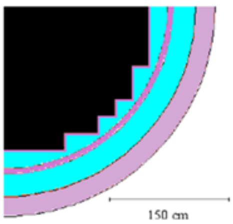
GEOMETRICAL MODEL

An explicit pin-by-pin description of the whole core was made. Two situations of reflector were compared: a 1 inch thick baffle (followed by water) of current operating PWR plants and a thick steel reflector (with coolant water channels) as in certain current PWR designs:

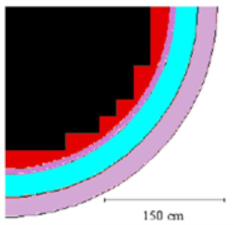
Segment of outer core showing pin-by-pin description



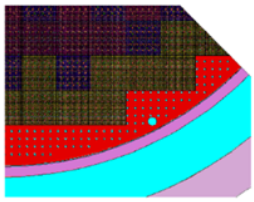
1/4 Section of Core with 1 inch thick Steel Baffle



1/4 Section of Core with thick Steel Reflector



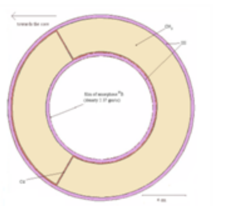
1/8 Section of Core showing the Water Lattice in the Steel Reflector



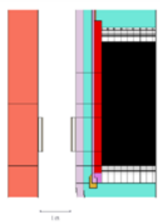
The detector was modelled explicitly, scoring the ^{10}B(n,α) reaction rate on the inner (cylindrical) surface. Two possible positions of the detectors were considered: attached to the outer surface of the PV or to the inner surface of the concrete in the PV well. In nearly all the calculations, the position was that attached to the PV.

For the calculations at 0.95 sub-criticality, the primary (^{252}Cf) and secondary (Sb-Be) source assemblies were explicitly modelled.

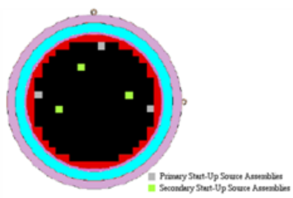
Ex-Core Neutron Detector: Horizontal Section



Vertical Section showing 2 Possible Positions of Neutron Detectors



Positions of the Assemblies with the Primary and Secondary Start-Up Sources



RESULTS – EX-CORE DETECTORS

The following results are ratios (R_{ex-c}) of the signal in the ex-core detector with water reflector (the baffle was made water which introduces a slight conservative bias) and with steel reflector:

With the primary sources only and with $k_{eff} \leq 0.95$: $5.4 \geq R_{ex-c} \geq 3.8$ (with the minimum value at $k_{eff} = 0.95$).

(If the primary source assemblies are moved 1 position inwards, this becomes: **$6.4 \geq R_{ex-c} \geq 3.8$**.)

With the primary sources only and with $0.95 \leq k_{eff} \leq 1$: $3.8 \geq R_{ex-c} \geq 2.7$.

With the secondary sources only and with $0.95 \leq k_{eff} \leq 1$: 4.1-$3.7 \geq R_{ex-c} \geq 2.7$ (depending on which ex-core detector is considered). (At reactivity values very much lower than $k_{eff} = 0.95$, the situation is inverted and R_{ex-c} becomes much less than 1 but at this point the signal is negligible.)

(From the above results) **With the fundamental fission mode and with $k_{eff} = 1$: $R_{ex-c} = 2.7$.**

Given that the sensitivity of the ex-core neutron detectors should be an order of magnitude higher in current designs compared with present-day operating plants, these results indicate that there should be sufficient margin to detect the neutron signal. Nevertheless this investigation is not comprehensive and care is to be recommended at reactor start-up and shut-down until sufficient operating experience has been accumulated.

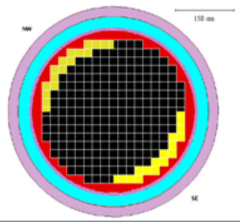
Finally the part of the signal in the ex-core detectors from the fundamental mode becomes comparable to that from the primary sources at $k_{eff} = 0.95$ when the reactor power (from the fundamental mode only) reaches 0.50 W for the steel reflector and 0.69 W for the water reflector.

FLUX TILT

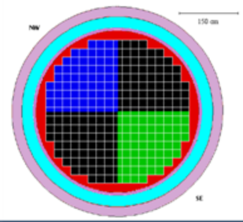
In current operating plants with large cores and a baffle-water configuration, it is known that relatively small azimuthal variations in the coolant pressure in the external assemblies can induce a proportionately high power asymmetry throughout the core (especially at low powers). Work is underway to see what impact the thick steel reflector has on this effect.

[The Monte Carlo treatment of such problems requires care to ensure a properly converged fundamental mode fission distribution. Also a reasonable signal-to-noise ratio should result (with correctly estimated statistical errors). These issues are currently being addressed.]

Assemblies with an increase (SE) and decrease (NW) in water density



Assemblies with an increase (SE) and decrease (NW) in power



This work has been carried out within the IRSN - ENEA joint collaboration to enhance nuclear safety.

***Acknowledgements:** Georgios Glinatsis supplied the local ACE format cross sections.*

Appendix 3: Methodological problems encountered in calculating the flux tilt with Monte Carlo

There are well known problems in employing Monte Carlo with the source-iteration method to calculate neutronic responses in large thermal reactor cores. The more (spatially) differential is a response, the more serious are these problems. They are linked to the difficulty in suppressing the higher order modes of the fission distribution and to the correlations between cycles in a strongly connected system. Note that the calculation of k_{eff} does not suffer from such serious problems because its integral nature means that the presence of higher modes has a much smaller effect.

A measure of the stability of the fission distribution in MCNP is the "Shannon entropy". This was employed but found to be insufficient, possibly due to the relatively large variation in entropy from cycle-to-cycle, even when the fission source had (presumably) converged.

The various steps that were taken were as follows:

- Some tens of thousands of cycles of gradually increasing size were executed to arrive at the fundamental mode and a cycle size of 250000.
- However for this cycle size, the standard *a posteriori* MCNP diagnostic employing the Shannon entropy sometimes indicated that the first cycles were often not within 1 standard deviation of the average source entropy of the last half of the problem. Running more cycles to achieve better convergence did not change this, neither did increasing the cycle size to 1000000.
- Anticipating that the error estimation would be inaccurate due to cycle-to-cycle correlations, a number (either 20, 30 or 40) of independent runs were made, generating statistics between the runs. For a cycle size of 250000, each run consisted of 1000 cycles. Instead for a cycle size of 1000000, each run consisted of 250 cycles. It was noticed that the distance of the estimated mean (for the energy deposition within a core quadrant) from one run, away from the best estimate of the population mean, was more than 100 times the standard deviation, estimated within the single run. This was for the heavy reflector case. For the conventional baffle+water reflector this ratio was instead around 50. Clearly in both cases the standard deviation estimated between cycles within a single run is a gross underestimate.
- It was decided to acquire another diagnostic tool to control the distribution of fission sites. The easiest was to impose a symmetry on the problem by requiring that the quadrants in the NE and SW directions (that do not contain the variation in water density in their outer assemblies) to be equivalent. For this, the primary and secondary source assemblies, present for the ex-core detector calculations, were substituted by normal fuel assemblies. It turned out that requiring the energy depositions in the NE and SW quadrants to be equal within their statistical errors was a reasonable condition. When this condition does not obtain, the starting fission source is not symmetric enough and/or the standard deviation, estimated between runs, is underestimated. Instead when this condition does obtain, the starting fission source may or may not be sufficiently symmetric and/or the standard deviation, estimated between runs, may or may not be a reasonable estimate. (This is just because we are comparing two numbers that may by chance be close.)

To summarize, a series of calculations were made, each calculation involving a substantial effort of further source convergence from the previous one. Each calculation consisted of 20, 30 or 40 independent runs, with each run consisting of 1000 cycles with a cycle size of 250000 or 250 cycles with a cycle size of 1000000. The results for the final calculation were used when a) the energy deposition in each of the four quadrants had stabilised from calculation-to-calculation and b) the energy depositions in the NE and SW quadrants were equal within their statistical errors. (The heavy reflector case nearly always required greater calculational effort compared with the conventional reflector.)

Finally the non-default l'Ecuyer 63-bit pseudo-random number 1 generator was employed in MCNP (period = 9.2E+18 numbers).