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A Simple Equation to Estimate the Neutron Flux Distribution in the Callisto Loop of the BR2 Reactor

R. Chaouadi

SCK•CEN, Boeretang 200
B-2400 Mol, Belgium.

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Abstract

The R&D related to reactor pressure vessel steels and fusion programs have seen an increasing use of the Callisto loop for investigating irradiation effects on materials. For reactor pressure vessel embrittlement, the Chivas (Callisto Hot Irradiation of Vessel Alloy Steels) irradiation program started in 1994. As a result, about ten irradiation campaigns were performed to date. The knowledge of the fast neutron exposure is of prime importance. Therefore, dosimetry monitors were incorporated in most of these irradiations.

However, due to the limited number of experimental results and the quasi-invariable distribution of the flux, it was interesting to investigate if a simple mathematical equation can be provided to estimate more accurately the neutron fluence of each sample, at any location into the in-pile section.

Therefore, the aim of this document is to report how a simple mathematical equation is obtained and validated with the experimental results obtained with dosimetry measurements.

Introduction

The Callisto (CApabiLity for Light water Irradiation in Steady state and Transient Operation) loop was built in the early 90 for fuel investigation under PWR conditions, in particular, the behavior of advanced PWR fuel up to high burnup. It has three in-pile sections, IPS 1, 2 and 3. The location of these sections in the BR2 reactor is shown in Figure 1. Each section can be loaded with nine fuel rods (see Figure 2).

After the decline of the fuel program in the mid-90's, it was suggested to investigate the feasibility of using such loop to study radiation damage mechanisms of reactor pressure vessel steels. Therefore, a demo irradiation experiment was performed in 1994 during the last cycle of the BR2 reactor where a number of key materials were selected for irradiation in one cycle. This irradiation program was called CHIVAS (Callisto Hot Irradiation of Vessel Alloy Steels). The basic idea was to replace the fuel rods with Charpy and tensile specimens of representative reactor pressure vessel steels. Among these steels, some reference steels are well known and their behavior under irradiation is well documented. Appropriate dosimetry was also included in this experiment. Preliminary examination of the results has confirmed the usefulness of such irradiation setup in the BR2 reactor for RPV group. It was, therefore, decided to perform subsequent Chivas-irradiation campaigns to investigate some aspects related to RPV embrittlement. To date, nine Chivas irradiation companions were successfully carried out (Chivas-0 to Chivas-8). Hence, irradiation at 150°C, 260°C, 290°C and 305°C were already performed for RPV embrittlement issues. Since, the corrosion (Coriolis, Corona) as well as the fusion materials (FINC, IRMAS) programs are among the other users of this irradiation installation.

Except for the Chivas-0 demonstration campaign, the dosimetry effort was drastically reduced for all other irradiations. Generally, only few flux monitors, located usually at the maximum flux level are incorporated for dosimetry measurement. However, due to non-uniformity of the neutron flux as a result of the reactor configuration, it is important to estimate as accurately as possible the neutron exposure of each sample for a better interpretation of the results. Therefore, the objective of this note is to provide a simple spatial equation that allows a reasonable representation of the fluence-flux distribution in the Callisto loop.

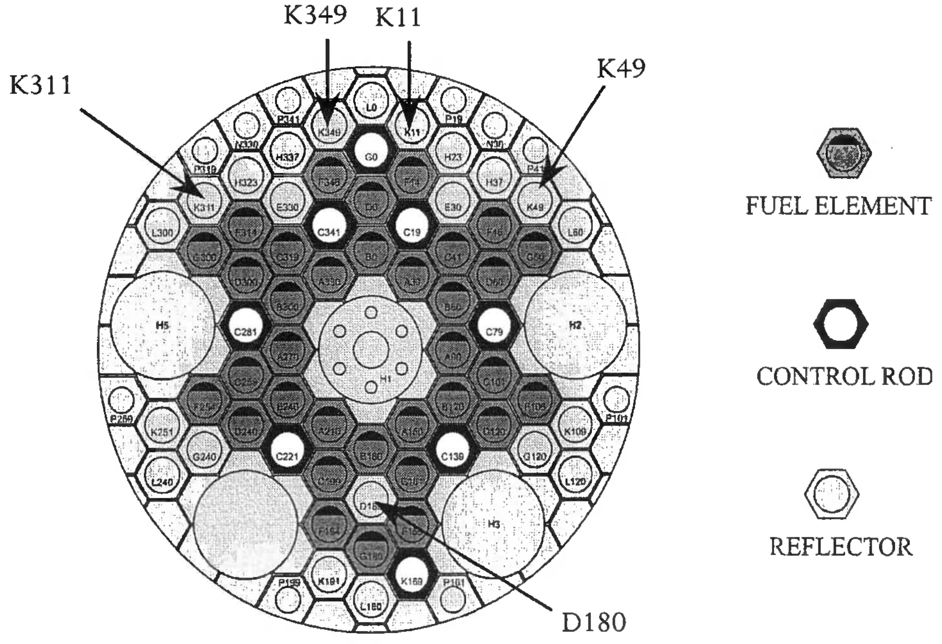


Figure 1. Horizontal cross section of the BR2 reactor at midplane (from [1]). The in-pile sections that have been used for Callisto are indicated.

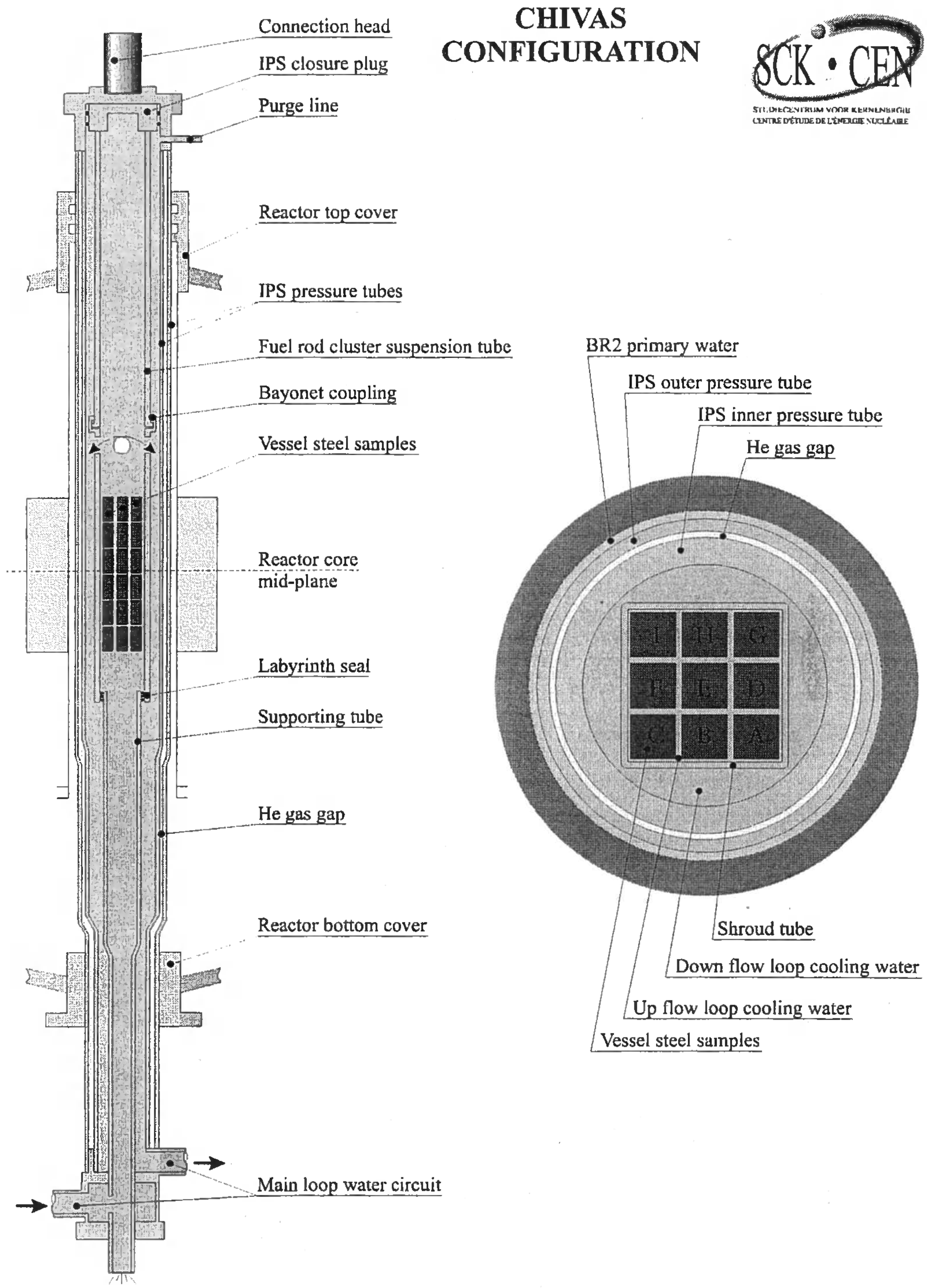


Figure 2. In-pile section in the Callisto loop.

Description of the in-pile section

The cross section of an in-pile section is schematically shown in Figure 3. It contains 9 square-shaped channels labeled A, B, ... , I. The cross section size of a single channel is about 1 cm². The neutron dose will be dependent on the axial (Z) position into the reactor but also on its cross-section position. Indeed, two of the in-pile sections of the Callisto loop are located in the reflector, and therefore, one side of the in-pile section, (A, B, C channels) is oriented to the reactor core while at the opposite side (G, H, I channels) no fuel element is present. As a result, the neutron exposure will be a function of the three axial positions X, Y and Z. However, in some cases, when the specimens are rotated at the mid-cycle of irradiation, there is a much better uniformity across the channel. Of course, in order to be able to correctly represent the flux distribution, a reference point - related to the time of irradiation and to the degree of burnup of the surrounding fuel elements - is required. In our case, this reference point is taken as the maximum neutron fluence at the central point of the channel, namely, channel E. The reasons of this choice will be given later. To simplify the mathematical formulation, the following coordinate system is used:

- The axial position, Z, into the BR2 reactor is given by the actual position according to ...
- For the lateral and transverse positions, the local coordinate system is used (see Figure 3)
  - X=0; Y=0 at the central position E
  - X=1 for positions A, D & G; X=–1 for positions C, F & I; X=0 for positions B and H;
  - Y=1 for positions G, H & I; Y=–1 for positions A, B & C; Y=0 for positions D and F;

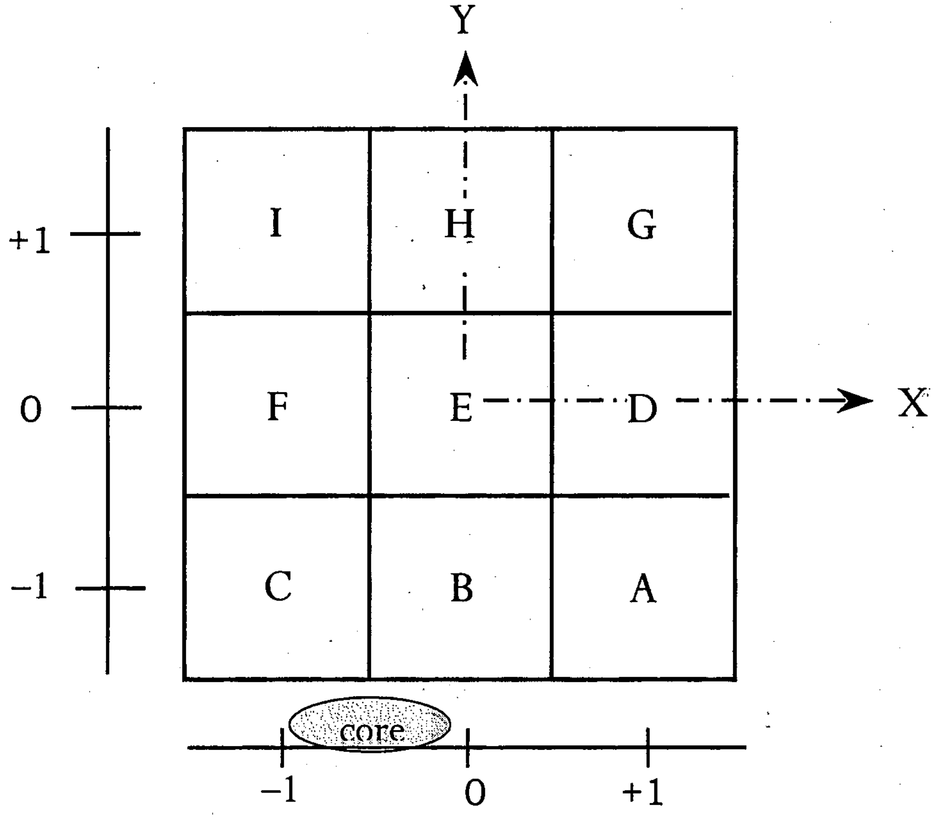


Figure 3. Schematic representation of the cross section of the in-pile section.

Review of the Chivas irradiation program

The Chivas irradiation program started in October 1994 with the aim of irradiating a number of RPV steels before the long shutdown and refurbishment of the BR2 reactor planned for mid 1995. The three in-pile sections were located at the reflector. After the successful demonstration of the ability to use the Callisto loop for radiation effects on materials (Chivas-0) it was followed by three additional irradiation campaigns, namely Chivas 1, 2 and 3. Note that, contrary to Chivas-0, the dosimetry effort for the subsequent irradiations was limited to the midplane level in some of the channels. It was also demonstrated that other irradiation temperatures could be achieved: 150°C for Chivas-1 and 260°C for Chivas-2 and 3. After the refurbishment, one in-pile section was transferred into the reactor to increase the neutron flux (D180). The two other in-pile sections were maintained in their initial positions in reflector (K11 and K311). As a result, eight irradiation campaigns (Chivas-0 to 6 + FINC-IRMAS) were successfully performed. In one case, Chivas-6, no dosimeter was included due to lack of time. However, some measurements were performed directly on the broken Charpy specimens. For all these irradiations, a special attention was given to appropriately select the location of the samples in the in-pile section to reduce as much as possible the fluence deviation for a specific set of samples of a specific material. However, this was not easy and in some of cases, it was found that the fluence of individual samples from one set of specimens might vary in large proportions from one to an other. Hence, within the IAEA round robin on WWER-440 RPV weld, where one material was irradiated but in various conditions of testing (irradiated, irradiated annealed and irradiated-annealed-reirradiated) and test methodologies (tensile, Charpy impact and fracture toughness), the number of specimens was such that a uniform fluence is required. Therefore, the irradiation setup for Chivas-7 and 8 was 180° rotated at the mid-cycle to flatten the cross sectional flux distribution. An axial translation would have been desirable to improve the axial uniformity as well but not possible in the actual Callisto configuration. Table 1 summarizes the irradiation conditions of the various Chivas irradiation programs used for RPV embrittlement investigations. The in-pile section located in channel D180 was used for the fusion program, FINC (Table 2). Some of the available free space was filled with samples of martensitic steels (IRMAS).

Table 1. Summary of the Chivas irradiations performed for RPV embrittlement issues.

	program	materials	IPS	total fluence (10^{19} n/cm^2)	$T_{irradiation}$ (°C)	rotation	dosimetry
Chivas-0	demonstration	various RPV steels	K11 & 349	3.0	290	no	yes
Chivas-1	R&D	various RPV steels	K11, 49, 311	4.5	150	no	midplane
Chivas-2	R&D	various RPV steels	K11, 49, 311	4.0	260	no	midplane
Chivas-3	R&D	various RPV steels	K11, 49, 311	8.0	260	no	midplane
Chivas-4	R&D	73W weld	K311	2.6	290	no	midplane
Chivas-5	R&D	various RPV steels	K311	4.0	305	no	midplane
Chivas-6	IAEA CRP-4	JRQ	K311	4.5	290	no	no
Chivas-7	IAEA	WWER-440 weld	K11 & 311	6.5	270	yes	yes
Chivas-8	IAEA	WWER-440 + JSPS	K311	6.0	270	yes	yes

Table 2. FINC-IRMAS irradiation (IPS-2, Channel D180).

	program	materials	IPS	total fluence (10^{19} n/cm^2)	$T_{irradiation}$ (°C)	rotation	dosimetry
FINC-IRMAS	fusion	Inconel 718	D180	38	300	no	yes
	ADS	HT9		35	300		midplane

Mathematical formulation

In order to mathematically formulate a spatial-dependent flux distribution function, the available experimental data were fitted for two configurations: axial and cross-section distribution. As it can be seen from Table 1, Chivas-0, Chivas-7, Chivas-8 and FINC dosimetry measurements are used to determine the fitting fluence equation as a function of axial position. The fluence distribution, which was found to fit well the experimental data, is a sine-type equation:

$$\Phi = \frac{\Phi_{\max}}{2}\left[1-\cos\left(\frac{Z(\mathrm{mm})}{199}-2.78\right)\right]$$

where $\Phi_{\max}$ is the maximum fluence measured at the midplane of a specific channel, and Z is the axial position into the reactor. The axial position Z is expressed in mm while the fluence Φ is expressed in the same units as $\Phi_{\max}$, namely n/cm² or dpa.

A typical example is given in Figure 8 for the Chivas-8 irradiation. Note than in the case of Chivas-8, the irradiation setup was rotated at the mid-cycle to flatten the cross-sectional flux distribution. As it can be seen, the deviation does not exceed 5% from the average curve. Other examples will be given later.

It should be noted that $\Phi_{\max}$ in the case of Chivas-8 can equally be taken as the maximum fluence at each channel, at the E-channel or an average value of all channels.

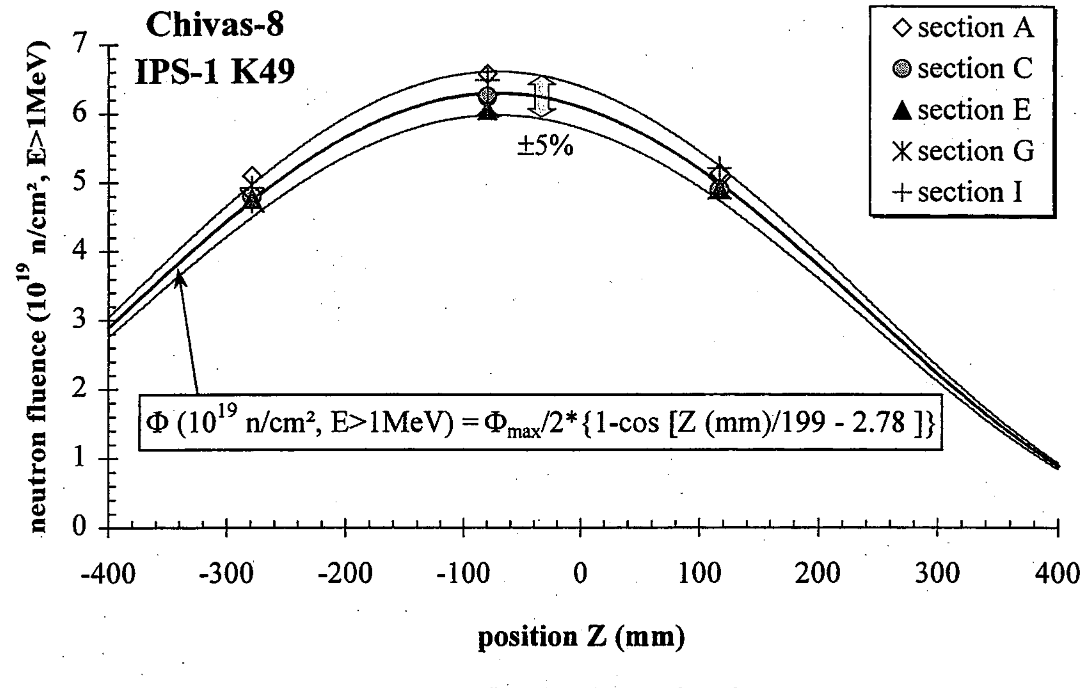


Figure 4. Neutron flux distribution for Chivas-8.

There is a significant neutron flux gradient across each in-pile section. Indeed, contrary to Chivas-7 and Chivas-8, all other irradiation campaigns were not rotated. As a result, in particular for the in-pile sections located in the reflector, the channels that are close to the fuel elements, are more exposed than the others. The experimental data have shown that the flux variation is the in-pile cross section is a linear function with both radial and transverse directions.

In order to represent the cross section distribution of the flux, the following procedure is adopted. The three-dimensional axis system is chosen such that the center position, E, is the 0-axis:

- X-axis represents the horizontal axis (example ABC) where X=0 for BEH positions and –1 for CFI positions and +1 for ADG positions;
- Y-axis represents the transverse axis (example CFI) where Y=0 for FED positions and –1 for CBA positions and +1 for IHG positions;
- Z-axis represents the vertical axis of the axial position into the reactor. The Z-axis takes the actual value of the position as defined for the BR2 reactor. The maximum flux is located at Z≈-65 mm.

The axial (Z) distribution of the flux is taken similar to the one given before. However, the maximum flux, Φ_{max}, is replaced by Φ_{Emax}, which is the Φ (0,0, -50). The flux at a specific Z level of the cross section is then fitted with the following equation:

$$\Phi = \Phi_{Emax} \left\lfloor 1 + \alpha X + \beta Y \right\rfloor$$

where α and β are constants, and X and Y the horizontal and transverse position with respect to the E channel (X,Y=–1, 0 or +1).

Figures 5 and 6 give two examples of such cross-sectional distribution in two in-pile sections, K311 and D180. As it can be seen, even D180, which is surrounded by fuel elements, is not uniform. The channels A, B, and C closer to the reactor core exhibiting higher fluences.

Combining both the axial and the cross-sectional flux distribution functions leads to:

$$\Phi = \frac{\Phi_{max}(1 + \alpha X + \beta Y)}{2}\left[1 - \cos\left(\frac{Z}{199} - 2.78\right)\right]$$

where X=-1,0 or +1; Y=-1;0 or +1 and Z is expressed in mm. For the in-pile sections K11 and K311, α≈-0.08 and β≈-0.22. Note that in Chivas-7 and Chivas-8, α and β are close to 0.

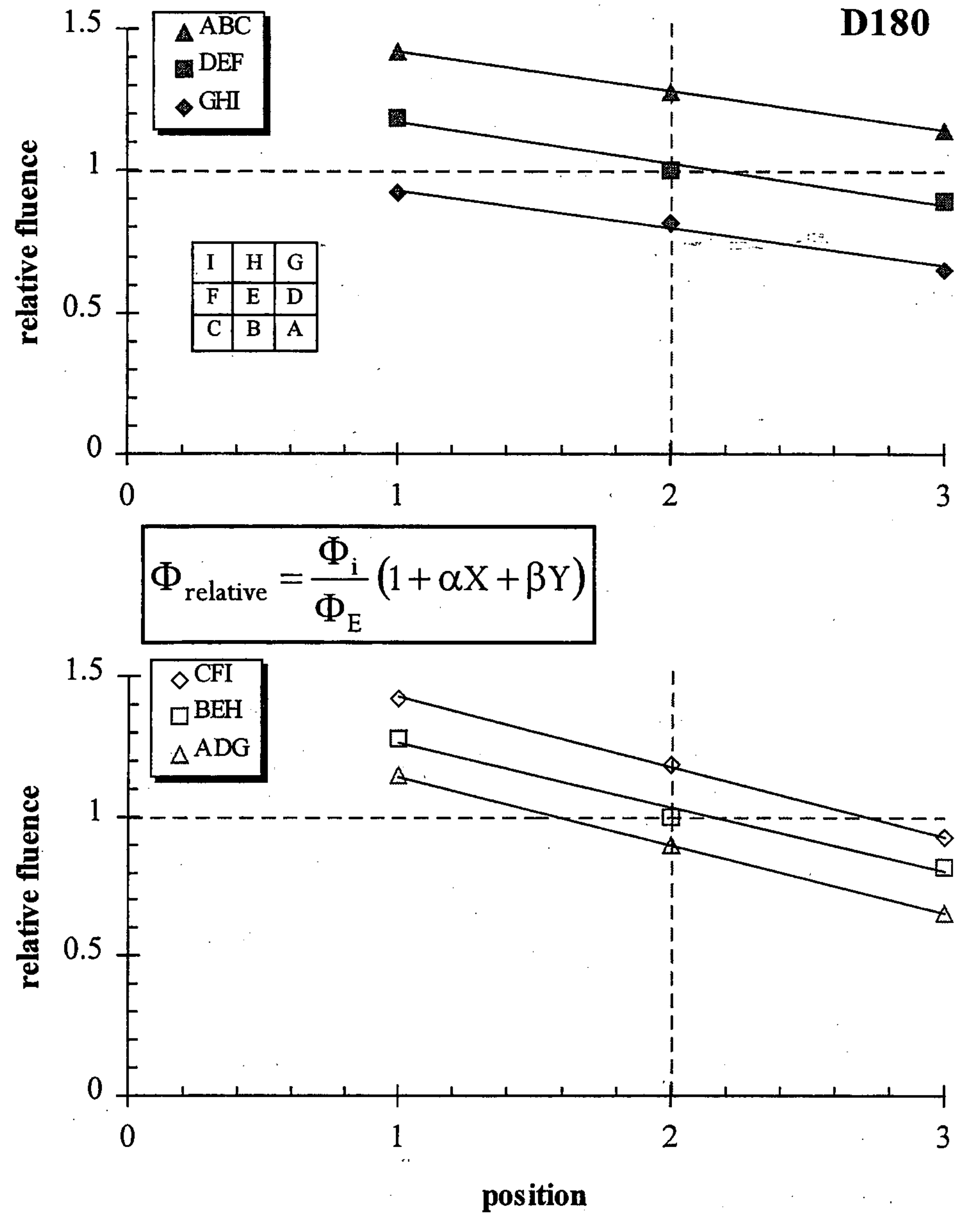
Φ_{max} is the maximum fluence in the specific channel. However, if not available, this maximum value can be estimated, with a reasonable accuracy, from the neighboring experimental values. More specifically, it is found that:

$$\Phi_{max} \approx \Phi_{E\,max} \approx \frac{1}{9}\sum_{i=A}^{I}\Phi_i \approx \frac{\Phi_A + \Phi_C + \Phi_G + \Phi_I}{4} \approx \frac{\Phi_B + \Phi_D + \Phi_F + \Phi_H}{4}$$

Four examples are given in Figures 7 to 10 from which the theoretical fluence distributions are derived from one single value, Φ_{max}, taken equal to $\Phi_{E\,max}$ when available and calculated from four crossing channels, otherwise.

Finally, it is important to note that, in absence of dosimetry data, the neutron calculations allow to estimate Φ_{max} with sufficient accuracy. The later can be used in the above distribution function to determine the neutron fluence of each specimen.

Figure 11 compares all available experimental data to estimated ones using the simple equation developed here and using one single reference maximum fluence, Φ_{max}, defined from the E channel if available and averaged value, otherwise. As it can be seen, 90% of the data are within the 10%-deviation bounds of the 1:1 line. A better agreement can be obtained if specific parameters of the in-pile section are used (α, β and Φ_{max}).



$$\Phi_{\text{relative}} = \frac{\Phi_i}{\Phi_E}\left(1+\alpha X+\beta Y\right)$$

Figure 5. Neutron flux distribution in the cross section of the D180 in-pile section (FINC).

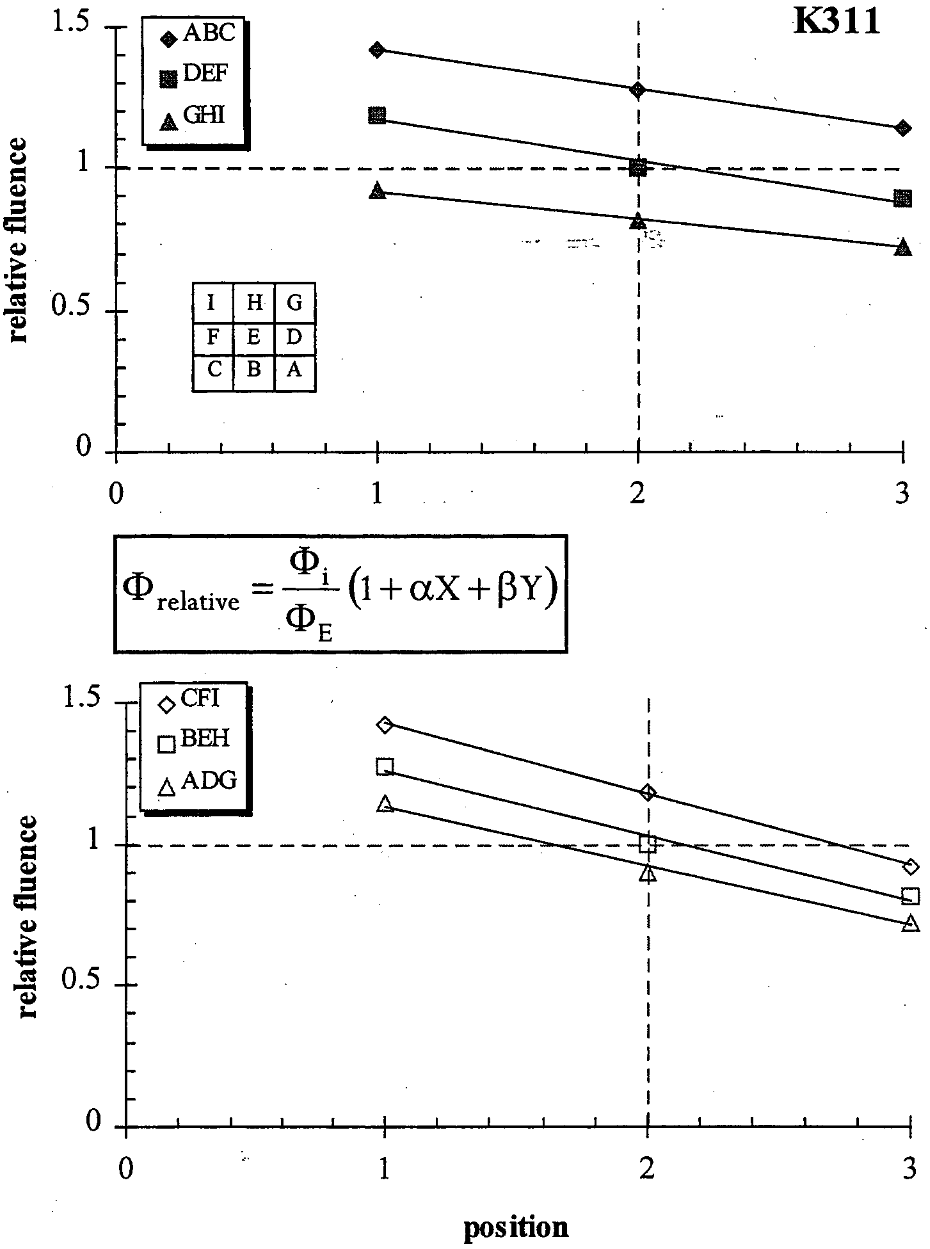


Figure 6. Neutron flux distribution in the cross section of the K311 in-pile section (Chivas-5).

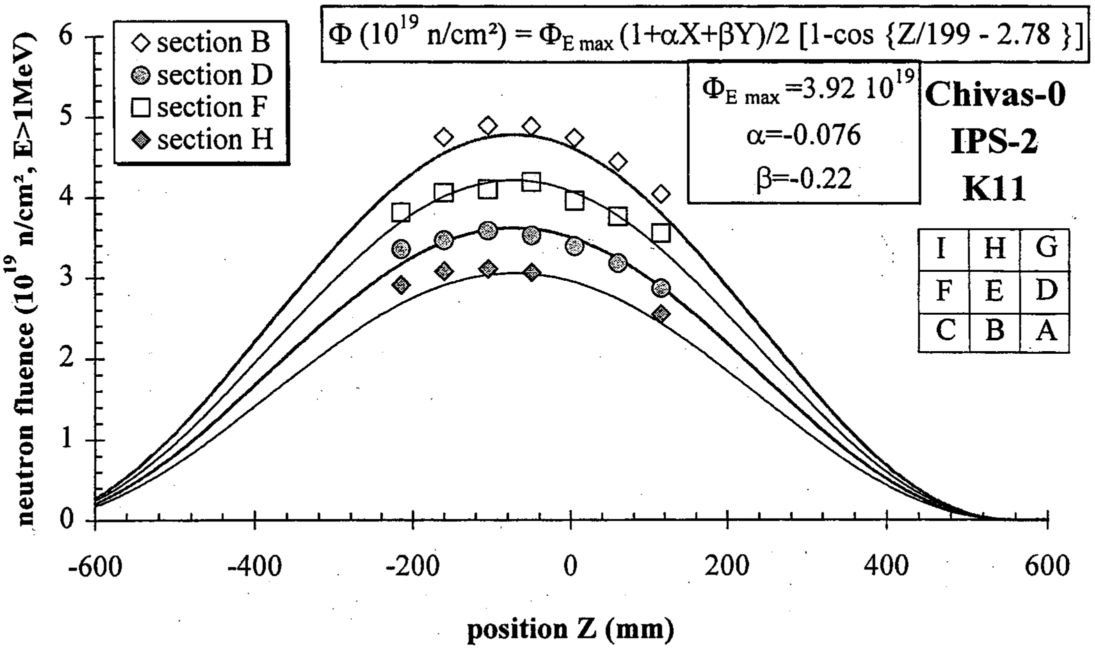


Figure 7. Neutron flux distribution for the in-pile section K11 (Chivas-0).

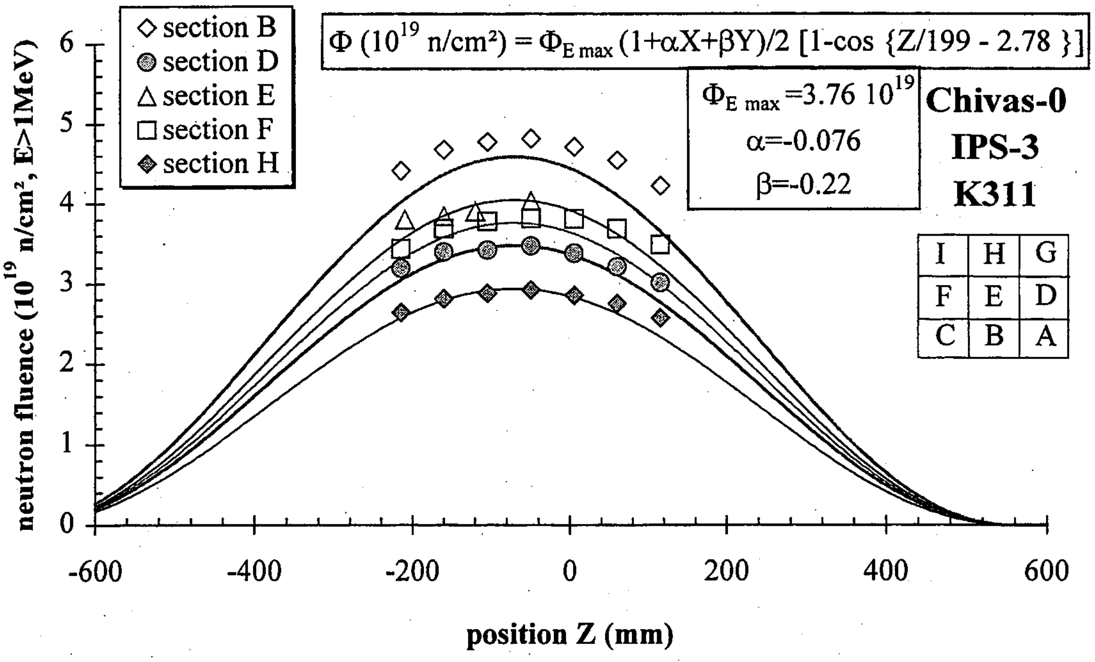


Figure 8. Neutron flux distribution for the in-pile section K311 (Chivas-0).

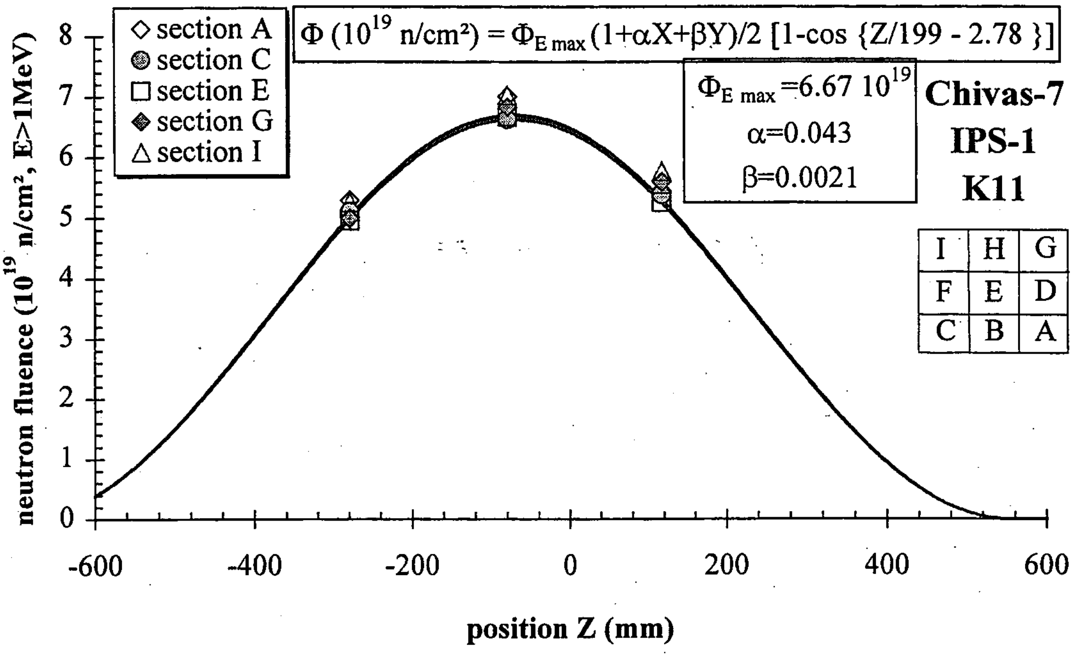


Figure 9. Neutron flux distribution for the in-pile section K311 (Chivas-7). Note that $\alpha \approx \beta \approx 0$ which lead to a flat cross sectional distribution.

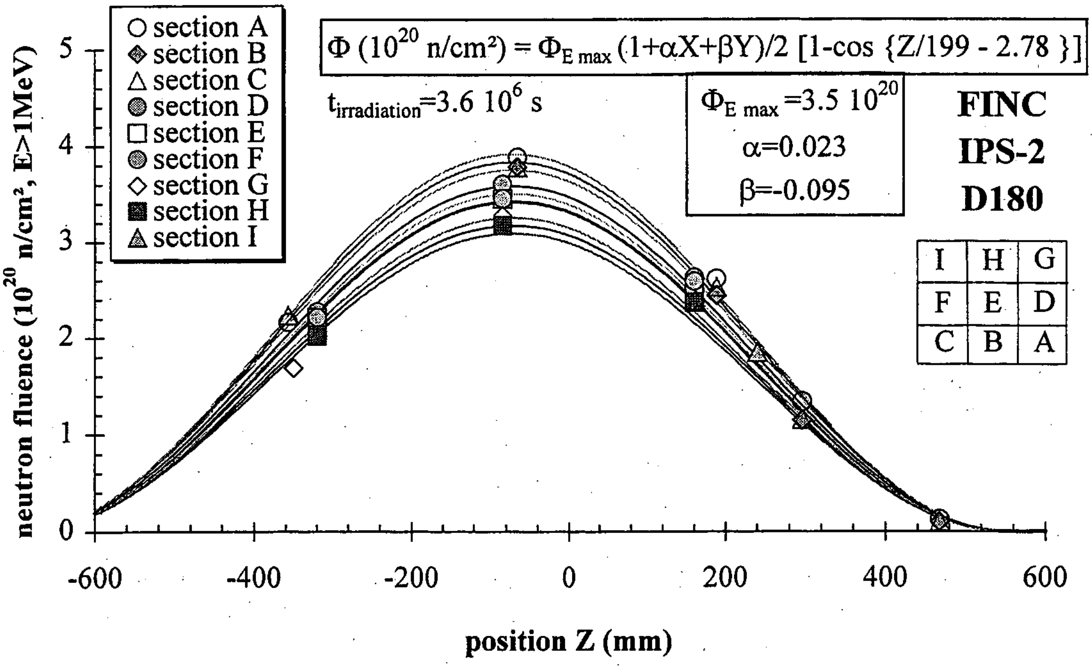


Figure 10. Neutron flux distribution for the in-pile section D180 (FINC-IRMAS).

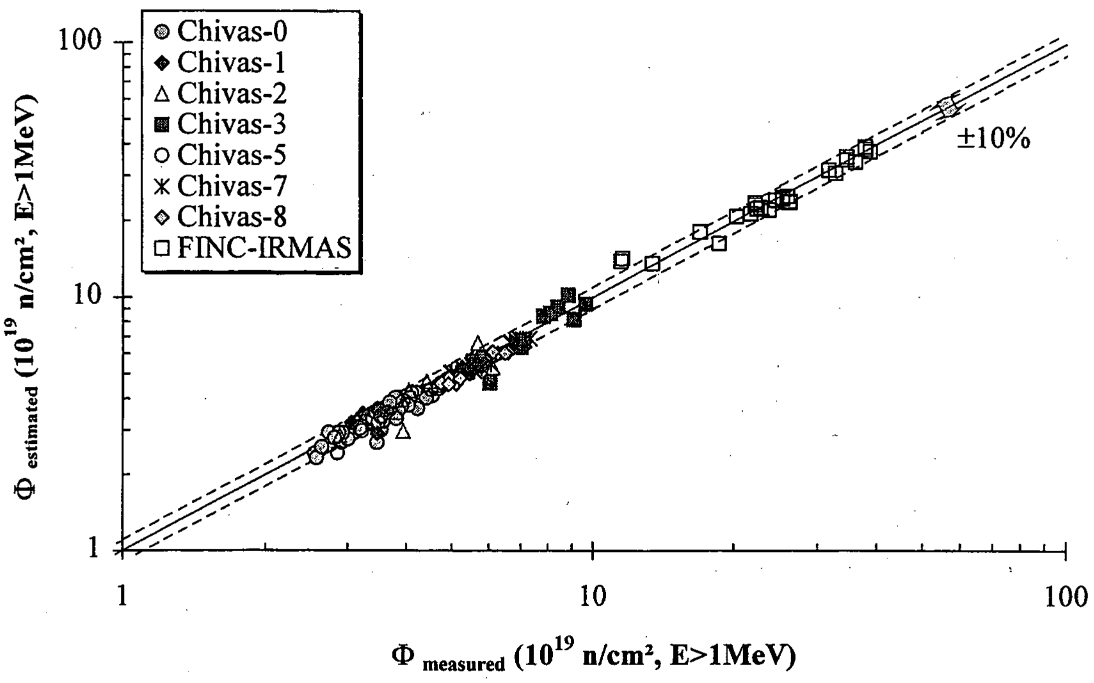


Figure 11. Comparison of experimentally measured fast fluences with estimated ones using the simple equation.

Conclusions

The dosimetry measurements collected during the irradiation campaigns of reactor pressure vessel and fusion materials in the Callisto loop were used to provide a mathematical equation that allows a reasonable estimation of the fast neutron fluence at each position into the in-pile sections of the Callisto loop. The distribution can be written as:

$$\Phi = \frac{\Phi_{max}\left(1+\alpha X+\beta Y\right)}{2}\left[1-\cos\left(\frac{Z}{199}-2.78\right)\right]$$

While the axial distribution does not vary form one in-pile section to another, the constants α and β for the cross sectional distribution may vary. However, it is found that $\alpha \approx -0.08$ and $\beta \approx -0.22$ for the in-pile section K11 and K311. For D180, $\alpha \approx 0.02$ and $\beta \approx -0.1$. The constants α and β tend to 0 if the irradiation setup is 180° rotated at mid-cycle, as with Chivas-7 and Chivas-8.

Acknowledgements

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Reference

[1] B. Verboomen, A.Beeckmans de West-Meerbeeck, Th.Aoust, and Ch. De Raedt, "The Monte Carlo Modelling of the Belgian Materials Testing Reactor BR2", Monte Carlo 2000 International Conference, Lisbon, 23-26 October 2000.

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