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New Dosimetric Interpretation of the DV50 Vessel-Steel Experiment Irradiated in the OSIRIS MTR Reactor Using the Monte-Carlo Code TRIPOLI-4®

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Abstract. An irradiation program DV50 was carried out from 2002 to 2006 in the OSIRIS material testing reactor (CEA-Saclay center) to assess the pressure vessel steel toughness curve for a fast neutron fluence (E>1MeV) equivalent to a French 900-MWe PWR lifetime of 50 years. This program allowed the irradiation of 120 specimens out of vessel steel, subdivided in two successive irradiations DV50 n°1 and DV50 n°2. To measure the fast neutron fluence (E>1MeV) received by specimens after each irradiation, sample holders were equipped with activation foils that were withdrawn at the end of irradiation for activity counting and processing. The fast effective cross-sections used in the dosimeter processing were determined with a specific calculation scheme based on the Monte-Carlo code TRIPOLI-3 (and the nuclear data ENDF/B-VI and IRDF-90). In order to put vessel-steel experiments at the same standard, a new dosimetric interpretation of the DV50 experiment has been performed by using the Monte-Carlo code TRIPOLI-4 and more recent nuclear data (JEFF3.1.1 and IRDF-2002). This paper presents a comparison of previous and recent calculations performed for the DV50 vessel-steel experiment to assess the impact on the dosimetric interpretation.

1 Introduction

Within the framework of the French NPPs lifetime extension program, an R&D irradiation program DV50 was carried out from 2002 to 2006 in the OSIRIS material testing reactor (CEA-Saclay center) [1] to assess the pressure vessel steel toughness curve for a fast neutron fluence (E>1MeV) equivalent to a 900-MWe PWR lifetime of 50 years.

Material Toughness (resistance to crack growth) is governed by the energy absorbed as the crack moves forward. This mechanical property depends on chemical composition, temperature and also neutron fluence for a material under irradiation. The nil-ductility temperature (above which a material is ductile and below which it is brittle) increases with the fluence of fast neutrons (E>1MeV).

The DV50 program allowed the irradiation of 120 CHARPY specimens out of 16MND5 vessel steel, subdivided in two successive irradiations DV50 n°1 and DV50 n°2. To measure the fast neutron fluence (E>1MeV) received by specimens after each irradiation, sample holders were equipped with activation foils that were withdrawn at the end of irradiation for activity counting and processing. The

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dosimeter processing (giving neutron fluences and fluxes from dosimeter activities) needs fast effective cross-sections (ratio of reaction rate and fast flux) determined with a specific calculation scheme simulating the experiment irradiation in the OSIRIS reactor.

The dosimetric interpretation initially performed for the DV50 experiment was based on the following tools and nuclear data:
- The Monte-Carlo code TRIPOLI-3 [2],
- The nuclear data evaluation ENDF/B-VI [3],
- The dosimetric response library IRDF-90 [4].

In order to put vessel-steel experiments at the same standard, a new dosimetric interpretation of the DV50 experiment has been performed by using more recent tools and nuclear data:
- The Monte-Carlo code TRIPOLI-4 [5],
- The nuclear data evaluation JEFF3.1.1 [6],
- The dosimetric response library IRDF-2002 [7].

TRIPOLI-4 code has been validated against experimental results based on neutron flux measurements performed in ex-core and in-core experiments in the case of the OSIRIS reactor [8, 9]. This paper presents a comparison of previous and recent calculations performed for the DV50 vessel steel experiment to assess the impact on the dosimetric interpretation.

In this paper, DV50 experiment and its surveillance dosimetry will first be described. Then, the initial dosimetric interpretation of the DV50 experiment will be presented. Afterwards, the methodology and results of the new dosimetric interpretation will be detailed. Finally, results of initial and new interpretations will be compared and discussed.

2 DV50 experiment

2.1 OSIRIS reactor and DV50 irradiation position

OSIRIS is a material testing reactor located at the CEA-Saclay site and operated since 1966. It is a 70 MWth pool type light water reactor with an open core. The core is a compact unit (70×80×90 cm^3). The core tank contains a centrally located rack containing 56 cells (8×8×90 cm^3, see Figure 1). These cells are loaded with 38 standard fuel elements, 6 control elements (hafnium absorber in upper part and fuel in lower part) and up to 7 beryllium elements (in row 10, south side). The remaining cells (in particular 24, 44 and 64) are dedicated to in-core experiments with high fast neutron flux (about 2×10^{14} $n.cm^{-2}.s^{-1}$).

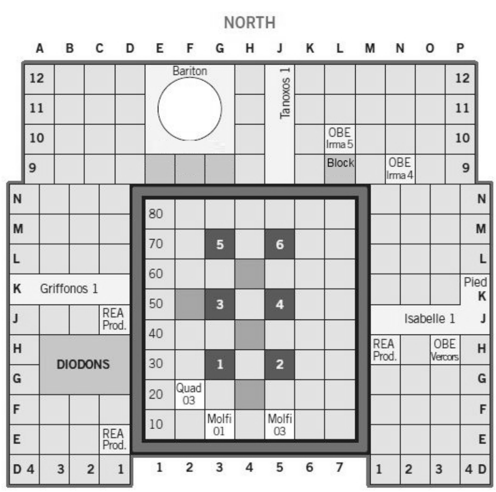

Figure 1. Schematic representation of the core of the OSIRIS reactor in its tank, the six control rods, and the in-core and ex-core experimental positions.

External grids surround the core, on 3 faces of the tank (north, east and west), making it possible to set up to 27 experimental devices on the first periphery (where the fast neutron flux is about 10 times less important than in the core) and many others on the second and the third peripheries.

The DV50 irradiation was carried out in the position L10 of the second periphery north and behind a stainless-steel block located at the position L9 of the first periphery for gamma shielding.

2.2 DV50 device

The DV50 program allowed the irradiation of 120 CHARPY specimens out of 16MND5 vessel steel, subdivided in two successive irradiations DV50 n°1 and DV50 n°2. For each irradiation, 60 specimens were piled-up inside the IRMA5 irradiation device and irradiated in the OSIRIS ex-core position L10 of the second periphery north. IRMA is a cylindrical capsule (75 mm in external diameter) designed for the irradiation, in an inert environment, of structural materials and more particularly, the steels used in pressurized water reactors. It comprises a double jacket (constituting a heat shield) equipped with heating elements distributed along the capsule to regulate the temperature of irradiated specimens (Figure 2).

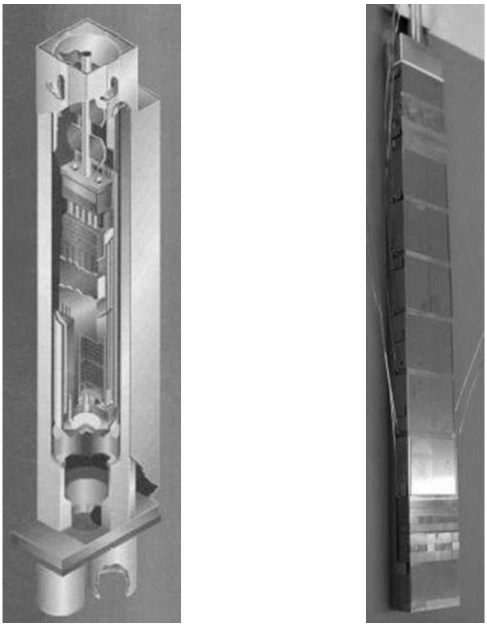

Figure 2. IRMA irradiation device (on the left) and steel specimens piled-up in the DV50 sample-holder (on the right).

2.3 DV50 dosimetry

To measure the neutron fluence received by specimens after each irradiation DV50 n°1 and DV50 n°2, sample holders were equipped with activation foils that were withdrawn at the end of irradiation for activity counting and processing. Different types of dosimeters were used: nickel (Ni), copper (Cu), iron (Fe), niobium (Nb) foils for fast fluence; copper-cobalt (CuCo) foils for thermal fluence. Fast dosimeters were placed along the sample holder at 7 axial levels; each level contains a set of 4 foils: Ni, Cu, Fe and Nb. Thus, each type of dosimeters can provide an axial distribution of fast fluence. Using different types of foils allows us to investigate consistent results among them in terms of axial neutron flux profiles and levels.

3 Initial dosimetric interpretation of the DV50 experiment

At the end of each irradiation DV50 n°1 and DV50 n°2, activation foils (Ni, Cu, Fe and Nb) equipping the sample holder were withdrawn for activity counting.

A dosimeter under neutron flux $\phi(E,t)$ becomes more or less radioactive according to a neutron reaction of interest characterized by a microscopic cross-section $\sigma(E)$. From the dosimeter activity measured after an irradiation of a duration T, we can deduce the microscopic reaction rate (integrated in time) τ, which is ultimately the neutron amount directly accessible by measurement:

$$\tau = \int_{0MeV}^{\infty} \int_{T} \sigma(E)\, \phi(E,t)\, dE\, dt \tag{1}$$

Fast neutron fluence (E>1MeV) $\Phi_{E>1MeV}$ can be experimentally determined from the microscopic reaction rate (integrated in time) τ of a given dosimeter, using a "fast effective cross-section" $\sigma_{E>1MeV}$:

$$\Phi_{E>1MeV} = \frac{\tau}{\sigma_{E>1MeV}} \tag{2}$$

If the neutron energy spectrum does not vary or varies little during the irradiation, we have:

$$\phi(E,t) = \varphi(E) \tag{3}$$

$$\sigma_{E>1MeV} = \frac{\tau}{\Phi_{E>1MeV}} = \frac{\int_{0MeV}^{\infty} \sigma(E)\, \varphi(E)\, dE}{\int_{1MeV}^{\infty} \varphi(E)\, dE} \tag{4}$$

Fast effective cross-sections (ratio of reaction rate and fast flux) used in the initial dosimetric interpretation of DV50 experiment were determined with a specific calculation scheme based on:
- The Monte-Carlo code TRIPOLI-3 used for simulating the DV50 experiment in the OSIRIS reactor,
- Its associated multigroup-wise data library from the nuclear data evaluation ENDF/B-VI for Monte-Carlo transport simulation,
- The dosimetric response library IRDF-90 used for the fast dosimeters Ni, Cu, Fe and Nb.

In the TRIPOLI-3 calculation, a 3D-modeling of the core geometry was performed with homogenous blocks of fuel elements (Figure 3). This was a fixed-source simulation using a neutron-source 2D-distribution based on a power map calculated by the 2D-diffusion code DAIXY [10] (used in the operation of the OSIRIS reactor); a cosine-shaped profile was considered for the axial distribution and taken from previous measurements in the OSIRIS core. The neutron-source intensity was normalized to correspond to the rated power of the OSIRIS reactor (70 MWth).

Table 1 presents the values of the fast effective cross-sections used in the initial dosimetric interpretation of DV50 experiment. At the end of the dosimeter processing, 4 axial distributions of fast neutron fluence were obtained corresponding to the 4 types of fast dosimeters (Fe, Ni, Nb and Cu). The final measured distribution of fast fluence was the average of the four ones.

Table 1. Fast effective cross-sections issued form TRIPOLI-3 calculation and used in the initial dosimetric interpretation (standard deviation is about 4% for Fe, Ni and Nb dosimeters, and about 6% for Cu dosimeters).

Dosimeter		Iron	Nickel	Niobium	Copper
Reaction of interest		$^{54}Fe(n,p)^{54}Mn$	$^{58}Ni(n,p)^{58}Co$	$^{93}Nb(n,n')^{93m}Nb$	$^{63}Cu(n,\gamma)^{60}Co$
Fast effective cross-section (mbarn)	DV50 n°1	83.28	116.57	200.97	0.6685
	DV50 n°2	85.24	115.53	197.03	0.6061

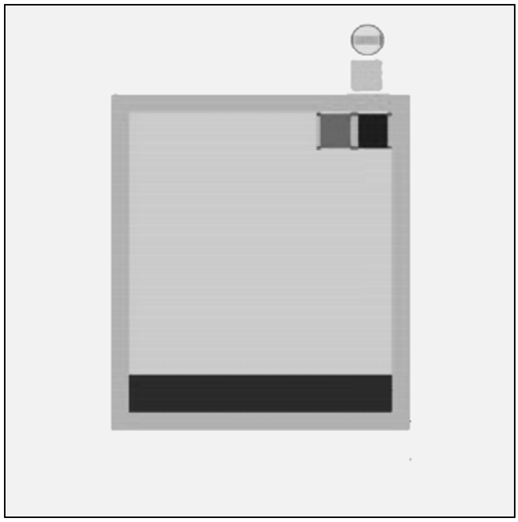

Figure 3. Geometry modeling of the OSIRIS core and the DV50 experiment with the TRIPOLI-3 code.

4 New dosimetric interpretation of the DV50 experiment

The principle of this new dosimetric interpretation of the DV50 experiment is to reassess the fast effective cross-sections used in the dosimeter processing by using more recent tools and nuclear data, in order to put vessel-steel experiments at the same standard. Thus, a new calculation has been performed based on:

- The Monte-Carlo code TRIPOLI-4 used for simulating the DV50 experiment in the OSIRIS reactor,
- Its associated point-wise data library from the nuclear data evaluation JEFF3.1.1 for Monte-Carlo transport simulation,
- The dosimetric response library IRDF-2002 used for the fast dosimeters Ni, Cu, Fe and Nb.

For a given dosimeter *i*, the microscopic reaction rate (integrated in time) τ is the amount directly accessible by neutron measurement and therefore independent from the fast effective cross-section used in the dosimeter processing. So, we have:

$$\tau = \left(\sigma^{i}_{E>1MeV}\right)^{T3} \cdot \left(\Phi^{i}_{E>1MeV}\right)^{T3} = \left(\sigma^{i}_{E>1MeV}\right)^{T4} \cdot \left(\Phi^{i}_{E>1MeV}\right)^{T4} \quad (5)$$

$$\left(\Phi^{i}_{E>1MeV}\right)^{T4} = \frac{\left(\sigma^{i}_{E>1MeV}\right)^{T3}}{\left(\sigma^{i}_{E>1MeV}\right)^{T4}} \cdot \left(\Phi^{i}_{E>1MeV}\right)^{T3} \quad (6)$$

With:

- $\left(\sigma^{i}_{E>1MeV}\right)^{T3}$ and $\left(\Phi^{i}_{E>1MeV}\right)^{T3}$ respectively the fast effective section of the dosimeter *i*, issued from the "TRIPOLI-3" calculation scheme, and the corresponding "measured" fast neutron fluence (the result of the initial dosimetric interpretation).
- $\left(\sigma^{i}_{E>1MeV}\right)^{T4}$ and $\left(\Phi^{i}_{E>1MeV}\right)^{T4}$ respectively the fast effective section of the dosimeter *i*, issued from the "TRIPOLI-4" calculation scheme, and the corresponding "measured" fast neutron fluence (the result of the new dosimetric interpretation).

In the TRIPOLI-4 calculation, a 3D-modeling of the whole core geometry has been performed, including the exhaustive plate-by-plate description of the OSIRIS fuel elements, in order to take into account the transport of neutrons through water layers between fuel plates (Figure 4).

The composition of the fuel plates is fixed for each fuel element according to the burnup of the latter. The core burnup map is issued from the DAIXY code for a representative mid-cycle configuration. The radionuclide inventory as a function of burnup is previously calculated by the APOLLO-2 lattice transport code [11]. The criticality mode has been used in the TRIPOLI-4 calculation; a neutron-source distribution is only needed to initiate simulation.

Table 2 presents the values of the fast effective cross-sections issued from the TRIPOLI-4 calculation and used in the new dosimetric interpretation of DV50 experiment.

Table 2. Fast effective cross-sections issued form TRIPOLI-4 calculation and used in the new dosimetric interpretation (standard deviation is about 1% for Fe, Ni and Nb dosimeters, and about 2% for Cu dosimeters).

Dosimeter	**Iron**	**Nickel**	**Niobium**	**Copper**
Reaction of interest	$^{54}Fe(n,p)^{54}Mn$	$^{58}Ni(n,p)^{58}Co$	$^{93}Nb(n,n')^{93m}Nb$	$^{63}Cu(n,\gamma)^{60}Co$
New fast effective cross-section (mbarn)	83.9	114.4	198.4	0.636

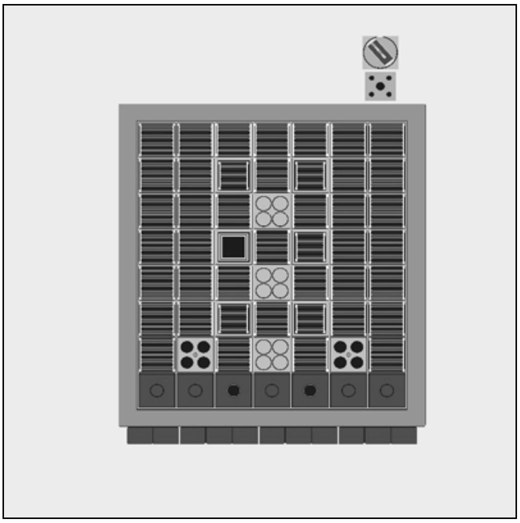

Figure 4. Geometry modeling of the OSIRIS core and the DV50 experiment with the TRIPOLI-4.

5 Discussion

Tables 3 presents a comparison of fast effective cross-sections issued from TRIPOLI-3 and TRIPOLI-4 calculations. Differences are less than 2% for iron, nickel and niobium dosimeters, and about 5% for copper dosimeters (whose threshold energy is about 6 MeV). The final measured fast neutron fluence was the average of the four ones obtained by the 4 types of dosimeters; the difference between measured fast fluences determined by initial and new dosimetric interpretations is finally less than 3%. This difference is still smaller than the measurement 1σ-uncertainty (5%). The new interpretation does not challenge the initial one; this is an important issue.

Table 3. Comparison of fast effective cross-sections issued from TRIPOLI-3 and TRIPOLI-4 calculations.

Dosimeter		**Iron**	**Nickel**	**Niobium**	**Copper**
Difference between fast effective cross-sections (T3-T4)/T4	DV50 n°1	-0.7 %	1.9 %	1.3 %	5.1 %
	DV50 n°2	1.6 %	1.0 %	-0.7 %	-4.7 %

Furthermore, similarity of fast effective cross-sections issued form TRIPOLI-3 and TRIPOLI-4 calculations does not imply necessarily similarity of calculated reaction rates and fast neutron fluxes (the fast effective cross-section is the ratio of reaction rate and fast flux).

In Table 4, we present a comparison of the nominal fast neutron flux (E>1MeV) obtained at the core midplane of the DV50 experiment by measurement and by TRIPOLI-3/TRIPOLI-4 calculations. The nominal fast flux is the ratio of the fast fluence and the irradiation time expressed in equivalent full-power days (EFPD) at the OSIRIS rated power (70 MWth). The nominal fast neutron flux issued from TRIPOLI-4 calculation is in better agreement with measurements (discrepancy is about 2σ-uncertainty of measurement) than the value issued from TRIPOLI-3 calculation (discrepancy is about 4σ-uncertainty of measurement).

So, the calculation scheme, based on the TRIPOLI-4 Monte-Carlo code and the recent nuclear data, allows better prediction of fast flux in vessel steel experiment irradiated in the OSIRIS reactor.

Table 4. Comparison of the nominal fast neutron flux (E>1MeV) obtained at the core midplane of the DV50 experiment by measurement and by TRIPOLI-3/TRIPOLI-4 calculations.

	Measurement	**TRIPOLI-3 calculation**	**TRIPOLI-4 calculation**
Nominal fast flux at the core midplane ($n.cm^{-2}.s^{-1}$)	4.9E12 (± 5%)	3.9E12 (± 3%)	4.4E12 (± 1%)
Discrepancy between calculation and measurement	-	-20%	-10%

6 Conclusion and prospects

In this paper, we present a new dosimetric interpretation of the DV50 experiment performed by using the Monte-Carlo code TRIPOLI-4 and more recent nuclear data (JEFF3.1.1 and IRDF-2002). Obtained results show consistency of previous and new calculated fast effective cross-sections used for dosimeter processing and hence consistency of measured fast fluences determined by initial and new dosimetric interpretations. The new interpretation does not challenge the initial one.

However, new values of calculated fast neutron fluxes are found in better agreement with measurements. So, the calculation scheme, based on the TRIPOLI-4 Monte-Carlo code and the recent nuclear data, allows better prediction of fast flux in vessel steel experiment irradiated in the OSIRIS reactor.

This work is being extended to other vessel-steel experiments carried out in the OSIRIS reactor, in order to put them at the same standard.

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