Annals of Nuclear Energy 36 (2009) 1706–1710

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Estimation of irradiated control rod worth

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ARTICLE INFO

Article history:
Received 29 April 2009
Received in revised form 18 August 2009
Accepted 9 September 2009
Available online 8 October 2009

ABSTRACT

When depleted control rods are planned to be used in new core configurations, their worth has to be accurately predicted in order to deduce key design and safety parameters such as the available shutdown margin. In this work a methodology is suggested for the derivation of the distributed absorbing capacity of a depleted rod, useful in the case that the level of detail that is known about the irradiation history of the control rod does not allow an accurate calculation of the absorber's burnup. The suggested methodology is based on measurements of the rod's worth carried out in the former core configuration and on corresponding calculations based on the original (before first irradiation) absorber concentration. The methodology is formulated for the general case of the multi-group theory; it is successfully tested for the one-group approximation, for a depleted control rod of the Greek Research Reactor, containing five neutron absorbers. The computations reproduce satisfactorily the irradiated rod worth measurements, practically eliminating the discrepancy of the total rod worth, compared to the computations based on the nominal absorber densities.

1. Introduction

The efficiency of a control rod to absorb excess reactivity in a nuclear reactor is a subject of major interest since it is directly related to the reactor safety. Thus, several works have been reported concerning the assessment of a control rod worth (e.g. Bretscher, 1997; Salvatores, 1992; Fadaei and Setayeshi, 2009) or the analysis of parameters that may affect it (e.g. Williams, 2004). The determination of the actual control rod worth after a significant period of reactor operation is an important issue (Hong, 1999). The accurate assessment of the actual worth is even more important in case of re-utilization of used rods after major core modifications such as the conversion of a research reactor from high to low enrichment fuel (Pond et al., 1998) and reactor upgrade (Aoyama et al., 2007) or even refueling (Hosoya et al., 2007), which change important parameters in the rod's environment, such as the power distribution per fuel assembly and the fuel burnup in the vicinity of the rod. The reliable assessment of key design and/or safety neutronic parameters such as the available shutdown margin and the rod failure criterion requires the accurate prediction of the depleted rod's worth in the new core configuration.

The normal procedure for assessing the depletion of a rod involves the reconstruction of its exact operational history, including different grid positions occupied by the rod for various core configurations, varying insertions during operation, varying local neutron fluence depending also on the reactor power level, etc., in case that the above parameters are known at a sufficient level of detail. A rough estimation of the rod's divergence from its original state, can be obtained by approximating the reduction dN_j of the jth absorber's atom density N_j for an irradiation period dt, with $dN_j = -N_j\left(\sum_{g=1}^{G}\sigma_{j,g}\Phi_g\right)dt$, where Φ_g is the neutron flux in the energy group g and $\sigma_{j,g}$ is the neutron absorption cross section of the absorber averaged over the energy group g. The absorbers' depletion during a time period ΔT, for example between two successive re-arrangements of fuel assemblies or rod position changes, can be estimated by integration, assuming that during ΔT the neutron flux in the vicinity of the rod is constant. The final atom density of the absorber thus becomes $N_j^{\Delta T} = N_j^0\exp[-(\sum_{g=1}^{G}\sigma_{j,g}\Phi_g)\Delta T]$, where N_j^0 is the absorber's atom density at the beginning of time step ΔT. This analytical approach can be applied for the successive historical core configurations to provide an estimation of the absorbers' densities depletion.

Unfortunately, the above procedure is rather unenforceable in many real cases of older research reactors, where no digital recordings of the operational parameters existed for many years, while their core configuration and operational scheme are too variable, adapted also to varying irradiation needs and occasional requirements of the experimentalists. On the other hand, any computation based on the nominal (i.e. non-depleted, given by the rod's Manufacturer) atom density of the rod absorber, which is the only

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doi:10.1016/j.anucene.2009.09.002

density precisely known, clearly overestimates the actual rod's worth. This raises serious safety concerns in case of inclusion of a depleted rod in new core designs.

In this work a methodology is suggested for predicting the actual absorption cross section of a depleted rod, allowing thus the accurate assessment of its absorbing capacity in a new core environment; the methodology is based on measurements of its integral worth conducted during the rod's operation in its former core environment, and on corresponding calculations performed using the nominal absorber concentration in the rod. In the frame of the proposed methodology, an incremental determination of the neutron absorption macroscopic cross section in user-defined horizontal layers of the rod is performed. The methodology is formulated for the general case of the multi-group theory and for more than one absorbers present in a rod.

Verification calculations are performed for one depleted control rod of the Greek Research Reactor, using the absorbers' macroscopic cross section distribution derived from the proposed methodology. The computations reproduce very satisfactorily the irradiated rod worth measurements, eliminating practically the overestimation of the total rod worth obtained with the utilization of the nominal absorbers' density. The methodology is tested by computing the depleted absorbing cross section in one energy group which comprises most of the absorbing capacity of the rod's constituents.

2. Methodology

Let $N(z,t)$ be the absorber atoms density (atoms/cm^3) at position z of the control rod, at time t. The linear rate of neutron absorptions (absorptions/cm/s) for the neutron-energy group g at position z will be

$$S\sigma^g N(z,t)\Phi^g(z,t) = S\Sigma^g(z,t)\Phi^g(z,t) \tag{1}$$

where σ^g is the microscopic neutron absorption cross section, $\Sigma^g(z,t)$ the macroscopic neutron absorption cross section, $\Phi^g(z,t)$ the neutron flux at position z for the neutron-energy group g and S the absorber's cross sectional area, constant along the rod's length. If the rod is assumed to be immersed in depth δ_n with the reactor critical at this position, then the rate of neutron absorptions in the rod for the neutron-energy group g is

$$A_n^g = S\sigma^g \int_0^{\delta_n} N(z)\Phi_n^g(z)dz = S\int_0^{\delta_n} \Sigma^g(z)\Phi_n^g(z)dz \tag{2}$$

where $\Phi_n^g(z)$ is the neutron flux of the group g in the control rod. Let now the rod be withdrawn, so that it is immersed in depth δ_{n-1}. The rate of neutron absorptions in the rod at its new position will be

$$A_{n-1}^g = S\int_0^{\delta_{n-1}} \Sigma^g(z)\Phi_{n-1}^g(z)dz \tag{3}$$

where $\Phi_{n-1}^g(z)$ is the neutron flux of group g in the control rod, for the second rod position. Let $A_{w,n}^g$ be the absorption rate of neutrons of group g in the pool water filing the empty zone created by the rod withdrawal from δ_n to δ_{n-1}, i.e.

$$A_{w,n}^g = S\sigma_w^g \int_{\delta_{n-1}}^{\delta_n} N_w\Phi_{w,n}^g(z)dz = S\int_{\delta_{n-1}}^{\delta_n} \Sigma_w^g\Phi_{w,n}^g(z)dz \tag{4}$$

where σ_w^g and Σ_w^g are (respectively) the microscopic and macroscopic neutron absorption cross section of the water in group g, N_w is the atom density of the water and $\Phi_{w,n}^g(z)$ is the neutron flux of group g in the zone $\delta_{n-1} < z < \delta_n$ with the rod immersed in depth δ_{n-1}. The change Δk_n of the core multiplication factor between the two rod positions (i.e. the relative rod worth) can be measured and it is proportional to $\sum_g[A_n^g - (A_{n-1}^g + A_{w,n}^g)]$, i.e.

$$\begin{aligned}\Delta k_n &\propto \sum_g \left[A_n^g - A_{n-1}^g - A_{w,n}^g\right]\\ &= S\sum_g\left[\int_0^{\delta_n}\Sigma^g(z)\Phi_n^g(z)dz - \int_0^{\delta_{n-1}}\Sigma^g(z)\Phi_{n-1}^g(z)dz - A_{w,n}^g\right]\end{aligned} \tag{5}$$

Let $\Delta k_n^{c,nom}$ be the change of the multiplication factor, computed with the rod's nominal (i.e. given by the rod manufacturer) absorber density $N^{nom}(z)$. Assuming that:

(a) for the same reactor power level, the neutron flux in the rod increases by a factor of c ($c \geqslant 1$) from $\Phi^g(z)$ to $c\Phi^g(z)$ when the absorber's density is depleted from its nominal value $N^{nom}(z)$ to its actual value $N^{act}(z)$ – when, correspondingly, the macroscopic absorption cross section varies from Σ^{nom} to Σ^{act} – and
(b) $A_{w,n}^g$ is negligible compared to the absorption rate in the zone $\delta_{n-1} < z < \delta_n$ with the rod immersed in depth δ_n, it is:

$$\frac{\Delta k_n^{m,act}}{\Delta k_n^{c,nom}} = \frac{S\sum_g\left[\int_0^{\delta_n}\Sigma^{g,act}(z)c\Phi_n^g(z)dz - \int_0^{\delta_{n-1}}\Sigma^{g,act}(z)c\Phi_{n-1}^g(z)dz\right]}{S\sum_g\left[\int_0^{\delta_n}\Sigma^{g,nom}(z)\Phi_n^g(z)dz - \int_0^{\delta_{n-1}}\Sigma^{g,nom}(z)\Phi_{n-1}^g(z)dz\right]} \tag{6}$$

where $\Delta k_n^{m,act}$ is measured while $\Delta k_n^{c,nom}$, $\Phi_n^g(z)$ and $\Phi_{n-1}^g(z)$ are reliably computed. Hence,

$$\begin{aligned}&\sum_g\left[\int_0^{\delta_n}\Sigma^{g,act}(z)\Phi_n^g(z)dz - \int_0^{\delta_{n-1}}\Sigma^{g,act}(z)\Phi_{n-1}^g dz\right]\\ &= \frac{1}{c}\frac{\Delta k_n^{m,act}}{\Delta k_n^{c,nom}}\sum_g\left[\int_0^{\delta_n}\Sigma^{g,nom}(z)\Phi_n^g(z)dz - \int_0^{\delta_{n-1}}\Sigma^{g,nom}(z)\Phi_{n-1}^g(z)dz\right]\\ &= C_n\end{aligned} \tag{7}$$

with C_n being a known quantity, as far as factor c is known. The procedure to obtain a representative value of c parameter is described in Section 4.

Lets now assume that the rod's absorber is essentially absorbing neutrons in the thermal energy group and that it is practically "transparent" to neutrons of higher energies. By "thermal energy group" is meant here the whole energy range where the rod's absorber exhibits an appreciable absorption cross section. Eq. (7) reads:

$$\begin{aligned}&\int_0^{\delta_n}\Sigma^{th,act}(z)\Phi_n^{th}(z)dz - \int_0^{\delta_{n-1}}\Sigma^{th,act}(z)\Phi_{n-1}^{th}dz\\ &= \frac{1}{c}\frac{\Delta k_n^{m,act}}{\Delta k_n^{c,nom}}\left[\int_0^{\delta_n}\Sigma^{th,nom}(z)\Phi_n^{th}(z)dz - \int_0^{\delta_{n-1}}\Sigma^{th,nom}(z)\Phi_{n-1}^{th}(z)dz\right]\\ &= C_n\end{aligned} \tag{8}$$

where th stands for "thermal energy group". In (8) the quantity C_n is known. Consider now that the rod is incrementally immersed by steps of length w (cm), at depths $w, 2w, 3w, \ldots, Mw$ and that the corresponding reactivity worth is measured for each rod position. Let $\overline{\Sigma}_n^{th}$ be the average value of $\Sigma^{th,act}(z)$ at rod zone $[(n-1)w, nw]$ with $n = 1,\ldots,M$ (Fig. 1), i.e.

$$\overline{\Sigma}_n^{th} = \frac{1}{w}\int_{(n-1)w}^{nw}\Sigma^{th,act}(z)dz \tag{9}$$

If the rod is considered to be immersed at depth w and then withdrawn, the application of Eq. (8) gives:

$$\overline{\Sigma}_1^{th}\int_0^w \Phi_1^{th}(z)dz = C_1 \tag{10}$$

from which $\overline{\Sigma}_1^{th}$ is estimated. Further, if the rod is withdrawn from depth $2w$ to w, the application of Eq. (8), using the average values of $\Sigma^{th,act}(z)$ at each rod compartment, leads to:

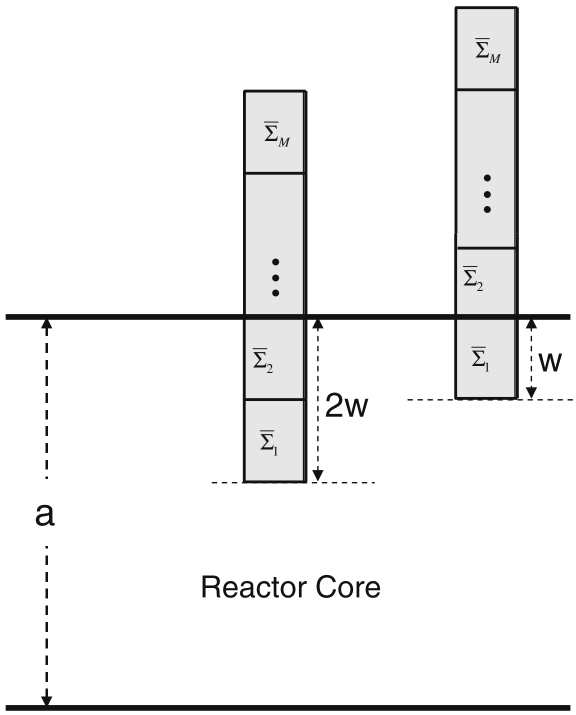

Fig. 1. Schematic representation of the control rod incremental vertical movement by steps of equal length w. $\overline{\Sigma}_i$ is the macroscopic absorption cross section of the ith rod compartment ($i = 1,\ldots,M$). The rod's active length (Mw) equals the active core depth (a).

$$\int_0^{2w} \Sigma^{th,act}(z)\Phi_2^{th}(z)dz - \int_0^{w} \Sigma^{th,act}(z)\Phi_1^{th}(z)dz = C_2$$

or

$$\int_0^{w} \Sigma^{th,act}(z)\Phi_2^{th}(z)dz + \int_w^{2w} \Sigma^{th,act}(z)\Phi_2^{th}(z)dz - \int_0^{w} \Sigma^{th,act}(z)\Phi_1^{th}(z)dz = C_2$$

or

$$\overline{\Sigma}_1^{th}\int_0^{w} \Phi_2^{th}(z)dz + \overline{\Sigma}_2^{th}\int_w^{2w} \Phi_2^{th}(z)dz - \overline{\Sigma}_1^{th}\int_0^{w} \Phi_1^{th}(z)dz = C_2 \qquad (11)$$

From Eq. (11), $\overline{\Sigma}_2^{th}$ is computed. In general, using the notation

$$a_{i,j} = \int_{(i-1)w}^{iw} \Phi_j^{th} dz \qquad (12)$$

with $i \leqslant j$, the application of Eq. (8) for the Nth $(1 < N \leqslant M)$ rod compartment leads to:

$$\overline{\Sigma}_N^{th} = \frac{C_N - \sum_{i=1}^{N-1}\overline{\Sigma}_i^{th}(a_{i,N} - a_{i,N-1})}{a_{N,N}} \qquad (13)$$

where

$$C_N = \frac{1}{c}\frac{\Delta k_N^{m,act}}{\Delta k_N^{c,nom}}\left(\sum_{i=1}^{N}\Sigma_i^{nom}a_{i,N} - \sum_{i=1}^{N-1}\Sigma_i^{nom}a_{i,N-1}\right) \qquad (14)$$

Eqs. (12)–(14) allow the successive estimations of $\overline{\Sigma}^{th}$ values, up to $\overline{\Sigma}_M^{th}$. It should be noted that the constancy of w, the rod incremental withdrawal, is not mandatory; it has been chosen here for presentation clarity purposes. In fact, the algorithm is valid for any variable step of rod withdrawal. At each step of the algorithm's application, $\Delta k^{m,act}$ and $\Delta k^{c,nom}$ must correspond to the same rod insertion level, as can be seen in Eq. (14). This can be achieved by re-distributing the measured $\Delta k^{m,act}$ values on the grid of the computed ones $\Delta k^{c,nom}$.

3. The case of many absorbers

In many real cases, more than one neutron absorbers are present in a control rod. For example, the control rods of many research reactors contain an alloy of cadmium, indium and silver. Considering a content of L absorbers with nominal (i.e. given by the rod's manufacturer) number densities N_j^0 $(j = 1,\ldots,L)$ and corresponding macroscopic absorption cross sections Σ_j^0, the methodology of Section 2 does not allow retrieval of the individual cross sections Σ_j^1 after rod irradiation. Instead, the proposed methodology is applied to a so-called effective absorber, having a nominal absorption cross section given by

$$\Sigma^0 = \sum_{j=1}^{L}\Sigma_j^0 \qquad (15)$$

Therefore, the total (sum for all rod absorbers) macroscopic cross section of the effective absorber after irradiation i.e. $\Sigma^1 = \sum_{j=1}^{L}\Sigma_j^1$ is deduced. The actual rod worth may thus be estimated, based on Σ^1.

It should be noted that in this case, the definition of the "thermal group" used for the derivation of Eq. (8) has to be extended, to comprise the whole energy range where the various individual absorbers exhibit an appreciable absorption cross section.

4. Application

Application of the above methodology was made for a depleted control rod of the Greek Research Reactor (GRR-1). GRR-1 is pool type, light water moderated and cooled, using beryllium reflectors and MTR-type fuel elements of slab geometry, normally operating at 5 MW. The necessity to develop and apply this methodology arose since: (a) an accurate estimation of the depleted absorbers concentrations using the methodology indicated in the Introduction is unfeasible for GRR-1 which used the same rods for about three decades while operation parameters were not digitally recorded and (b) the reactor is planned to convert to low enrichment, continuing to use the same (depleted) control rods.

GRR-1 uses five shim/safety control rods with absorber length 60 ± 0.2 cm, i.e. approximately equal to the length of the fuel plate. Their active part has a cross section of rectangular shape with rounded sides, as shown in Fig. 2. The absorber material is by weight composed of 82.4% silver, 10.7% indium and 6.9% cadmium, with respective smeared densities 7.77 g cm^{-3}, 1.01 g cm^{-3} and 0.65 g cm^{-3}. The cladding consists of 70% by weight iron, 18% chromium, 10% nickel and 2% manganese, with smeared densities 5.6 g cm^{-3}, 1.44 g cm^{-3}, 0.80 g cm^{-3}, and 0.16 g cm^{-3} respectively.

According to Section 2 (Eqs. (12)–(14)), an estimation of the factor c is required for the methodology application. In order to appoint a representative range of c values, the formulation was initially applied for $c = 1$. Then the GRR-1 core was simulated (with the neutronics code system described below) considering as rod absorbers: (a) the nominal ones and (b) those obtained by the application of the methodology for $c = 1$. The comparison of the neutron flux profiles in the lower energy group (see below) within the rod, for 100% rod insertion, led to a c factor ranging between 1.1 and 2.1; the bigger values were found in the upper 20% core part and the smaller ones in the lower 25%, while in the intermediate core depths a value of $c \approx 1.4$ prevails. The methodology was applied using c values in the above range. The application proceeded as described in the following paragraphs.

The required total absorption macroscopic cross section of the depleted effective rod absorber was derived for ten successive

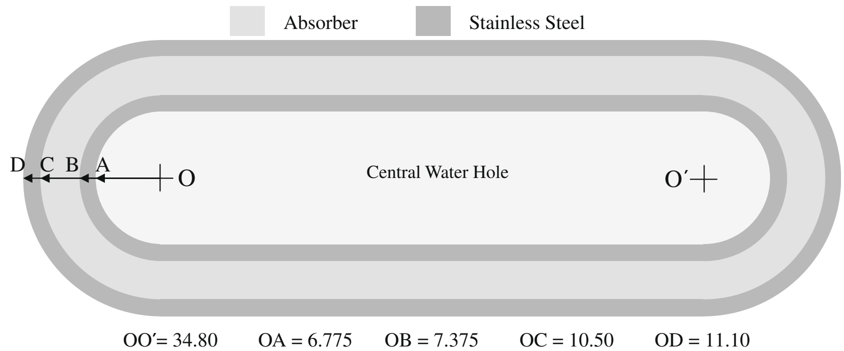

Fig. 2. Cross sectional area of the GRR-1 control rod. The dimensions are in mm.

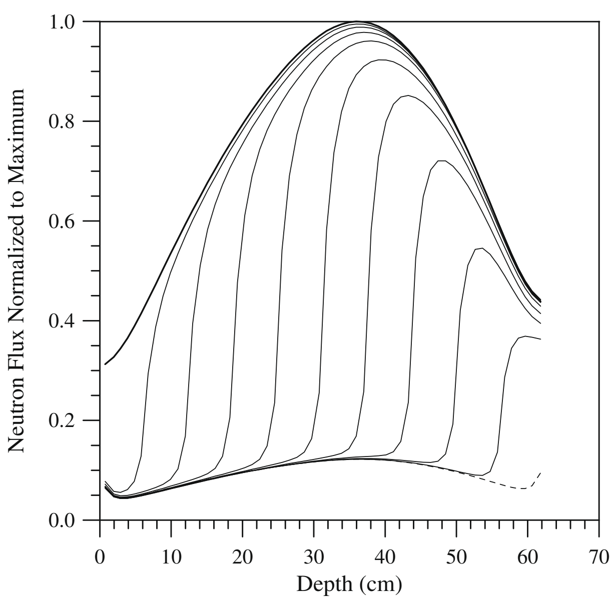

Fig. 3. Variation of the lower neutron-energy group flux along the rod channel for successive rod withdrawals per 10%. The lower dashed line corresponds to 0% and the upper thick line to 100% withdrawal.

rod compartments of equal length. For the neutron fluxes $\Phi_n^{th}(z)$ appearing in the formulation, the computations of CITATION code (see following paragraph) for successive rod withdrawals of the non-depleted control rod were used. Fig. 3 shows the utilized fluxes normalized to the maximum. Due to steep gradients, an accurate interpolation scheme (Akima, 1970) was used to estimate neutron flux values at core depths lying among the vertical computational grid points of the neutronic code calculations. The integrations in Eq. (12) were performed using a numerical method based on second degree polynomials (Catsaros and Ribon, 1987). Two neutron-energy groups were defined in the sense described in Section 3, with upper boundaries at 3.9×10^3 eV and 2.0×10^7 eV respectively. The best results of total rod worth, concerning the comparison with measurements, were obtained for c values between 1.3 and 1.5. The total absorption macroscopic cross section derived for the depleted control rod in the lower neutron-energy group, is shown in Table 1 for the above c values, in comparison with the nominal absorption cross section.

The calculation of the control rod worth was made using the code system NITAWL (resonance shielding calculations; Greene and Petrie, 2000), XSDRNPM (cell calculations; Greene and Petrie, 2000) and CITATION (core analysis; Fowler et al., 1971). Using the above system, the core analysis and the control rod representation were made as described in Varvayanni et al. (2009). NITAWL and XSDRNPM are modules of the SCALE code (SCALE, 1995). For the non-depleted control rod, the 238 groups-NDF5 library released with SCALE was used and the equivalent macroscopic cross sections for the contained nuclides collapsed to the two neutron-energy groups mentioned above were derived using NITAWL and XSDRNPM. CITATION calculations were performed considering: (a) a non-depleted control rod, using the total absorption macroscopic cross section corresponding to the nominal absorber densities and (b) a depleted control rod, using for the lower neutron-energy group a total macroscopic absorption cross section that corresponds to the effective absorber as defined in Section 3, varying along the rod's length according to Eq. (13).

The computations were compared with measurements, which were realized following the procedure of successive rod withdrawals from 0% to 100% of the absorber length, compensated by successive insertions of a relatively distant rod from 0% to 100%, while keeping the other three rods submerged to a constant depth

Table 1
Derived total macroscopic absorption cross section (cm^{-1}) of the lower neutron-energy group for the effective absorber from the lower (zone 1) to the higher (zone 10) rod compartment, vs the non-depleted (nominal) value.

Rod compartment	Nominal absorber	Effective absorber		
		$c = 1.3$	$c = 1.4$	$c = 1.5$
Zone 1	2.3675E−01	4.7749E−02	4.4339E−02	4.1383E−02
Zone 2	2.3675E−01	9.0157E−02	8.3717E−02	7.8136E−02
Zone 3	2.3675E−01	1.1017E−01	1.0230E−01	9.5480E−02
Zone 4	2.3675E−01	1.1986E−01	1.1130E−01	1.0388E−01
Zone 5	2.3675E−01	1.2290E−01	1.1412E−01	1.0651E−01
Zone 6	2.3675E−01	1.2865E−01	1.1946E−01	1.1149E−01
Zone 7	2.3675E−01	1.4091E−01	1.3084E−01	1.2212E−01
Zone 8	2.3675E−01	1.5361E−01	1.4264E−01	1.3313E−01
Zone 9	2.3675E−01	1.7997E−01	1.6712E−01	1.5598E−01
Zone 10	2.3675E−01	2.0553E−01	1.9085E−01	1.7813E−01

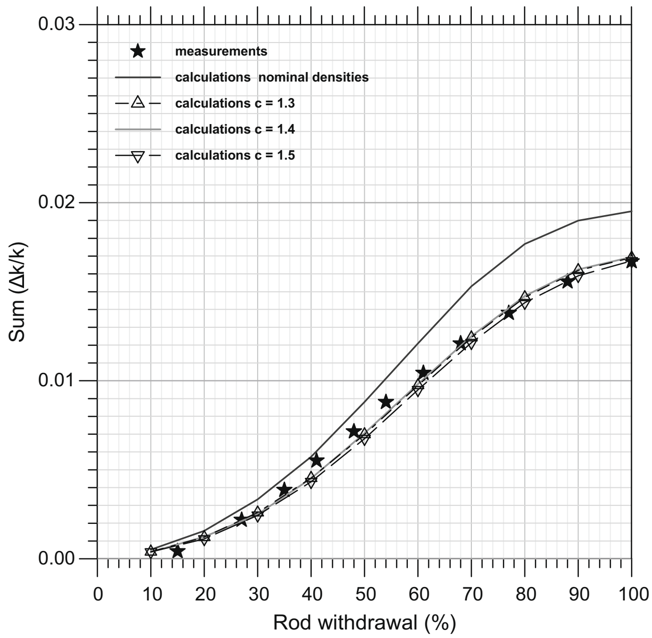

Fig. 4. Calculated control rod worth using (a) the nominal and (b) the derived, progressively varying, total macroscopic absorption cross section of the effective absorber, compared with measurements.

in the core. The worth of the measured control rod was obtained by recording the period at each withdrawal and by assessing the reactivity change through the in-hour equation, while at each step the integral rod worth was obtained by summing the reactivity changes corresponding to the preceding, successive steps. Fig. 4 shows the computations results for the worth of both the non-depleted and the depleted rod, the latter corresponding to the effective absorber macroscopic cross sections of Table 1, in comparison with measurements performed for the depleted rod. In Fig. 4, the integral control rod worth, $\sum_1^N (\Delta k/k)_n$, where $(\Delta k/k)_n$ is the reactivity change induced by withdrawal of the nth rod compartment, is plotted. As can be seen in Fig. 4, the curves corresponding to the derived total absorption macroscopic cross sections approach considerably the measured one, compared with that corresponding to the non-depleted rod. More specifically, the discrepancy of 280 pcm for the total rod worth obtained with the nominal macroscopic cross sections, is reduced to less than 3 pcm for $c = 1.5$.

5. Conclusions

A simple methodology is proposed for assessing the total macroscopic absorbing cross section of a depleted control rod. The suggested procedure can prove useful in the case that the level of detail known about the irradiation history of the control rod does not allow an analytical calculation of the absorber burnup, while the rod is planned to be utilized in a modified core environment. The methodology is based on measurements of the integral rod worth in its former core environment and on computations performed with the nominal absorber density. The included algorithm is conceived such as to provide an effective macroscopic absorption cross section which permits to accurately reproduce the depleted control rod worth, regardless the level of depletion.

Application was made for a depleted control rod of GRR-1 containing five neutron absorbers. The calculated total rod worth for a progressively varying total macroscopic absorption cross section of an effective absorber using the methodology described in this work, almost eliminates the discrepancy with measurements compared to the computations made with the absorption cross section corresponding to the nominal absorber densities. This makes the rod worth assessment in case of planned core modifications, more realistic.

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