DIFFUSION CALCULATIONS FOR THE SLOWPOKE-2 REACTOR USING DONJON

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Abstract

The SLOWPOKE reactor at Ecole Polytechnique will be refueled with a Low Enriched Uranium (LEU) fuel in place of a High Enriched Uranium (HEU) fuel used until now. The purpose of this study is to provide various models, using the reactor physics chain of codes DRAGON/DONJON, in order to predict the behavior of the new LEU Slowpoke. In particular, we will present some numerical results concerning the separate temperature effects of the main components of the core, the effect of a partial void appearing near the fuel pins and the axial and radial flux distributions. Finally the difference between the present HEU and the future LEU fuel power will be given.

I. INTRODUCTION

SLOWPOKE is an acronym for Safe Low Power Critical Experiment. It is a pool-type reactor developed by Atomic Energy of Canada Limited as a neutron source for isotope production and neutron activation analysis.
The HEU-fueled Slowpoke reactor, installed at Ecole Polytechnique of Montreal in 1976, will be replaced by Low Enriched Uranium (LEU) fuel. The newly developed LEU fuel was used for the first time in the Slowpoke installed at the Royal Military College in Kingston in 1985. A HEU fuel element is an Aluminum-Uranium metal pin sheathed by Aluminum; while a LEU fuel element is based on a Zircalloy-4 clad UO2 fuel, with a smaller outside diameter. LEU fuel contains uranium with an enrichment of $\approx$ 20% wgt U235, compared to 93% wgt in HEU fuel. However, LEU fuel has a much higher uranium density than HEU. As a result the number of elements within the same core volume required to reproduce a given reactivity is lower with LEU fuel. The exact fuel load design of the LEU core at Ecole Polytechnique is not yet established, so we decided to use specifications identical to the one currently installed at RMC.

To support the Slowpoke core refueling, various reactor models were prepared using the reactor physics chain composed of the transport code DRAGON[1] and the diffusion code DONJON,[2] which calls TRIVAC-3[3] modules. Work regarding transport models and studies are reported in another paper presented in this conference.[4] Here we will be interested in the diffusion part only.

A 6-energy group diffusion model of the entire reactor core, along with its reflector and some structural material was developed,[5] using a 3D hexagonal geometry.[6] The nuclear properties to be included in this model were produced using an homogenization/condensation process for macroscopic cross sections and diffusion coefficients issued from transport calculations. Global temperature effects and control rod worth were already reported for the HEU Slowpoke reactor.[5, 7, 8] Following these efforts, LEU core models were produced and used to compute various steady-state data.

The goal of this paper is to present new numerical results for the LEU Slowpoke reactor,[9] namely the separate temperature reactivity coefficients of the main components of the reactor, the effects of a partial void, the radial and axial flux distributions and finally, the LEU/HEU power ratio for a fixed detector reading. These DONJON results will be used in the SLOWKIN model for the simulation of transients.[10]

II. DIFFUSION CALCULATION

The transport calculations were performed in DRAGON using a microscopic library based on ENDF/B5.[5] The cross section of the Beryllium isotope in this library have been tabulated in temperature. The diffusion code DONJON, is then used to compute fluxes and multiplication factor. The computer codes DRAGON and DONJON are set up in a modular form which allows the user to break up his calculation in procedures having a smaller number of steps. Relevant data can then be easily passed from one process to the other through hierarchical data files and/or its sequential export facilities. The standard calculation procedure we carry is in two steps:

1. Perform critical transport calculations on the transport model and generate a consistent set of multigroup properties (various cross sections and diffusion coefficients) for each different material;

2. Introduce these nuclear properties in the DONJON full core model and compute the macroscopic flux distribution and the multiplication factor of the core.

The DRAGON generated macroscopic properties are stored in COMPO files. This type of file has been developed to unify output storage and to be able to keep macroscopic as well as microscopic cross sections with a variable number of energy groups and eventually for different steps of evolution (burnup steps). The COMPO files will be directly accessed in the DONJON computation to ensure adequate communications between transport and diffusion calculations.

The location of fuel pins in Slowpoke reactor can be reproduced by a hexagonal geometry. A full 3D hexagonal diffusion model of the LEU reactor was set up. The model is constructed to fit the reactor dimensions used in DRAGON model geometry. It is also expanded beyond the Beryllium reflector to about 35 cm from core center. In axial direction, the bottom Beryllium (Be) reflector, the top and bottom water zones were explicitly modeled. Beryllium plates in the upper shim tray were included in the model, when appropriate. However in the case of LEU reactor, none were present at the commissioning.

In the DONJON static simulations, all fuel rods share the same nuclear properties issued from the transport calculations. The diffusion calculations were performed using mesh centered finite difference discretization (MCFD) with one mesh per hexagonal cell. To accelerate the flux convergence, at least two ADI calculations per outer iteration were necessary. Flux was converged to a precision of 10^{-5}.

A convergence study with the model was performed to ensure a proper behavior of the solution. The axial mesh spacing and the number of energy groups used in the diffusion calculations were investigated. Our initial study has shown that there is no need to go beyond 6-energy groups because the reactivity is almost constant, although CPU time increases significantly.[5] The core model in diffusion represents about 50K unknowns per energy group.

The control rod device can also be taken into account by DONJON. The code allows different rod positioning along a simulation The actual position of the device is set in terms of fraction of full insertion and the affected mesh properties are adjusted by volumetric dilution.

On the other hand, using the resulting fluxes and energy conversion factors, (called H factors), DONJON can be used to normalize fluxes to a given total power. The local power in each fuel pin can then be estimated. However, the resolution geometry used is composed of many more regions than the fuel area. A fuel map object can then be defined to limit the regions of interest in the resolution domain. Power calculation over fuel pins of the reactor is done using this fuel map definition, as well as fuel average fluxes. The axial and/or radial flux shapes can also be recovered.

Detector readings can also be simulated. A detector is defined by coordinates for Cartesian and cylindrical geometries or by hexagon numbering for hexagonal ones. With this geometrical information, flux interpolation is performed to recover multigroup values at a special site. 6-group detector activation cross sections must be provided to measure detector sensitivity and to allow a prediction of the actual detector response. In the LEU core, a single Cadmium detector is used. So the spectral sensitivity of the Cadmium isotope to 6 energy groups was computed in DRAGON and input in DONJON to obtain a single response.

When used for regulation capability, detector responses are generally computed in fraction of full power with respect to a reference state. In our case, they are used to specify a flux value at the detector location and then to normalize the overall fluxes in order to obtain reactor power.

III. NUMERICAL RESULTS

III.A. Temperature reactivity coefficient

One of the most important properties needed for simulating the operating reactor is its temperature reactivity coefficients. Experiments were done in the LEU Slowpoke reactor at Royal Military College (RMC) to study the reactor behavior for various uniform temperatures. We have tried to reproduce the general trend of this experimental data. The separate temperature effects of the main components (fuel, coolant, Beryllium and outer water) of the reactor were also evaluated. For water temperatures varying from 10°C to 80°C, and for fuel temperature up to 300°C, DONJON calculations were done to determine the temperature reactivity coefficients of the different components, while keeping the control rod outside the core. Fig. 1 represents the trend of each separate coefficient and the total one.
Detailed transport calculations in DRAGON were also carried out to confirm the separate temperature effects and to provide a physical interpretation for the observed behavior of k_eff.[11]

The dominant effect is due to the coolant water which has an important negative reactivity. The effects of fuel temperature are not negligible because of the Doppler reactivity caused by large presence of U238 and the low conductivity of the ceramic fuel. The water outside the Beryllium reflector, nested as moderator, has a positive reactivity.

On the other hand, like in the temperature reactivity experiments, calculations to reproduce the measurements keeping the control rod inside the core were performed. Nuclear properties of all the components of the reactor, including those of the control rod, are computed at different temperatures from $10°C$ to $45°C$. Two calculations were performed: one using control rod properties at 20°C and another one using its temperature dependent properties. The control rod was inserted at 79% of full insertion (around the maximum axial flux) in the two cases. Fig. 2 shows the excess reactivities found for these cases as well as the calculation with the control rod out and the measurements performed in the RMC reactor. The advantage of temperature dependent nuclear properties of the control rod is clearly demonstrated.

III.B. Void effects

For high power transients, the fuel sheath temperature may exceed the coolant saturation temperature, and then the formation of void bubbles surrounding the fuel pins may occur. The volume of water displaced is small, but the negative reactivity introduced can be quite significant. A study of the effects of the void in a Slowpoke lattice has shown that the reactivity effects of the void is mostly a function of the average water density[11] and an uniform reduction of density produces nearly the same reactivity changes as void located near the fuel pin. On the other hand, our diffusion calculations show that the axial distribution of the void can be a factor. In order to study the effects of a partial void in the LEU reactor, the core model was divided in the middle and two different water density reductions (1% and 2%) are introduced respectively in the top region and uniformly in all the core respectively. The resulting reactivities are presented in Table 1. As we can see, the reactivity effect of the void is more significant when the same void fraction is introduced non-uniformly in the core volume(2% in the top half versus 1% uniformly).

III.C. Control rod worth

Two static calculations were performed with 6 energy group properties, at 20°C; one without the control rod and one with the control rod fully inserted. Since we are close to criticality, the control rod reactivity worth was simply taken as the difference between the two k_{eff} values obtained. The range of travel for the absorber rod is 8 inches in the core.

The control rod worth in the HEU reactor was measured in 1976 during the commissioning of the reactor. A worth of 5.4 mk was determined. For the new LEU reactor to be installed at Ecole Polytechnique, the control rod device should be the same as in HEU reactor. But its reactivity worth may change as the loaded fuel is not the same.

The control rod reactivity worth has been computed by DONJON and a value of about 4.35 mk was found when the control rod is inserted to 5.7 cm above the bottom reflector. Some calculations were carried out with a new rod maximum position at 1.6 cm above the bottom reflector (the control rod is more inserted inside the core). The control rod reactivity in this case is about 6.06 mk. Comparing these different values, one can see that inserting the control rod further in the core can give a significant increase in the control rod reactivity, so that matching the original control rod worth should be no problem in the new LEU core.

III.D. Flux and Power Distributions

The axial thermal flux distribution has been obtained from DONJON calculations. Fig. 3 shows the calculated axial flux distributions of LEU core with control rod out and no top plate along a specific fuel rod located at a radius of about 4.4 cm. This radius was chosen since it is more representative of the reactor core than the distribution along the center line at $r = 0$. The effects of the bottom Beryllium reflector and the water zones which produce a large peak can be clearly seen. Note that the lack of top reflector causes also the asymmetry of the flux shape.

The radial thermal and fast flux distributions are also been presented in Fig. 4 along a radial cut of the core from the center to the outside. As expected, the thermal flux in the coolant locations, where it is thermalized, is larger than that in the fuel locations, while the fast flux has the opposite effect. The thermal flux is also more peaked in the reflector and center regions.

Using the DONJON capability to obtain the detector responses, we have computed the LEU and HEU reactor powers with a same fixed flux at the detector site ($\Phi_d^{fixed} = 10^{12}$). The normalization factor is then :

$$f_n = \frac{\Phi_d^{fixed}}{\Phi_d^{comp}}$$

And the corresponding reactor power is obtained by:

$$P =< H\Phi > \times f_n$$

The involved LEU/HEU power ratio is about 1.0587. This value is used in the SLOWKIN model for the simulation transients of the LEU-Slowpoke reactor.[10]

IV. CONCLUSION

A 3-D full hexagonal model of the new LEU Slowpoke to be installed at École Polytechnique was set up. Nuclear properties for fuel and water holes meshes were performed by an accurate transport model by DRAGON code. Every material was exactly located and a sufficient axial mesh spacing and energy group decomposition were established to ensure convergence.

Using these models, steady state simulations were performed. Since the experimental data are not available, we have compared our numerical results to measurements of another LEU reactor installed at Royal Military College (RMC). Results are encouraging, but could be improved when some measurements will become available after commissioning of the new core at Ecole Polytechnique.

The static modelling could still be improved by using different nuclear properties for the fuel regions near the center of the core or the reflector. The core region could be split for example into three zones in order to reproduce more accurately the flux spectrum of the transport model. However, this approach would impose several constraints in the calculation flow-chart when going to burnup dependent properties.

ACKNOWLEDGMENTS

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Table 1: DONJON Void Reactivity in LEU SLOWPOKE-2

Moderator Density Reduction	Reactivity (mk)
1% in top half	-2.390
1% in all the core	-3.616
2% in top half	-4.656
2% in all the core	-7.218

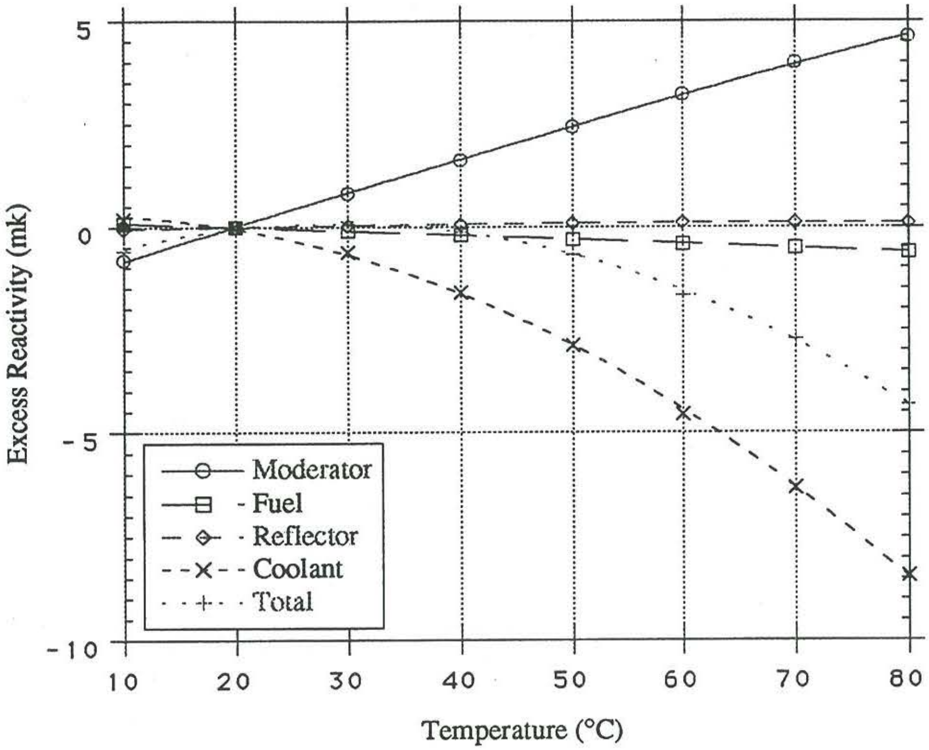

Figure 1: Separate Temperature Reactivity Effects

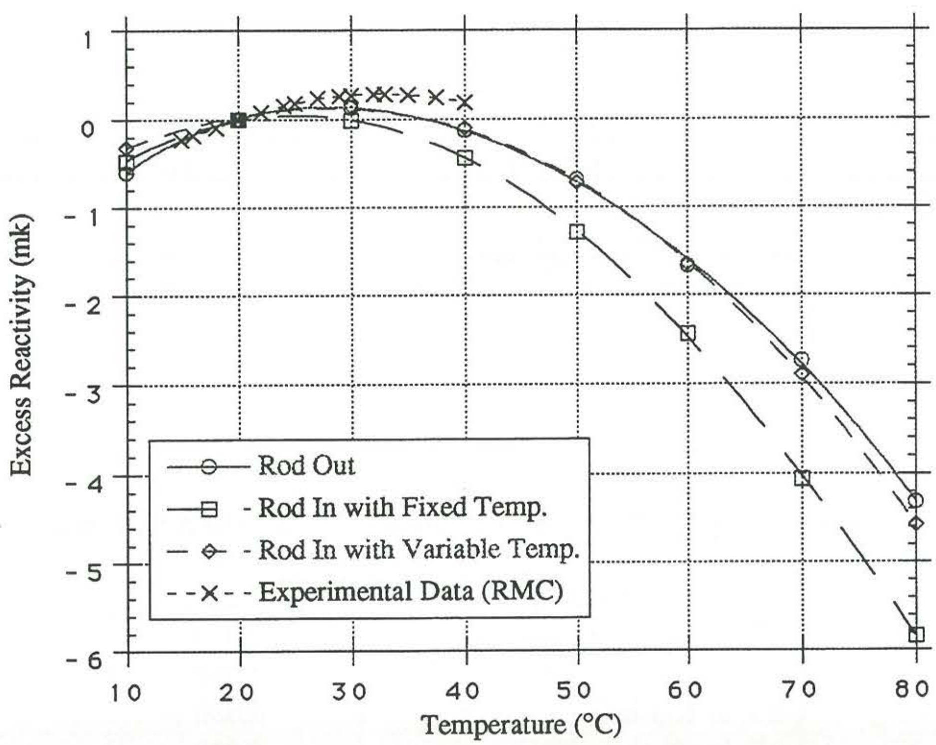

Figure 2: Influence of the Rod on the Temperature Reactivity

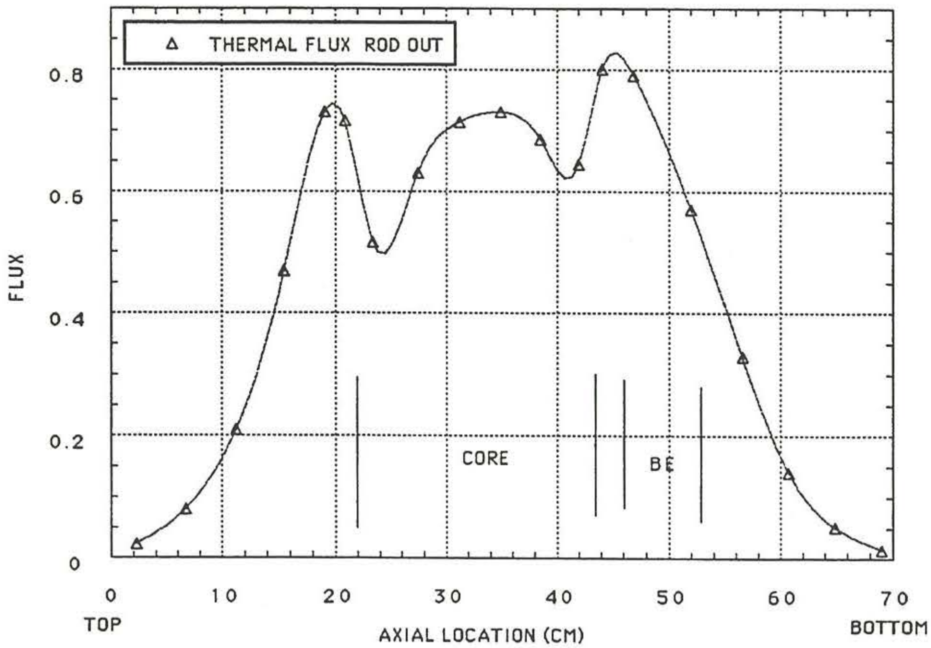

Figure 3: Axial Thermal Flux

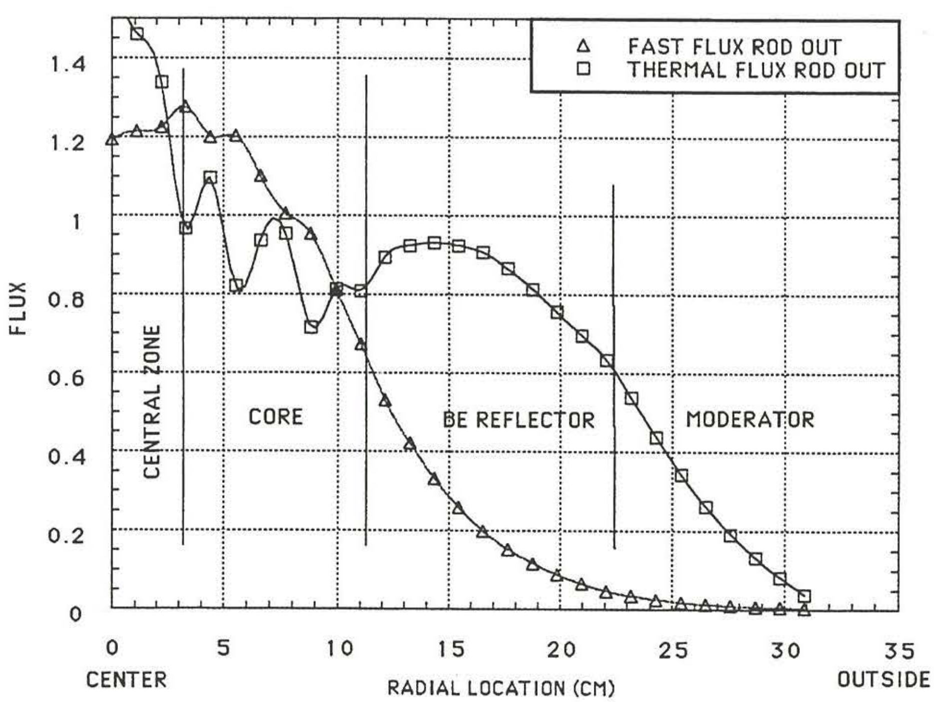

Figure 4: Radial Fast and Thermal Fluxes