REFUELLING THE SLOWPOKE-2 REACTOR AT ÉCOLE POLYTECHNIQUE: PROCEDURE AND PROPOSED EXPERIMENTS.

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ABSTRACT

As the expected lifetime of the present fuel in the SLOWPOKE-2 reactor at École Polytechnique de Montréal was seen to approach, a project was initiated which will lead to the refueling of the reactor in 1997. Two aspects of this project require major development work: the defueling and fuel loading procedures need to be revised since this is the first time a SLOWPOKE reactor will be refueled; work is also required to bring safety analysis and documentation in line with recent regulatory requirements. Here, we present the proposed overall refueling strategy and discuss the changes in the operation of the core resulting from the use of low-enriched fuel. Additional experiments, which should be carried out during commissioning, are also analyzed.

I. Introduction

The SLOWPOKE-2 reactor at École Polytechnique de Montréal has operated since 1976 with the original fuel which consists of 0.8 kg of 93% enriched Uranium (HEU). The 296 fuel pins contain Uranium-Aluminium alloy with Aluminium cladding. The core is surrounded by a Beryllium reflector and is moderated and cooled by light water which circulates by natural convection. The reactor is used for research involving neutron activation analysis and the use of radioactive tracers as well as for teaching.[1] As the lifetime of the present fuel was seen to approach, a project which was initiated three years ago will lead to the refueling of the reactor in 1997. Atomic Energy of Canada Limited has been contracted to carry out the refueling.

Proliferation concerns and technological advancements have led to the development of low-enriched (20%) Uranium-oxide SLOWPOKE fuel with zircaloy sheathing (LEU).[2] The new fuel will be identical to that used in the Royal Military College SLOWPOKE reactor since 1985. Three aspects of the refueling project require major development work. First, defueling procedures must be written since this is the first time a SLOWPOKE reactor will be refueled. The fuel loading procedure used in 1976 also needs to be revised based on the experience gained in the last 20 years and on the fact that it will take place in a reactor which has already been irradiated. Finally, work is required to bring safety analysis and documentation in line with recent regulatory requirements.

In this paper we first present the proposed overall refueling strategy and discuss specific points that must be considered when a new core is inserted in an already irradiated reflector. We will also discuss the changes resulting from the use of low-enriched fuel relative to the present fuel. Finally, the last section will analyze additional experiments that are proposed to gain a better understanding of the characteristics of the core including knowledge of the void reactivity feedback effect and the neutron flux distribution.

II. Refueling Procedure

II.A. Defueling

A defueling strategy, taking into account reactivity effects and core radioactivity, was designed so as to minimize shut-down time. The reactor will be defueled about ten days after shut-down, when the fission product activity is about 1000 Ci. A new procedure has been developed to safely defuel the reactor without disassembling the reactor water container. A remote handling machine was designed, constructed and tested. It will operate under the 76 cm thick concrete pool covers and will lift the core out of the container, move it horizontally 1 m and lower it to the bottom of the pool where it can easily be placed in the shipping flask.

The capacity of the reactor will be doubled by installing five new irradiation sites just outside the beryllium reflector. All associated equipment will be verified for fitness for another 20 years of use.

II.B. Fuel loading

The radioactive Beryllium reflector is a gamma-ray and neutron source which must be taken into account during fuel loading. These neutrons add to those emitted by the power-calibrated neutron source used for start-up and thus complicate the determination of reactor power. At the beginning of fuel loading, the gamma-rays emitted by the reflector will produce a non-negligible signal in the ionization chamber used for neutron detection and reactivity estimation. Therefore, a BF3 detector in the pulse counting mode will also be used.

Otherwise, the fuel-loading procedure is similar to that used previously at RMC and it is expected that 200 fuel pins will be needed. The reactor will have an excess reactivity near 4.0 mk with less than 4 mm of Beryllium reflector plates added above the fuel. Relative to the old reactor core, the increased amount of water within and just above the core will have a significant effect on reactor properties.

II.C. Commissioning Tests

Commissioning tests include:

- Calibration of the control rod,
- Adjustment of the control system set point neutron flux,
- Testing the auxiliary shut-down system,
- Measurement of reactivity worths of samples in the irradiation sites,

- Self-limiting power excursions
- Operation in automatic mode.

The most important tests are the self-limiting power excursions. These will demonstrate that the inherent negative feedback effects limit the reactor power to safe levels even for reactivity insertions in excess of 4.0 mk. They are also the most difficult to simulate. A significant part of the research effort at the institut in the last year has been devoted to predicting the transient behaviour of a core submitted to such experimental conditions. Details of this modeling will be presented in companion papers.[3, 4]

In the next section we will concentrate our discussions on experiments which are not part of the commissioning procedure but are useful towards getting a better understanding of the physics of the new LEU core.

III. Experiments and Pre-simulations

Here we will concentrate on three types of measurements which will be performed during or just after fuel loading.[5] One of these measurements is an integral part of the fueling procedure and involves the evaluation of the subcritical multiplication of the core. We also suggested two experiments which can only be performed while the reactor core is opened. These will be performed with a full core load and at very low power. The first experiment consists of evaluating the effect of coolant displacement (void effect) on the reactivity of the core while the second experiment aims at the characterization of the neutron flux distribution inside the core. Here we discuss how these experiments were analyzed using the lattice code DRAGON.[6]

III.A. Approach to Critical

The standard fueling strategy used for the SLOWPOKE-2 reactor is very different from that considered for most power reactors. Instead of inserting into the reactor core the full fuel load which should result in the required excess reactivity, a more empirical procedure is considered, namely, an increasing number of fuel pins are loaded in the core until the reactor reaches criticality. This strategy is dictated by the fact that there is only one control mechanism inside the core, the control rod, whose worth is only a few mk. Therefore it would be impossible to compensate easily for the error in reactivity associated with a given fuel load with this device alone.

A consequence of this procedure is that one must be able to measure the subcritical multiplication constant associated with each incremental fuel loading sequence. This is realized experimentally by measuring at a given point inside the reactor (the detector site) the neutron flux generated when a well known fixed source is inserted in the core. As the amount of fuel increases the multiplicative effect of fission should produce an increase in the flux level seen by the detector. In the limit where the core reactivity is very close to criticality, the relation between the integrated flux at the detector in the presence of n fuel pins ($\phi(n)$) and that measured when no fuel is present in the core ($\phi(0)$) should take the form:

$$K_{\text{eff}} = 1.0 - \alpha\frac{\phi(0)}{\phi(n)}$$

where α is a constant which depends on the type of fuel and on the reactor configuration.

The fueling of the SLOWPOKE-2 reactor therefore takes place in the presence of a source, producing neutrons having well defined energies, inserted in one of the irradiation site located inside the Beryllium reflector. The detector (an ionization chamber) on the other hand is situated outside the core in the water reflector.

In order to simulate this fueling experiment using DRAGON, a certain number of approximations are required.[7] We first assumed that neither the source nor the detector position will influence considerably the results for $\phi(0)/\phi(n)$. Accordingly, the transport problem was simplified by locating the neutron source in the center of the core (control rod location) while the detector was positioned in one of the Beryllium reflector irradiation sites. A second assumption concerns the neutron spectrum associated with the source. Here because our DRAGON calculations were performed using the 69 group Winfrith library, we will consider a source that has a non-zero flat spectrum only between 500 keV and 812 keV (group 6). It is also a distributed source of uniform density which occupies a volume identical to that of an irradiation site. Because the transport calculations were performed with the cell code DRAGON, using a 2–D model of the reactor, neutron leakage must be accounted for since it represents a loss in reactivity of over 200 mk.[5] However, in DRAGON no fixed source calculations can be performed with an imposed buckling. We therefore simulated the effect of leakage by adding an absorber (Boron) uniformly in the core in such a way that the last core load considered would result in an effective multiplication constant K_{eff}=0.997.

The above approximations can be easily justified. When the reactor is close to critical, the ratio decreases rapidly. In fact, when K_{eff}=0.9, $\phi(n)$ is already ten times larger than $\phi(0)$. This means that most of the neutrons in the cell were generated by fission and do not come directly from the source. Accordingly, most of the neutrons in the core are generated by fission and will therefore have no memory of the original fixed neutron source. For a reactor close to criticality the position and the spectrum of the fixed neutron source on the neutron flux distribution inside the core can therefore be considered as a second order effect. The justification for the independence of the results for $\phi(0)/\phi(n)$ on the position of the detector is similar, namely, a detector located outside the core will see this core as an attenuated point neutron source. Finally the use of Boron as an absorber to simulate leakage is acceptable from the point of view of neutronics since the leakage is generally taken into account in the 2–D transport problem by adding a contribution dB^2 to the absorption cross section.

In order to verify that our model was realistic, we first analyzed the old HEU core for which the experimental results of Fig. 1 were already available from the initial loading of the reactor. After performing successive transport calculations for various fuel loads, we evaluated the integrated flux at a the assumed position of the detector. Assuming the same normalization as that used in Fig. 1, the differences between the DRAGON results and experiment presented in Fig. 2 were obtained. As one can see, these differences can be relatively large. However, the large error oscillations are mainly observed when only a few pins are inserted in the core in a non symmetric way. On the other hand, one can see from Fig. 3 that the dependence of K_{eff} on $\phi(0)/\phi(n)$ as computed using DRAGON is nearly identical to that obtained experimentally. In fact, from our observations we obtain

$$\alpha_{\text{DRAGON}}^{\text{HEU}} = 3.66 \pm 0.05$$

while the experimental results is

$$\alpha_{\text{Exp}}^{\text{HEU}} = 3.6626.$$

This indicates that the approximations we used in the modeling of the HEU core are reasonable and can also be applied to the LEU fuel.

The same calculations were repeated for the proposed LEU core following a refueling scheme similar to that used for the old HEU core. One of the main differences in this case is the number of fuel pins loaded in the core. The core was fueled with a total of 192 LEU pins resulting in a final reactivity in the absence of leakage very close to that observed when the core was fueled with 296 HEU fuel pins. The Boron concentration was again selected in such a way that K_{eff}=0.997. One will find in Fig. 4 the DRAGON prediction for K_{eff} versus $\phi(0)/\phi(n)$ from which we derived

$$\alpha_{\text{DRAGON}}^{\text{LEU}} = 4.6 \pm 0.1$$

As can be seen, the slope α^{LEU} is steeper than that observed for the HEU core. Accordingly, for a fixed increase in reactivity, the LEU core generates more neutrons. This is due to the increased amount of coolant in the LEU relative to the HEU core therefore resulting in a more thermalized neutron flux.

III.B. Void Reactivity Experiment

The main reason for investigating the effect on reactivity of void is that one expects that for large reactivity insertions leading to higher powers, significant boiling will occur. This negative void reactivity effect is important to reactor safety. However, from the experimental point of view, inserting either a uniform void inside the coolant or around each fuel pin is not practical during the commissioning of the reactor.

Here, we suggest that the insertion of a specific amount of Aluminium in the control rod guide tube should have the same reactivity effect as a void insertion at the same location because of the reduce slowing down resulting form the coolant water displacement.[8] This is quite different from the effect that would be observed by inserting void in the water reflector where the resulting increase in reactivity results from a reduction of absorption in the water. However, it remains to be shown that the reactivity effect of the insertion of Aluminium in the core is still dominated by the effect of coolant water displacement since our experiment assumes that from a neutronics point of view, both the void and Aluminium should be nearly equivalent.

We first investigated the effect of filling the guide tube for the control rod with an identical volume of Void or Aluminium. In both cases a change in the reactivity of the core of -4.1 mk was observed. We also considered the case where the void is located around the fuel pins instead of being centered in the core. Assuming the same volume of void and Aluminium as that used in the first experiment is now distributed uniformly around each fuel pin, a slightly smaller change of reactivity is observed, namely -3.1 mk for void and -2.8 mk for Aluminium. Again this shows that both a void or Aluminium region will have nearly the same effect on the neutron flux distribution in the cell.

III.C. Neutron Flux Distribution Experiments

This last experiment concerns the evaluation of the axial and radial neutron flux distribution inside the core which can be measured indirectly by irradiating Copper and Gold wires located at different radial locations inside the core. Copper, which has a cross section which is nearly of the form $1/v$, will generally be more sensitive to the thermal neutron flux. Gold, on the other hand, will react more to the fast flux distribution because of the presence of epithermal resonances in its cross section. As a result, verifying that the DRAGON predictions for both the Gold and Copper activity are in agreement with experimental observations gives more confidence in the prediction and the validity of the code.

One will find in Fig. 5 to Fig. 7 respectively the integrated flux distribution at various radial locations inside the core, and the computed Copper and Gold activity per atom for the proposed LEU core. Here the flux and activities are normalized in such a way that the response in flux or activity in the irradiation sites is 1. The first observation is that the flux, at the empty fuel sites is somewhat smaller than that in the coolant at the same radial position while the reverse is true for the filled fuel sites. For the Gold activity simulations, the opposite behaviour is observed even if the difference is less important for Gold than Copper. One can also see that the rate of decrease in the Gold activity as a function of radius is much more important than for Copper. This is due to the fact that the fast flux decreases more rapidly than the thermal flux as one moves towards the exterior of the reactor core.

Looking at the results for Copper activity, one can also observe that the thermal flux is more peaked in the reflector region. Accordingly the radial dependence of the thermal neutron distribution inside the core is less important than that observed for the integrated flux. For the empty fuel sites, where the neutrons are more thermalized, the Copper activity is around 8 % larger than that computed for the surrounding annular region while a difference of about 4% was computed for Gold activity. The relation between the Copper activity and the radial position inside the LEU core is of the form :

$$A_{\mathrm{Cu}}(r) = [1.20 \pm 0.01] - [0.029 \pm 0.002]r$$

while the following relation is obtained

$$A_{\mathrm{Au}}(r) = [1.63 \pm 0.01] - [0.044 \pm 0.002]r$$

for Gold activity versus radial position.

IV. Conclusion

The first refueling of a SLOWPOKE reactor has required a considerable amount of development work but the inherently safe new core will be easy to maintain and operate and will provide a convenient tool for neutron activation analysis for the next twenty years.

The modelling work described here has already contributed to our understanding of the reactor; this will continue with the comparison of the calculations with the results of the measurements made during commissioning. The exercise is also proving to be extremely useful for code validation.

ACKNOWLEDGMENTS

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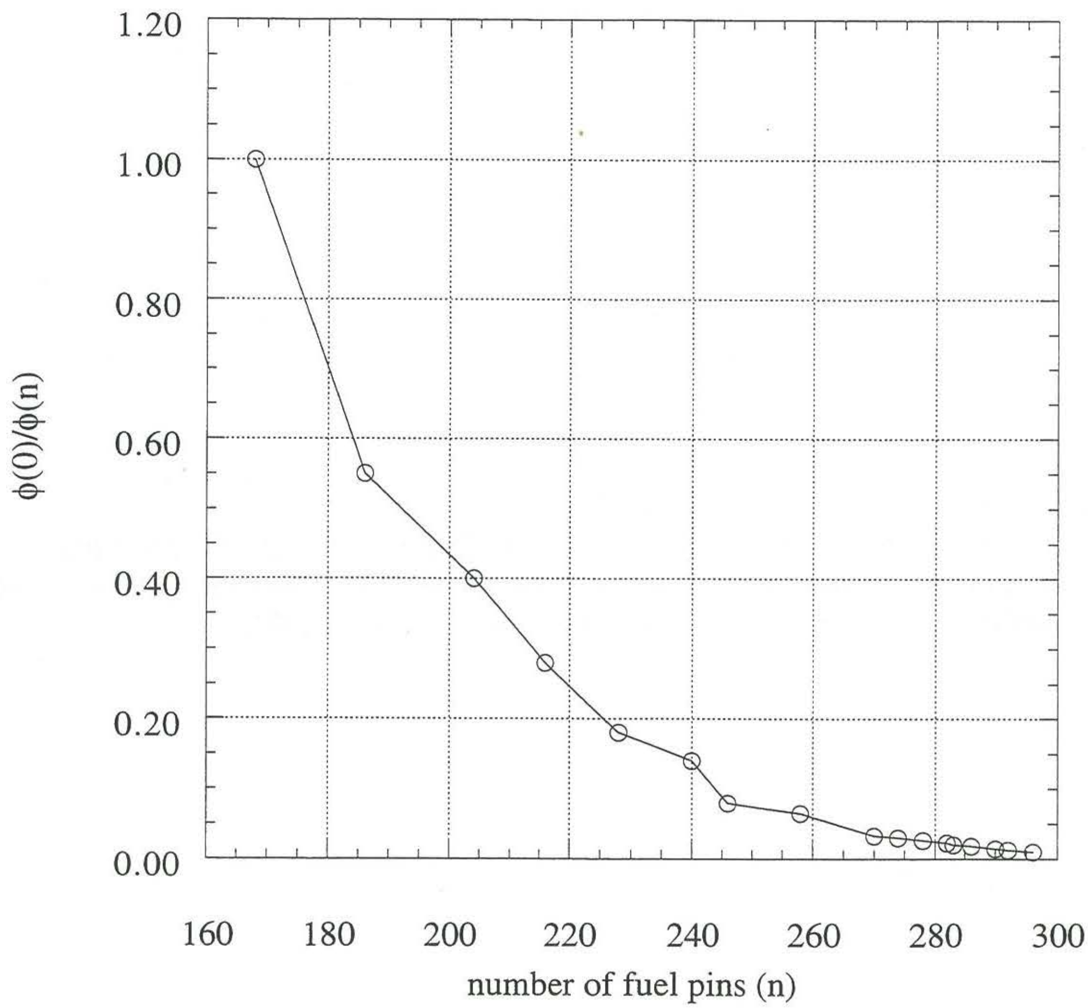

Figure 1: Measured flux as a function of the number of fueled sites for HEU SLOWPOKE.

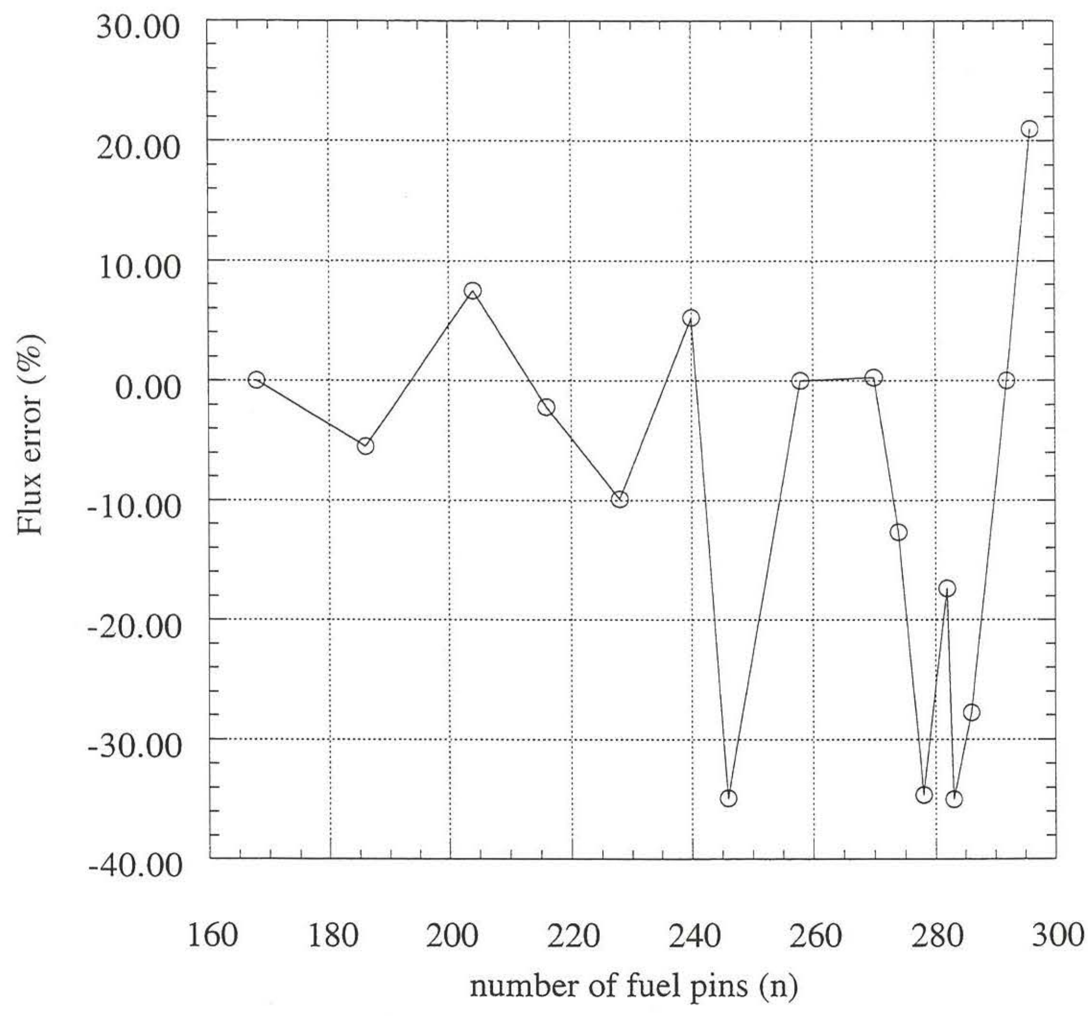

Figure 2: Differences between measured and computed flux for HEU core.

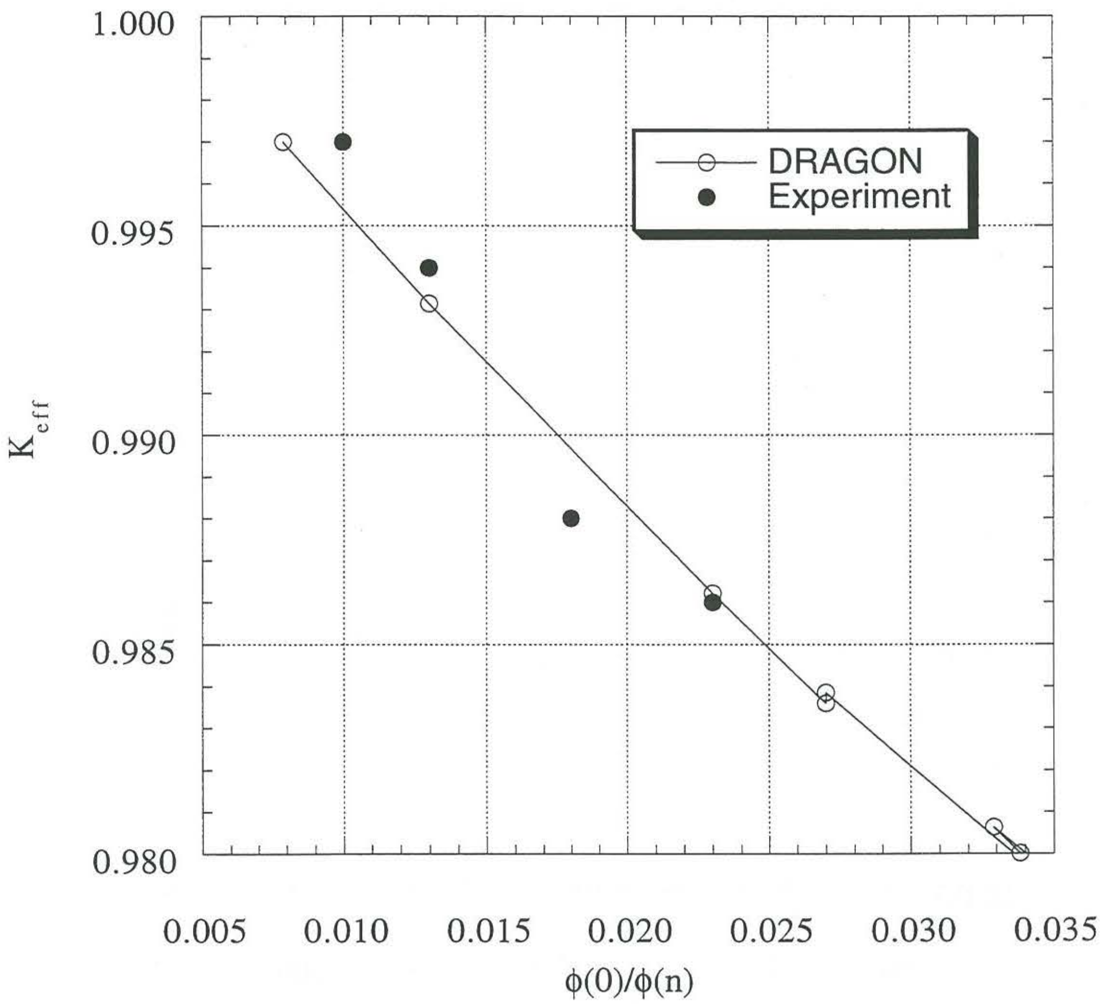

Figure 3: K_{eff} versus $\phi(0)/\phi(n)$ for HEU core.

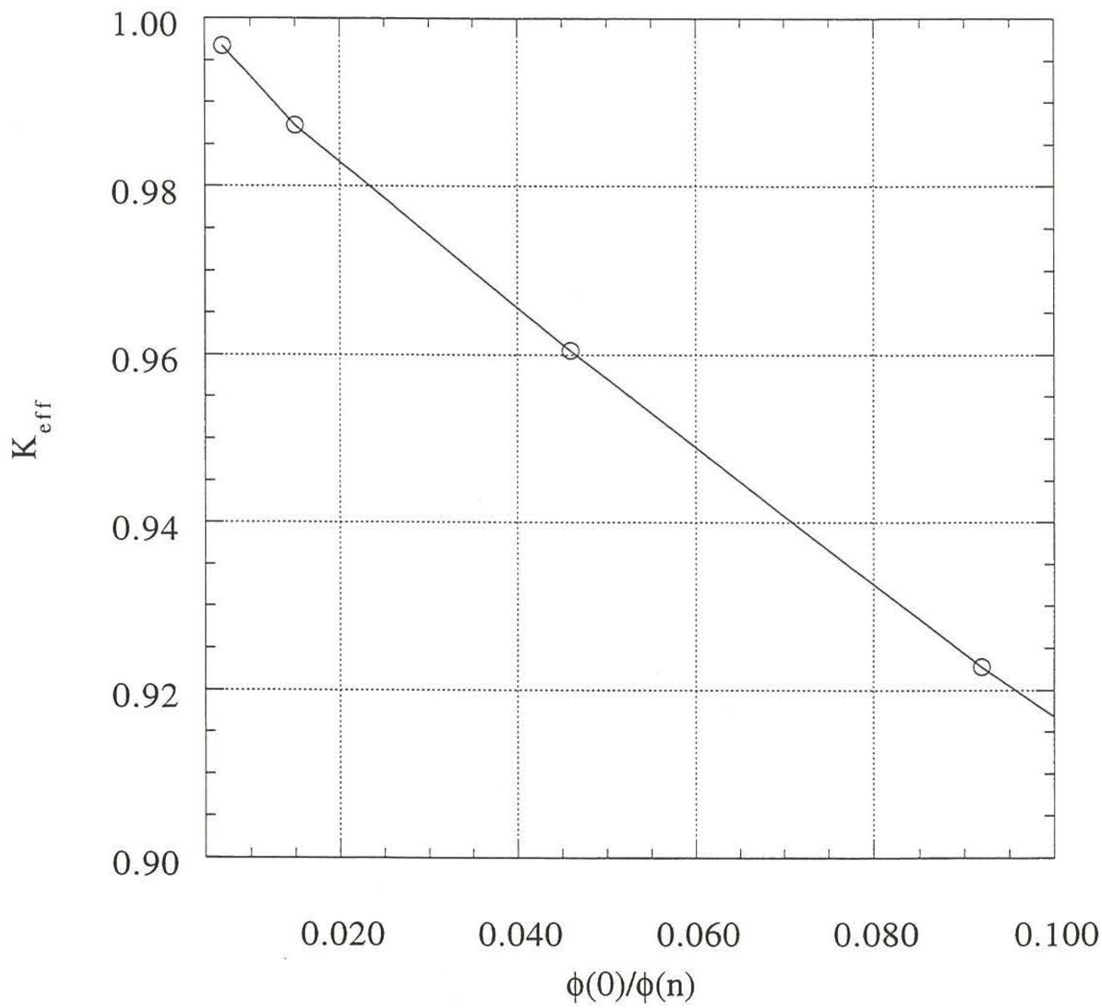

Figure 4: K_{eff} versus $\phi(0)/\phi(n)$ for LEU core.

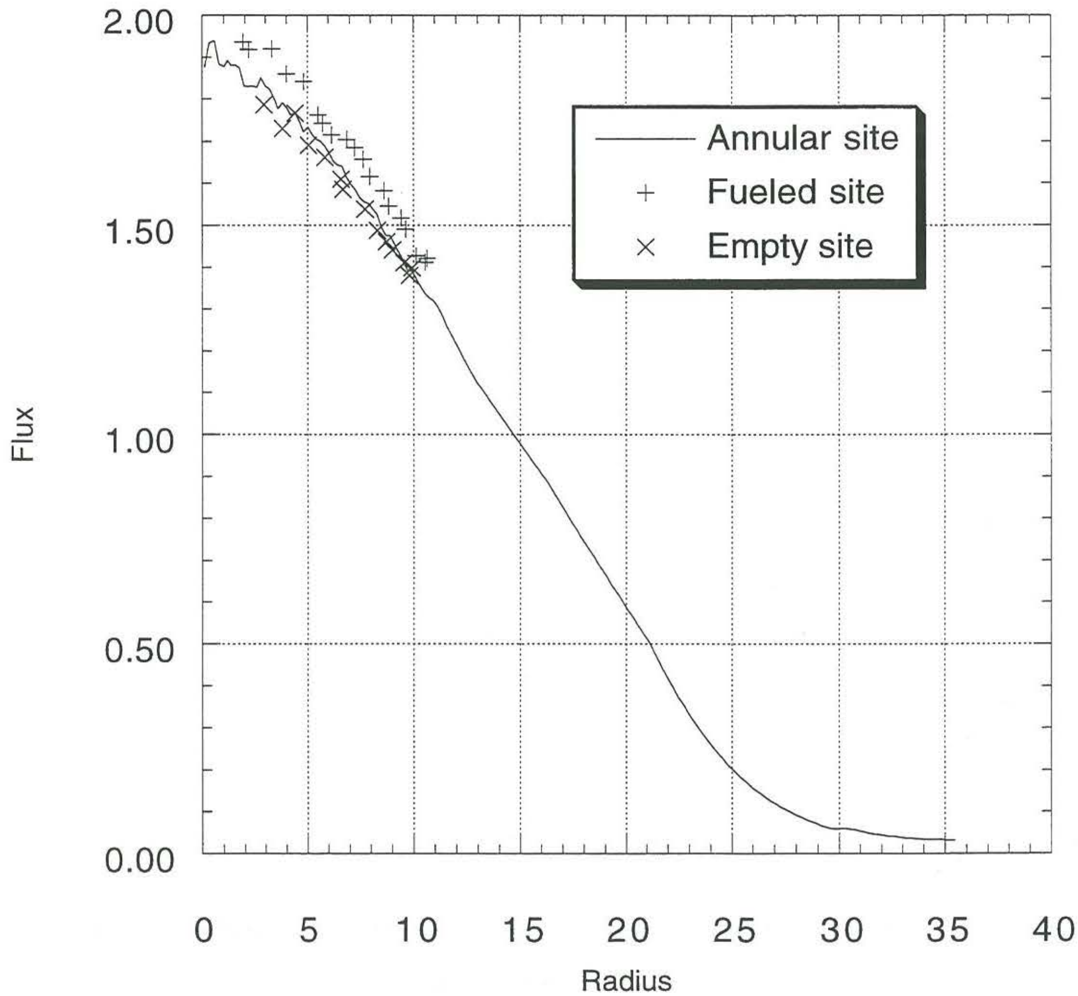

Figure 5: Radial distribution for the integrated flux in the LEU core.

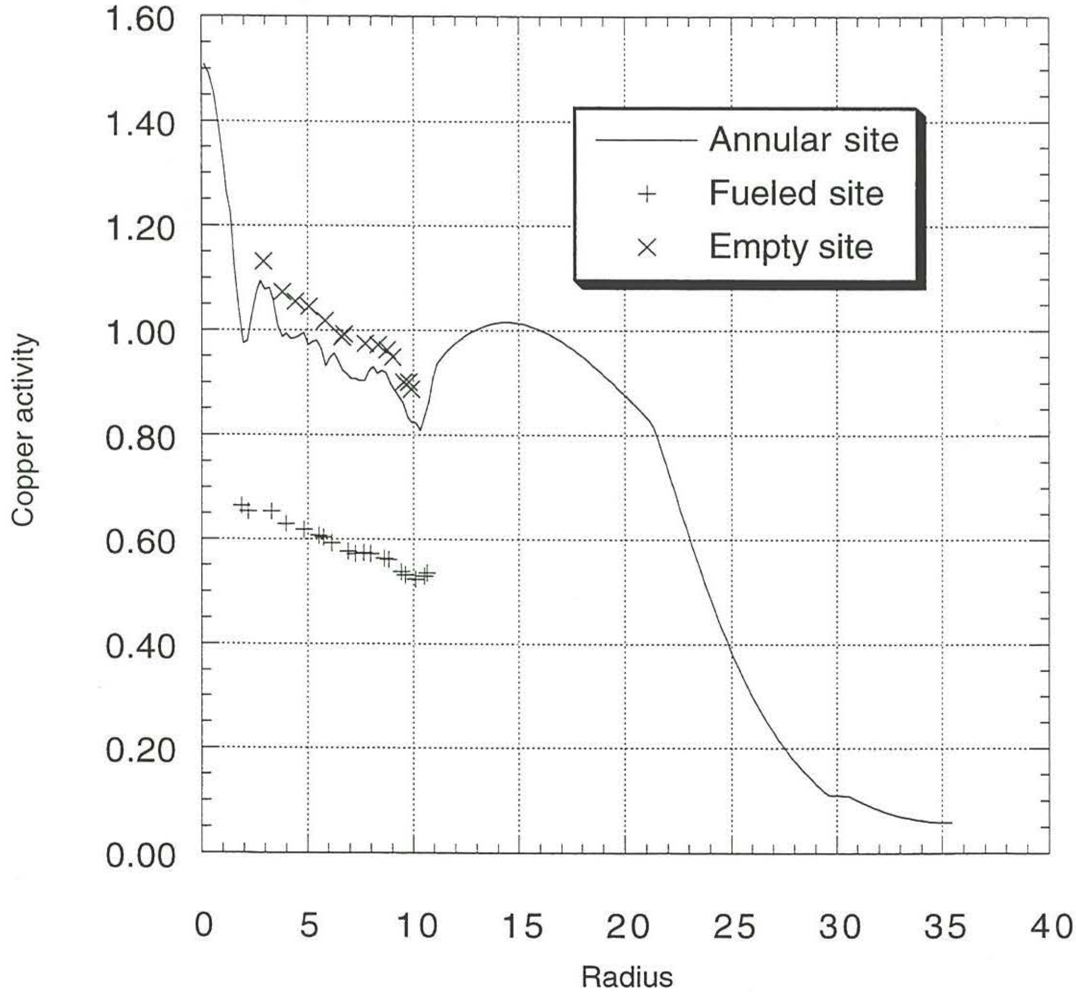

Figure 6: Radial distribution for the Copper activity in the LEU core.

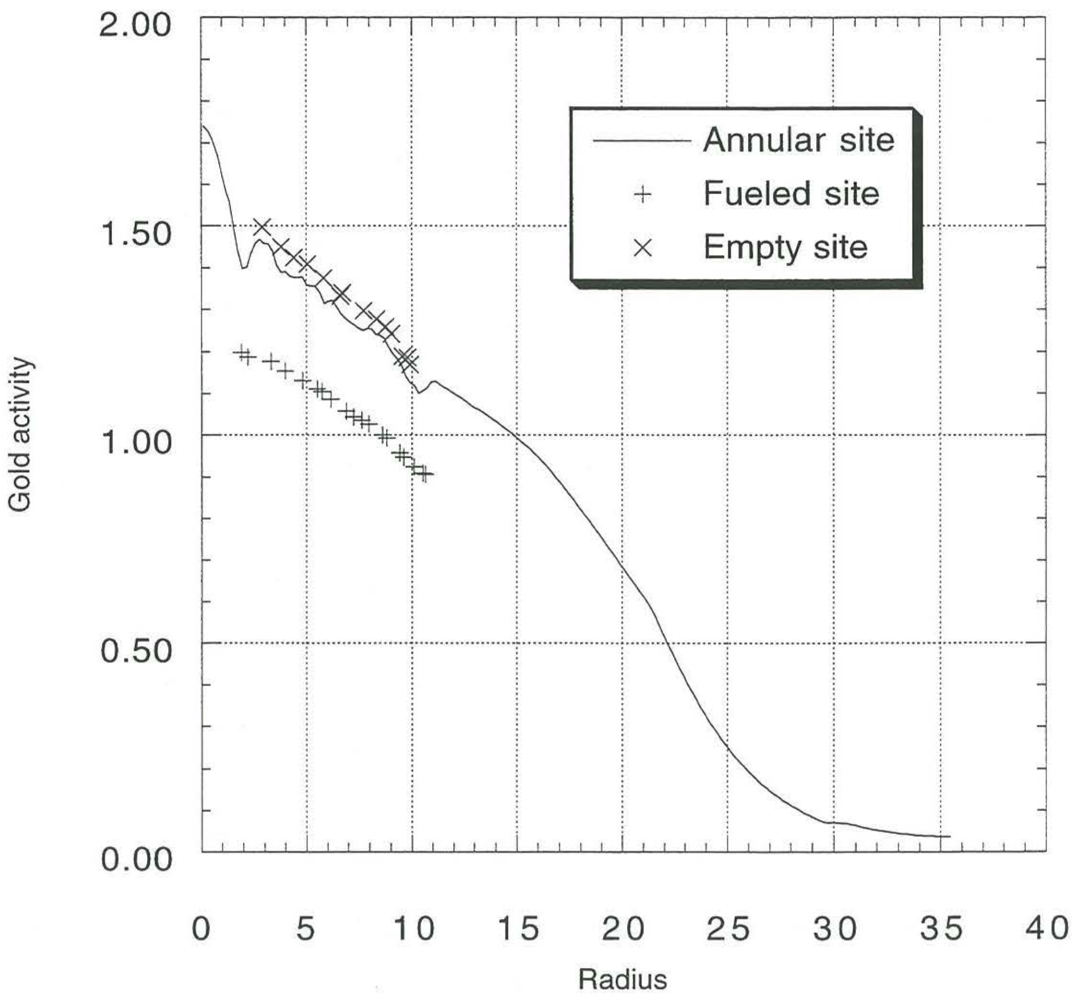

Figure 7: Radial distribution for the Gold activity in the LEU core.