ANALYSIS OF A POSSIBLE EXPERIMENTAL ASSESSMENT OF A PROTOTYPE FUEL ELEMENT CONTAINING BURNABLE POISON IN THE RA-3 REACTOR.

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ABSTRACT

The Argentine RA-3 research reactor (5 MW) is presently operated with LEU fuel by the National Atomic Energy Commission (CNEA). It belongs to the group of nuclear installations controlled, from the radiological and nuclear safety point of view, by the Nuclear Regulatory Authority (ARN).
A new type of fuel elements containing burnable absorbers, with similar enrichment as the standard fuel elements but greater fissile contents, has recently been proposed for a new Argentine reactor design (RRR).
In this framework the ARN considers interesting, if technically possible, the performance of an experiment in the RA-3 reactor. The experiment might enable, for such fuel element containing burnable poison, the verification of its neutronic behaviour under irradiation as well as a validation of the calculation line by comparison to measured values.
It should be desirable that such experiment could reproduce as much as possible those conditions estimated for the RRR reactor, still under design in Argentina, having Silicide fuel elements with burnable poison, in the shape of cadmium wires in their structure.
We here analyse a possible experiment consisting in the loading of a prototype fuel element with burnable poison in a normally loaded RA-3 core configuration. It would essentially be a standard RA-3 fuel element, having cadmium wires in its frame. This experiment would enable the verification of the prototype behaviour under irradiation, its operation limits and conditions, and particularly, the reactivity safety margins established in Argentine Standards, both calculated and measured. The main part of the experiment would imply some 200 full power days of operation at 5 MW, which would be drastically reduced if the reactor power is increased to 10 MW, as foreseen.
We also show that under the proposed conditions, the experiment would not represent a significant penalty to the reactor normal operation.

1 INTRODUCTION

The Nuclear Regulatory Authority of Argentina (ARN) has carried out an assessment of the Preliminary Safety Report of the 20 MW Replacement Research Reactor (RRR), designed by the Argentine company INVAP for the Australian Nuclear Science and Technology Organisation (ANSTO). This reactor will operate with LEU fuel elements (FE) having high contents of ^{235}U, so that the use of burnable poisons (BP) in the shape of cadmium wires in the FE frames is required. Although such kind of FE (BP-FE) has already been used in several reactors, the subject presents new aspects which, as it is well known, involve complex neutron calculations.

An experimental reference for BP-FE would add another piece of evidence to the validation of the neutron calculation line, and subsequently, of the design safety. It is in such framework that the ARN has carried out a feasibility analysis showing that it is possible to obtain interesting experimental data from the irradiation of a unique BP-FE in an Argentine research reactor as the RA-3 reactor which operates with non-BP FE.

On the other hand, irradiation and measurement in the RA-3 reactor could present some advantages as compared to equivalent information coming from foreign sources. Detailed information concerning measurements as well as the possibility of proposing new measurements if inconsistencies or errors are detected could be available.

2 ANALYSIS OF THE TECHNICAL FEASIBILITY

The purpose of this analysis is to estimate values to be afterwards measured, verifying that they are in fact observable. Moreover, this evaluation intends to demonstrate that the proposed irradiation does not mean a significant penalty to the reactor operation and that it will help in the definition of the amount of Cd to be inserted in the BP-FE frames.

2.1 Simplified model for the experiment.

The proposed experiment consists in the irradiation of a BP-FE in order to measure its contribution to core reactivity, as compared to that of a fresh standard non-BP FE (Fr-FE).
The measurement will be carried out for different burnups of the BP-FE.

The Fr-FE is a standard non-irradiated RA-3 FE, and it is loaded into the core just when the before mentioned reactivity is going to be measured. The BP-FE is completely equal to a standard RA-3 FE, with the unique difference of the Cd wires inserted into its frame, and that it remains in the core during operation, that is to say, it is increasingly irradiated.

In order to determine the reactivity worth previously mentioned, a direct measurement of the reactivity difference between two states could be directly measured. The first one is that corresponding to the Fr-FE loaded in a reference location (and the BP-FE withdrawn), and the second state has these two FE interchanged, that is to say, the Fr-FE withdrawn and the BP-FE loaded in the reference location. The reactivity difference (named Δ) we propose to measure, is the sum of two contributions:

- The reactivity loss of the BP-FE (related to the Fr-FE) due to the meat burnup.
- The reactivity loss of the BP-FE (related to the Fr-FE) due to the Cd inserted in its frame.

At the beginning of irradiation, the only difference between BP-FE and Fr-FE are the Cd wires inside the BP-FE frame (which has not yet begun its depletion). As irradiation goes on, the reactivity loss due to Cd begins to decrease (due to Cd consumption) while reactivity loss due to ^{235}U consumption in the meat increases. For sufficiently high burnup values, all the Cd will be consumed and the value of Δ will be exclusively due to meat burnup.

As concerns this assessment, there is no problem in idealising the experiment in order to simplify its analysis, provided results are not significantly altered. We here describe the ideal experiment modelled with the purpose of estimating values to be measured.

An actual RA-3 BOC configuration is considered. In fact, the BOC N94 configuration was chosen, introducing a slight change consisting in the interchange of the FE located in channels H-5 and I-5. The resulting burnup distribution is given in Figure 1, and we will identify the new configuration as N94-2.

H-5 is chosen as the "testing location". This location has a double objective. The BP-FE will be located in it for its irradiation, and the Fr-FE will also be located there to determine the value of Δ, the BP-FE reactivity loss as compared to the Fr-FE for different burnup values.

In order to simulate the FE burnup in H-5, and particularly its axial distribution, an evolution with CITVAP /1/ is carried out at a power of 5MW, in steps of 50 and 100 days until it approximately reaches its discharge burnup. At the end of each step the burnup distribution is forced to the initial burnup for every channel except H-5. With this trick we are able to generate states with an almost fixed power distribution, but different burnup states for the FE located in H-5. An intermediate insertion for B4 (control rod) was assumed, being all the other control rods withdrawn. This is a usual control rod configuration for the RA-3 during operation.

Cross section sets for FE were obtained from WIMS /2/ and CONDOR /3/.

The simulation described is an idealisation of what would be the BP-FE irradiation in a fixed location in the RA-3, operating with an (approximate) equilibrium core and a relatively steady power distribution.

The calculation was repeated with different BP-FE in H-5, one at a time, differing one from the other in their Cd loading. For such purpose, the length of Cd wires was modified between 0 and 61.5 cm (active length). As in CITVAP calculation model the active length is subdivided into 10 pieces (6.15 cm each), cases were run with BP-FE having wires that occupied 0, 2, 4, 6, 8 and 10 pieces. Wires were located in such a way that they were symmetric with respect to the core mid-plane. The case with 0 pieces corresponds to a standard FE; for such case Δ is exclusively due to ^{235}U consumption. We will identify BP-FE with different Cd wire lengths with the self-explaining notation: BP-FE-0, BP-FE-2, BP-FE-4, … up to BP-FE-10, or, in general, BP-FE-m.

Average burnups for these BP-FE and for different irradiation times do not change significantly from one BP-FE-m to other. This is understandable because the only reason for a change is the different perturbation each BP-FE-m introduces in radial and axial power distributions. Tables 1 and 2 show, as an example, burnup axial distributions for BP-FE-0 and BP-FE-10 for different irradiation times.

Note that for the purposes of this simulation, we could simply have invented these FE burnups without any need of calculating the evolution. The only objective of such calculation was to obtain a realistic axial burnup distribution as well as an adequate correlation between average burnup for BP-FE-m and irradiation time. The position H-5 was chosen because it is relatively unperturbed by control elements B1 and B4 (used during operation), and it has a rather high neutron flux, adequate for FE irradiation.

A set of burnup states corresponding to each of the BP-FE-m is then available as a function of the irradiation time up to its discharge burnup. The reactivity difference as a function of burnup is then determined for each of the BP-FE-m.

$$\Delta_m = \rho(\text{Fr-FE in H-5}) - \rho(\text{BP-FE-m in H-5})$$

Reactivity values ρ(Fr-FE in H-5) and ρ(BP-FE-m in H-5) are calculated in the BOC, N94-2, that is to say, the burnup distribution for every channel except H-5 remains unchanged and equal to that of BOC, N94-2.

Δ_0 , that is to say, the above difference evaluated for a standard (non BP) FE, represents the reactivity loss uniquely due to the meat burnup. Therefore, the difference:

$$P = \Delta_m - \Delta_0$$

gives the reactivity loss exclusively due to the Cd wires in BP-FE-m. The quantity P is also a measure (in terms of reactivity loss) of the penalty to the core due to BP-FE-m irradiation in H-5 instead of a standard RA-3 FE. Obviously, P achieves its maximum value at the beginning of the period (maximum Cd contents) decreasing as irradiation goes on, and reducing to zero when Cd has disappeared.

Figure 2 shows the reactivity loss Δ_m versus average burnup for different BP-FE-m (m = 0, 2, 4..10). From the analysis of this graph it may be concluded that the effect of BP (measured with a single BP-FE-m loaded in the core) is observable. Obviously, the greater m is (number of Cd occupied pieces), the greater is the effect, as can be noticed by comparing the larger distance of each curve Δ_m to the Δ_0 curve.

A reasonable proposal would then be to adopt a design with 4 pieces, as it is an acceptable compromise between a good detection of the BP effect and a small penalty to the reactor operation.

We will focus the rest of our discussion in a BP-FE-4 (m=4), having 4 Cd pieces (24.6 cm) in its frame. Figure 3 shows only those curves corresponding to 0 and 4 pieces as a function of % ^{235}U consumed.

It is also concluded that the irradiation period during which the BP (difference between 4 and 0 pieces) is observable lies within the range 0 - 18% of ^{235}U consumed (30000 MWD / Ton), being for this last value no difference between the BP-FE-4 and a standard FE with the same burnup. For a power of 5 MW, this period will be of some 175 full power days. A reasonable minimum number of measurements during such period is 5, approximately spaced 35 fpd one from the other.

Reactivity measurements should be carried out as accurately as possible, preferably with a cold Xe-free core, which will add some extra time. It would be desirable that apart from measuring Δ_4 , Δ_0 could also be measured, to separate the effect of Cd consumption from ^{235}U depletion. Measurement of Δ_0 represents no extra complication except that of having a standard FE available with a burnup varying between 0 and a value which should be higher than 18% ^{235}U consumed.

In order to calculate the isolated effect of Cd for different burnups, it is necessary to normalise all the measurements of Δ_4 as well as Δ_0 to the same core. Such normalisation is not necessary in this simulation because the reference core is maintained fixed (and equal to N94-2). In the actual experiment, an adequate correction should be evaluated because the core is not in an ideal equilibrium state.

2.2 Penalty in the reactor operation

We will here give only a rough idea of penalty. The quickest way of evaluating it is by estimating the core reactivity loss due to Cd. As already mentioned, this effect is accounted for by the quantity $P = \Delta_4 - \Delta_0$. Figure 4 shows P as a function of % ^{235}U consumed. Its maximum, 350 pcm, is obviously attained at zero burnup (maximum Cd load) and decreases to zero when fuel is depleted to some 17% ^{235}U consumed. It is thus clear that the experiment does not penalise the reactor significantly. During most of the BP-FE-4 stage in the core (from 17% up to its discharge burnup of ≅ 45 %), there is no difference between it and a standard FE. On the other hand, during the first part of its irradiation, P has a small value, equivalent to usual reactivity changes handled during normal operation, without meaning any limitation for carrying out experiments.

2.3 Sources of error

We believe that the most significant source of error would be and erroneous determination of the BP-FE-4 burnup. An important error in this quantity could invalidate the correlation measurement-calculation except for the initial zero burnup state. On the other hand, and for every case, an analysis of measurement errors is required, particularly for reactivity, taking special care in making sure that errors remain smaller than an acceptable maximum.

Another source of error, but less important than the previous one, is that coming from uncertainties in the remaining FE loaded in the core. While changing N94-2 configuration, we have noticed that Δ_4 values depend on the configuration in which they are measured, and particularly on the burnup of FE surrounding the testing location (H-5). Although there is a correlation between Δ_4 values and power distribution, we believe that an error in power distribution due to a mistaken determination of burnups, as concerns this experiment, is not very important.

RA-3 FE burnups are routinely calculated by the reactor staff. There are some uncertainties in such values, related to uncertainties in the determination of the reactor operation power. As has been explained, it would be important that such error did not affect the BP-FE-4 burnup determination. In order to make sure of these values, perhaps some experimental device such as (Cd or Co) monitors could be located in this FE. Measurement of the activity of the monitors could enable a better estimation of neutron flux in the BP-FE-4.

3 CONCLUSIONS

It is concluded that:

- A sort of experimental benchmark is feasible, consisting of a short irradiation to be carried out in the RA-3 reactor with the purpose of validating the calculation line with BP.

- Data coming from the experiment would be particularly useful to validate the calculation of reactivity variations versus Cd and ^{235}U consumption.

- It is possible to adopt different Cd contents in the FE to be irradiated. There is a compromise between the observability of the reactivity difference to be measured and the non-penalisation of the reactor operation. It comes out that an acceptable solution is the BP-FE-4 having 19x2 Cd wires of 0.4 mm in diameter and 246 mm long each. For the purposes of this experiment, two FE would be irradiated, the BP-FE-4 and the BP-FE-0, being this last one a RA-3 standard (non BP) FE. In the set of reactivity measurements these two FE would be involved, as well as a Fr-FE.

- Would such experiment be carried out, it would be of the greatest importance to plan it in detail, particularly ensuring the determination of BP-FE-4 and BP-FE-0 burnups, as well as the correct measurement of reactivity differences between the corresponding reactor states.

- The most important irradiation range in which BP-FE-4 and BP-FE-0 could achieve a burnup between zero and 18 % U_{235} consumed, will approximately last some 175 full power days, at a power of 5 MW.

4 REFERENCES

/1/ CITVAP 3.1. MTR_PC 2.6 User's Manual. July 1995.

/2/ WIMS-D/4. MTR_PC 2.6 User's Manual. July 1995.

/3/ CONDOR. MTR_PC 2.6 User's Manual. July 1995.

5 FIGURES AND TABLES:

TIME (fpd)	AXIAL BURNUP (MWD / TON)				
T=0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
T=50	5.7757E+03	7.1042E+03	8.8862E+03	1.0238E+04	1.1080E+04
	1.1352E+04	1.0985E+04	9.9224E+03	8.1851E+03	6.8087E+03
T=100	1.1404E+04	1.3998E+04	1.7457E+04	2.0066E+04	2.1683E+04
	2.2204E+04	2.1498E+04	1.9451E+04	1.6090E+04	1.3411E+04
T=150	1.6919E+04	2.0727E+04	2.5773E+04	2.9557E+04	3.1893E+04
	3.2645E+04	3.1629E+04	2.8668E+04	2.3782E+04	1.9862E+04
T=200	2.2313E+04	2.7282E+04	3.3825E+04	3.8706E+04	4.1708E+04
	4.2675E+04	4.1376E+04	3.7574E+04	3.1263E+04	2.6162E+04
T=300	3.2881E+04	4.0069E+04	4.9430E+04	5.6342E+04	6.0566E+04
	6.1928E+04	6.0117E+04	5.4771E+04	4.5805E+04	3.8469E+04
T=400	4.3007E+04	5.2206E+04	6.4021E+04	7.2630E+04	7.7847E+04
	7.9526E+04	7.7314E+04	7.0714E+04	5.9501E+04	5.0180E+04
T=500	5.2695E+04	6.3695E+04	7.7605E+04	8.7597E+04	9.3589E+04
	9.5516E+04	9.3004E+04	8.5425E+04	7.2354E+04	6.1299E+04

Table 1: Burnup axial distribution (10 pieces) in BP-FE-0 for different irradiation times.

TIME (fpd)	AXIAL BURNUP (MWD / TON)				
T=0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
T=50	5.1664E+03	6.3484E+03	7.9529E+03	9.1733E+03	9.9426E+03
	1.0206E+04	9.8951E+03	8.9532E+03	7.3904E+03	6.1629E+03
T=100	1.0237E+04	1.2563E+04	1.5708E+04	1.8092E+04	1.9590E+04
	2.0098E+04	1.9487E+04	1.7645E+04	1.4588E+04	1.2177E+04
T=150	1.5261E+04	1.8723E+04	2.3399E+04	2.6954E+04	2.9193E+04
	2.9951E+04	2.9030E+04	2.6275E+04	2.1726E+04	1.8136E+04
T=200	2.0283E+04	2.4917E+04	3.1191E+04	3.5985E+04	3.8995E+04
	4.0004E+04	3.8763E+04	3.5054E+04	2.8943E+04	2.4117E+04
T=300	3.0436E+04	3.7473E+04	4.6833E+04	5.3814E+04	5.8112E+04
	5.9533E+04	5.7756E+04	5.2423E+04	4.3481E+04	3.6224E+04
T=400	4.0637E+04	4.9747E+04	6.1620E+04	7.0334E+04	7.5640E+04
	7.7383E+04	7.5191E+04	6.8578E+04	5.7342E+04	4.8062E+04
T=500	5.0447E+04	6.1394E+04	7.5403E+04	8.5527E+04	9.1622E+04
	9.3612E+04	9.1108E+04	8.3490E+04	7.0356E+04	5.9312E+04

Table 2: Burnup axial distribution (10 pieces) in BP-FE-10 for different irradiation times.

	C	D	E	F	G	H	I	J
1		GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	
2	GRAPHITE BOX	IRRADIATION BOX	**E2:C034** 0.00%	**F2:A152** 47.72%	**G2:A093** 45.50%	**H2:C036** 0.99%	IRRADIATION BOX	GRAPHITE BOX
3	GRAPHITE BOX	**D3:P-01** 46.54%	**E3:C039** 16.07%	**F3:CS011** 8.39%	**G3:C031** 24.83%	**H3:C027** 3.56%	**I3:CS008** 0.00%	GRAPHITE BOX
4	GRAPHITE BOX	**D4:CS007** 0.01%	**E4:CS005I** 3.13%	**F4:C028** 24.31%	IRRADIATION BOX	**H4:CS005** 32.15%	**I4:A153** 48.78%	GRAPHITE BOX
5	GRAPHITE BOX	**D5:CS002** 41.46%	**E5:C030** 11.03%	**F5:CS009** 19.53%	**G5:C025** 25.33%	**H5:C032** 0.00%	**I5:C033** 2.02%	GRAPHITE BOX
6	GRAPHITE BOX	IRRADIATION BOX	**E6:C037** 0.00%	**F6:A088** 47.96%	**G6:A095** 47.30%	**H6:C041** 0.71%	IRRADIATION BOX	GRAPHITE BOX
7		GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	GRAPHITE BOX	

Figure 1 : N94-2 core diagram.

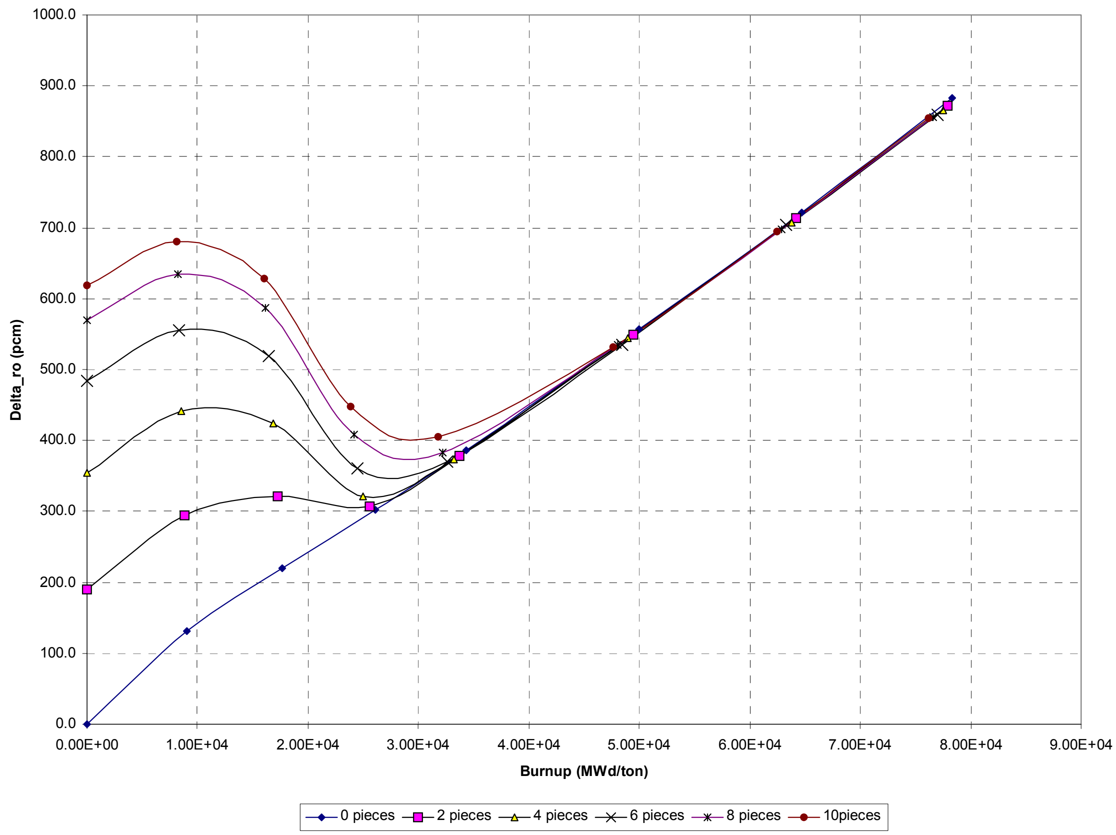

Figure 2: Δ_m = reactivity loss (defined positive) of BP-FE-m (m-pieces) with respect to Fr-FE for m = 0,2,4,…10

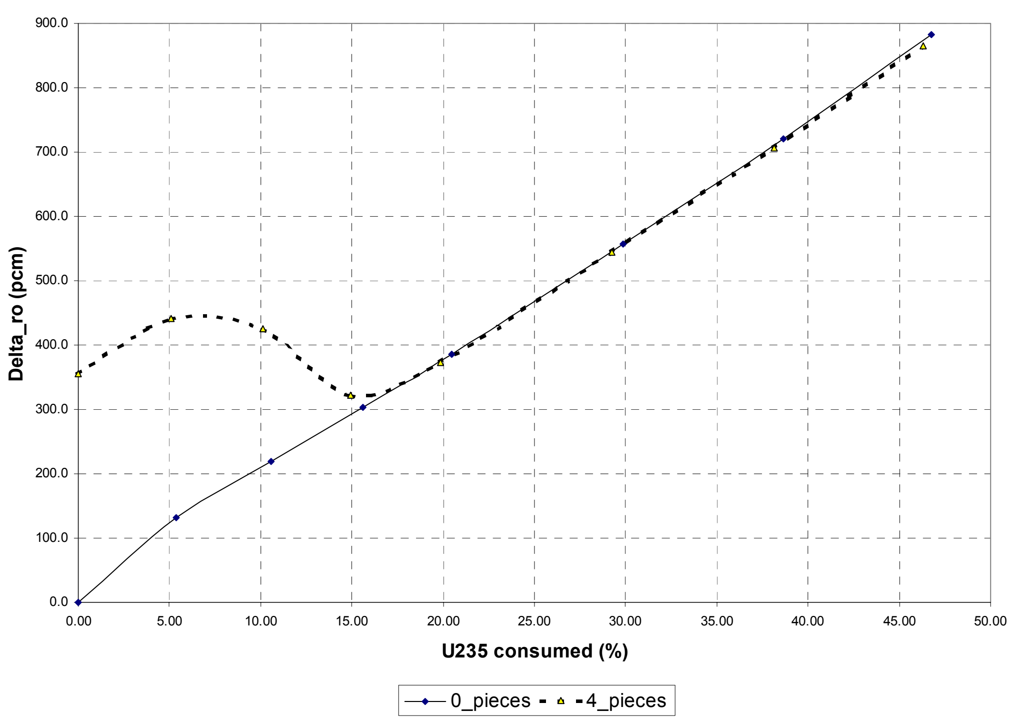

Figure 3: Δ_4= reactivity worth of BP-FE-4 and BP-FE-0 with respect to Fr-FE as a function of % ^{235}U consumed.

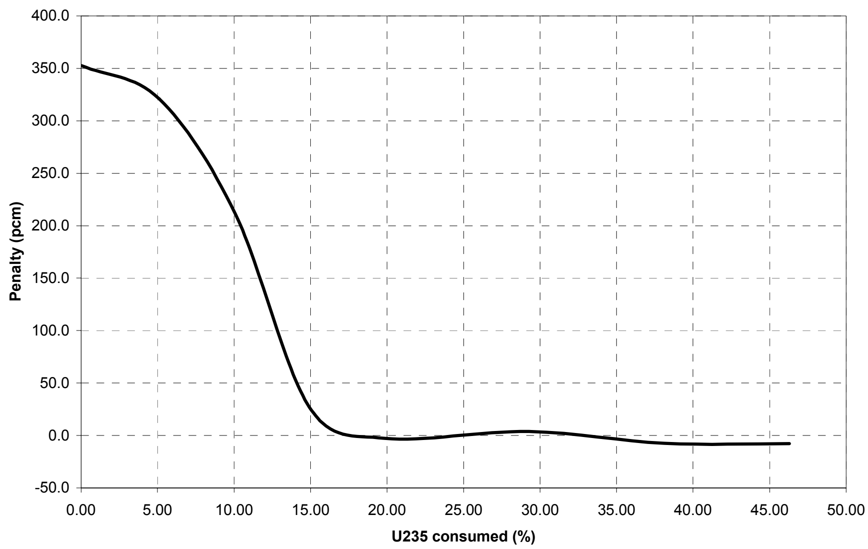

Figure 4: Reactivity penalty due to BP-FE-4 as a function of % ^{235}U consumed.