CONCEPTUAL ANALYSIS OF THE FUEL MANAGEMENT STRATEGY FOR THE RA-3 RESEARCH REACTOR AT 10 MW.

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ABSTRACT

The Argentine Research Reactor RA-3 was designed to produce radioisotopes and it operates with LEU (U_3O_8) fuel since 1990. Its initial power was 5 MW and it has recently been upgraded to 10 MW. The National Atomic Energy Commission (CNEA) is both its owner and operator.
At the beginning of this year, the Nuclear Regulatory Authority extended its operation license to an authorised power of 10 MW after a series of modifications and tests carried out by the installation during 2002 and 2003.
As a consequence of this power increase, the installation introduced some non-systematic modifications in its fuel management strategy with the purpose of preserving the operation period in 20 days approximately. The main change was to load 2 fuel elements per cycle in some cycles (instead of 1 as it used to be at 5 MW).
The purpose of this work is to perform a conceptual analysis of possible fuel management strategies for the RA-3 reactor, that could provide quantitative elements for a safety assessment, as well as to evaluate the fuel management flexibility at 10 MW in compliance with standards in force.
It is concluded that operation at 10 MW with a 2 FE/cycle strategy leads to a significant excess reactivity at the beginning of cycle, but still in compliance with the margins established by the standards of application.

1. Introduction

The Argentine Research Reactor RA-3 was designed to produce radioisotopes and it operates with LEU (U_3O_8) fuel since 1990. Its initial power was 5 MW and it has recently been upgraded to 10 MW. The National Atomic Energy Commission (CNEA) is both its owner and operator.
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The purpose of this work is to perform a conceptual analysis of possible fuel management strategies for the RA-3 reactor, that could provide quantitative elements for a safety assessment, as well as to evaluate the fuel management flexibility at 10 MW in compliance with standards in force.
The installation has already submitted documents [1] showing that the reactor can operate at 10 MW, with, for example, a 1 FE/cycle strategy, similar to that used at 5 MW. In other words, it is already demonstrated that the reactor is operable at 10 MW. We are here only interested in analysing the limitations that this upgraded power may impose on the fuel management, and particularly the feasibility of changing to a permanent 2 FE/cycle strategy.
As concerns the core safety, the two interesting items related to fuel management are: compliance with reactivity safety margins and limitation of the power peaking factor (PPF smaller than 3.5 for the present configuration with 25 FE).

According to the corresponding thermal-hydraulic analysis [2], the improvements carried out in the cooling circuit are such that the power upgrade from 5 to 10 MW does not require a modification of the maximum power peaking factor (PPF) allowed. Therefore, if no increase of the actual core PPF occurs, the safety margin that guarantees the correct fuel element cooling will not decrease. The actual PPF value can change as a consequence of a change in the burnup distribution, or because the control rods will be more inserted due to the increase of the beginning of cycle (BOC) reactivity.
In several opportunities the RA-3 core was loaded with fuel elements containing more uranium mass than the standard, be the case of a U_3Si_2 FE or 2 standard fresh FE in the same cycle. In every case the PPF was always smaller than 3.1 with an average value of 2.8. This shows that there is an adequate margin to the maximum value allowable of 3.5.
On the contrary, a new fuel strategy with a permanent loading of 2 FE/cycle, will undoubtedly lead to an increase of the BOC reactivity. Moreover, even without a change in the fuel strategy, the power upgrade from 5 to 10 MW implies a certain BOC reactivity increase. It is because of this fact that this paper mainly concentrates on the analysis of the compliance with reactivity safety margins.

2. Calculation model

The model chosen in order to carry out the conceptual analysis of different fuel management strategies is simple, and enables to achieve some general conclusions quite easily. It consists of a 5x5 grid without control rods. Except its central position, in which an irradiation box has been located, all the other positions are filled with standard fuel elements (SFE) of the U_3O_8 type, giving a total of 24 FE. The fuel region is surrounded by a first annulus of graphite blocks and by a second outer annulus of a water reflector. The dimensions are those of the corresponding RA-3 reactor regions. A simplified graph is shown in Figure 1 as well as the refuelling chains used.
For the description of the FE in the reactor model, an explicit frame model was used.
For the 5 MW case, a usual cross section (XS) library generated with WIMS for all the involved materials was used [3]. This library is routinely used in the ARN for the RA-3 reactor calculations at that power. For the 10 MW case, only the XS for fuel and frames have been recalculated.

Based on this model the following working plan was proposed:

a) Generate (macro) XS = f(Bu) with equilibrium Xe for 5 and 10 MW (**WIMS**)

b) Prepare a simple reactor model with 24 FE and central irradiation box (**CITVAP**)

c) Obtain equilibrium core for the standard previous conditions: P=5MW, T=20 days, 1 FE/cycle. The end of cycle reactivity ρ_{EOC} thus obtained will be used as a reference value.

d) Obtain new equilibrium cores changing 5 to 10 MW; 1 to 2 FE/cycle and matching ρ_{EOC} to the reference value previously obtained.

e) Comparing ρ_{BOC} (c and d) obtain $\Delta\rho_{BOC}$ due to the different effects.

f) Using e extrapolate new values of ρ_{BOC} and analyse compliance with standards in force.

3. Effects on reactivity

We will estimate the reactivity changes (BOC without xenon) due to the three effects described in what follows. We will consequently estimate the shut down margin decrease produced according to the results.

3.1. Xenon effect

Comparing theoretically the equilibrium BOC cores when the reactor is operating at 5 MW and 10 MW, with the same fuel shuffling strategy, particularly 1 FE/cycle, it may be concluded that:
The cycle length changes from a value of T_5 to a new value T_{10} .
If no changes were produced due to xenon poisoning, it would result that $T_{10} = 1/2\ T_5$.
Thus, the FE would achieve exactly the same discharge burnup and burnup distribution in both cores would be the same. In that situation, the maximum reactivity value (BOC, cold without Xe) would be the same for both cases, 5 and 10 MW.
As Xe is not saturated at 5 MW, the reactivity loss due to Xe undergoes a certain increase (at 10 MW as compare with 5 MW).
If a fixed reference value for reactivity is considered at the EOC, the cycle length results somewhat smaller, $T_{10} < 1/2\ T_5$. Therefore the average BOC core burnup is smaller and thus the maximum reactivity (cold without Xe) is increased.

3.2. Modified fuel strategy (1 → 2 FE/cycle)

A systematic strategy change from 1 FE/cycle to 2 FE/cycle preserving the strategy type (out → in or in → out, represented with the symbols OI o IO) enables, on one hand, to increase the cycle length significantly re-establishing a value $T_{10} \cong T_5$. Thus the average core burnup difference between BOC and EOC increases, therefore increasing the reactivity change during the cycle.
Again, as the EOC reactivity value is fixed, the <u>maximum excess reactivity</u> also increases.

3.3. Modified fuel shuffling (OI → IO)

We here refer to the effect produced when inverting the trajectory sense of the FE in the core (OI → IO). This effect is not too important but has been also analysed.
When the fresh FE are loaded into the core in its central region (IO), the BOC reactivity undergoes an increase as compared with the equivalent OI strategy.

4. Calculations and results

Using the program CITVAP, the equilibrium state was found for the core described, operating at 5 MW, with a cycle length fixed in 20 days, corresponding to an average actual cycle length. For such equilibrium condition the BOC and EOC reactivity values were calculated. Some graphite blocks surrounding the fuel region were eliminated in order to achieve a not so high EOC reactivity for the hot, non-Xe state (ρ_{EOC}).
Although the value obtained $\rho_{EOC} =$ 2052.6 pcm is not the actual EOC reactivity (near to 1000 pcm), this value is useful as a reference to define the comparison criterion with other cycles. Independently of the fuel management strategy and/or the power at which the reactor is operating, the core should always provide the same EOC reactivity reserve in order not to

penalise the irradiation capacity of the installation. Therefore, it will be considered an imposed condition to have ρ_{EOC} = 2052.6 pcm in the new cycles with modified power or fuel strategy.
Several strategies were then analysed, varying the number of FE discharged per cycle, the type of strategy and the power, adjusting the cycle length in order to obtain ρ_{EOC} = 2052.6 pcm for every case.
Two basic variations were considered as concerns the number of FE discharged per cycle:

- 1 FE/cycle
- 2 FE/cycle

and two different types of strategy for each case:

- From the outer region to the inner one (**OI**)
- From the inner region to the outer one (**IO**)

Table 1 shows the general results obtained with CITVAP for the BOC and the EOC reactivities in different situations.
The Xe reactivity worth for all the analysed situations was approximately 2830 pcm at 5MW, and some 3250 pcm at 10 MW.
The BOC reactivity increase for the hot, non-Xe state due to each of the analysed changes is shown in Table 2. As a consequence of the fact that the temperature effect is essentially the same for 5 and 10 MW, the previous results also correspond to the BOC reactivity increase for the cold non-Xe state.
It is noticed that an increase from **5 to 10 MW**, and almost independently of the fuel management strategy, produces a BOC reactivity increase of some **330 pcm**.
If **2 FE** are discharged per cycle instead of **1,** the reactivity increases in about **650 pcm**, while a modification in the type of strategy from OI to IO produces an increment of at least **150 pcm** for each fresh FE loaded per cycle.
The actual fuel management strategy used in the reactor is not completely systematic, so that it is not possible to describe it clearly as belonging to the OI or the IO type, so that the values here shown should be considered only as a trend.

5. Estimation of the new shut down margins

Table 3 shows the excess reactivity, the reactivity worth of the safety rods, the shut down margin (SM) and the reactivity safety factor (RSF) for different situations. The corresponding values for 5 MW are representative of a typical core and were obtained as a conservative average of several actual configurations with greater excess reactivity, having smaller burnup values than the equilibrium ones. These values correspond to a cold non-Xe core with 6 mini-plates of approximately 1 g U_{235} each, loaded at the central irradiation box.
The new operation margins for 10 MW were estimated by adding to the typical values for 5 MW, an increment of 330 pcm due to the Xe effect plus another 650 pcm due to the change of fuel management strategy from 1 FE/cycle to 2 FE/cycle when corresponds.
As it may be noticed, for both the 1 FE/cycle and 2 FE/cycle fuel strategies, the margins established by the Argentinean Standards are by far fulfilled [4]. Even taking into account the approximations in the conceptual model used, it may be concluded that the operation at 10 MW does not impose a restriction on the type of fuel management strategy, at least for a 2 FE/cycle strategy.
Nevertheless, as it may be seen in Table 3, the condition of subcriticality with two control rods only (CR1+CR4), results preserved with difficulty. For the case of 1 FE/cycle, the shut down margin with only two rods $SM_{(CR1 + CR4)}$ is only 170 pcm. For a 2 FE/cycle strategy, and

in the most reactive condition with CR1 and CR2 inserted, the core is super-critic with a reactivity $\rho_{CR1+CR4}$ = + 480 pcm. It should be noticed that this reactivity is almost equal to the reactivity provided by the 6 mini-plates for ^{99}Mo production.
The preceding values show that if a permanent 2 FE/cycle strategy is used at 10 MW, it is very probable that under certain circumstances, the pair CR1+CR4 could result insufficient to maintain the BOC core in a subcritical state. In such case, the first start up should be carried out decreasing the excess reactivity, for instance, withdrawing some graphite blocks of the reflector.
Another choice could be to replace (permanently) the pair of control rods defined as Safety and Compensating Rods (at present CR1 and CR4) by some other pair with greater reactivity worth.
For instance, the pair (CR2,CR4) is frequently more absorbing than the pair (CR1,CR4) being its reactivity worth between 200 and 900 pcm greater according to the burnup distribution. The drawback of using this pair (CR2,CR4) would be that during the first operation day with CR2 inserted, while the Xe is established, it will affect the neutron flux at the central irradiation box in a greater amount than CR1.
The pair (CR1,CR3) could also be chosen, being the one having the greatest reactivity worth for almost every core configuration. Such pair would result in an addition of approximately 1000 pcm or more to the shut down margin. The drawback of using this pair is that the flux perturbation on the central irradiation box would occur during the whole cycle. Symmetry would also be broken, although it is not a strict symmetry due the asymmetric flux distribution. Nevertheless, this could be solved moving the rods symmetrically.

6 Conclusions

It is concluded that the operation at 10 MW with both types of fuel management strategies, 1 FE/cycle and 2 FE/cycle, is completely compatible with the Argentinean Standards in force [1].
It is probable that the condition fixed by the reactor logic (CR2 and CR3 withdrawn while rising power), could not always be fulfilled for the BOC, cold, non-Xe core when loading two fresh FE per cycle. Although this is not an original regulatory requirement, it has been added by the installation into the mandatory documentation of the RA-3 reactor.
In view of the results obtained it would be convenient for the installation to define a long-term fuel strategy, loading 1 or 2 FE/cycle. If the second option were chosen, the installation should evaluate the actions to be followed in order to guarantee subcriticality during start up with the above mentioned two control rods withdrawn.

7 References

[1] Technical Report CNEA-CAB 047-023/02, "Simulation of a fuel management for the RA-3 reactor at 10 MW". O. Serra
[2] CNEA.C.RCN.ITE.153, “Thermal-hydraulic analysis of the RA-3 reactor for its operation at 5 and 10 MW, with a configuration with 25 FE".
[3] IT-571/2000. "New model for the follow up of the RA-3 reactor operation having a central irradiation device". A. M. Lerner - M. Madariaga. ARN.
[4] Standard AR 4.2.2 and Regulatory Guide GR 4. ARN.

8. Tables

Power (MW)	Cycle length (days)	N° FE / cycle	Strategy type	ρ(BOC) hot with Xe (pcm)	ρ(BOC) hot without Xe (pcm)	ρ(EOC) (pcm)
5	**20**	**1**	**OI**	2716.0	5562.8	**2052.6**
5	38.65	2	OI	3315.7	6149.7	2056.2
5	23.12	1	IO	2880.4	5715.8	2042.7
5	44.30	2	IO	3628.8	6442.6	2054.2
10	9.59	1	OI	2654.3	5911.5	2052.5
10	18.54	2	OI	3202.6	6460.1	2055.6
10	11.10	1	IO	2813.2	6062.5	2039.6
10	21.25	2	IO	3509.1	6750.8	2054.6

Table 1. BOC reactivity for the hot, with and without Xe core, and EOC reactivity for the 5 and 10 MW and two different fuel management strategies.

Cause of $\Delta\rho_{BOC}$ (cold, no Xe): →			
POWER	**Refuelling strategy**		**$\Delta\rho_{BOC}$ (pcm)**
5 → 10 MW (Xe increase)	1 FE/cycle	OI	348.7
		IO	346.7
	2 FE/cycle	OI	310.4
		IO	308.2
5 MW	1 → 2 FE/cycle	OI	586.9
		IO	726.8
	1 FE/cycle	OI → IO	153.0
	2 FE/cycle		292.9
10 MW	1 → 2 FE/cycle	OI	548.6
		IO	688.3
	1 FE/cycle	OI → IO	151.0
	2 FE/cycle		290.7

Table 2. BOC reactivity increase for the cold, non-Xe core.

Parameter	Range established by standards	5 MW (6 minipl. IN)	10 MW (6 minipl. IN) [2]	
		1 FE / Cycle [1]	1 FE / Cycle	2 FE / Cycle
Excess reactivity (pcm)	No limit	6200	6530	7180
Reactivity worth of the safety rod bank (pcm)	No limit	16000	16000	16000
$SM_{4\ SE}$ (pcm)	≥3000	9800	9470	8820
$SM_{(4-1)SE}$ (pcm)	≥1000	4800	4470	3820
$SM_{(CR1+CR4)}$ (pcm)	≥0	500	170	CR1 + CR4 **do not** make the reactor subcritical (cold, non Xe)
RSF	≥1.5	2.58	2.45	2.23

Table 3. Estimated BOC, cold, non-Xe reactivity values for the operation at 10 MW and safety reactivity margins.

(1) Typical values, taken from the analysis of historical values for 5 MW.

(2) Estimated values on the basis of [1] and corrected with the variations shown in Table 2.

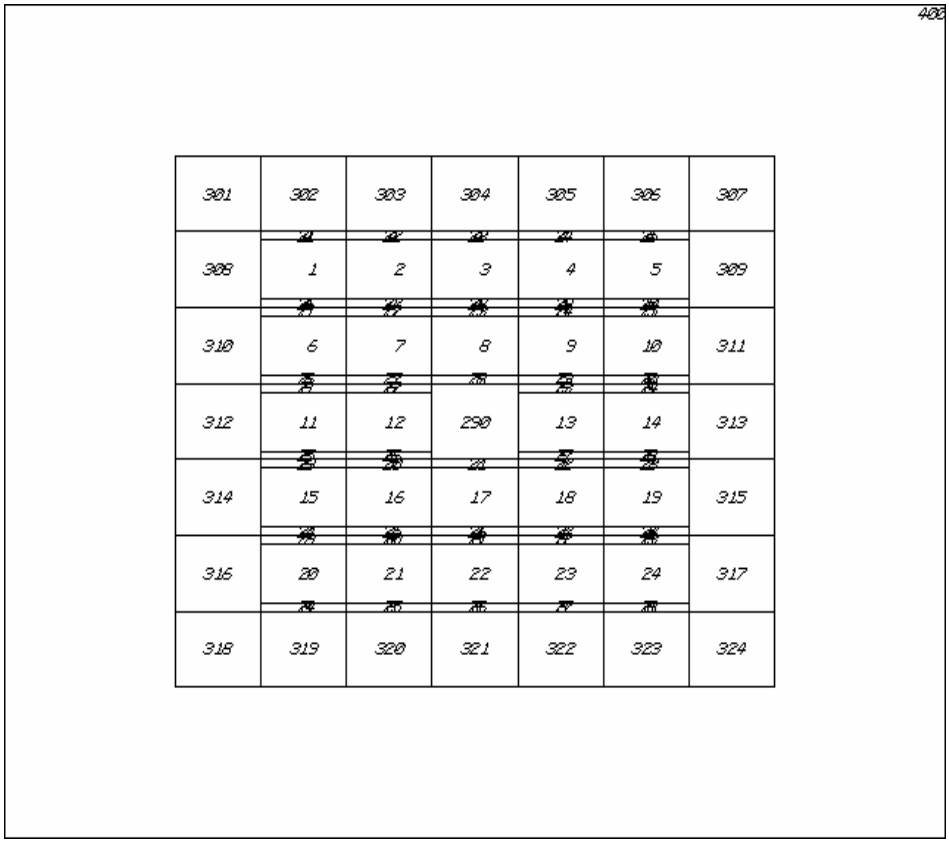

Figure 1. Schematic cross section of the core according to the proposed model.

Unique refuelling chain for 1 LEU FE/cycle

FRESH → 1→ 5→ 24→ 20→ 2→ … → 13→ 17→ 12→ 8

Two refuelling chains for 2 LEU FE/cycle

FRESH → 1→ 24→ 2→ … → 13→ 12

FRESH → 5→ 20→ 10→ … → 17→ 8

OBS. : 21 SFE + 4 CFE ≅ 24 SFE