ACTIVITIES IN ARGENTINA RELATED TO THE USE OF SLIGHTLY ENRICHED URANIUM IN HEAVY WATER REACTOR NPPs

XA9953249

R. CORCUERA
Division of Nuclear Reactor and Power Plant Activities,
National Atomic Energy Commission,
Buenos Aires

and

Atucha-1 Nuclear Power Plant,
Nucleoelectrica Argentina S.A.

Argentina

Abstract

An overview of activities related to the use of Slightly Enriched Uranium (SEU) fuel in HWR type NPPs, currently under execution in Argentina, is presented. The activities here described cover certain *R&D lines* as well as the main aspects of the *Project "Transition from full Natural-U to full SEU core in Atucha-1 NPP"*. Concerning the R&D lines, a summary is given on investigations related to reduction of void-coefficient using SEU fuel assemblies, annular pellet SEU fuel for bundle power flattening, etc. The main aspects of the above mentioned Project are outlined. At present, Atucha-1 core is approaching a 40. % of core load with SEU fuel, while the target of full SEU fuel core should be reached in 2-3 years. The expected exit burnup for such a core, namely 11000 MWD/tnU, is already currently obtained for SEU fuel in the present mixed core, while an increase in exit burnup of Natural-U fuel has also been obtained in very good agreement with reactor physics calculations. The comprehensive safety analysis carried out for each phase of the Project showed very moderated changes in plant behaviour under the set of postulated accidents and abnormal transients. A recent development, namely the CARA Project, aimed at unifying manufacturing of fuel assemblies for both operating NPPs in Argentina is presented in an accompanying paper.

1. INTRODUCTION

The two NPPs currently under operation in Argentina are both of the HWR type, with on-power refueling and designed for Natural-U fuel in the form of UO2 pellets located in annular fuel assemblies with 37 rods. However, while the 648 MWe Embalse NPP is of the CANDU-6 type using 0.5 m long fuel bundles loaded in sets of 12 bundles within 380 horizontal pressure-tube channels, the 360 MWe Atucha-1 NPP has a pressure-vessel reactor with 252 vertical fuel channels, each one accommodating one 6.5 m long fuel assembly.

A third NPP, Atucha-2, still under construction with nearly 80. % completion, is of Siemens design as Atucha-1 and has a very similar conceptual design. Capacity is 745 MWe and the pressure-vessel reactor has 451 vertical fuel channels.

Natural-U fuel exit-burnup in Atucha-1 (6000 MWD/tnU) is lower than the equivalent for Embalse (7100 MWD/tnU), and at the same time the manufacturing cost is much higher for Atucha-1 fuel than that for Embalse, mainly due to the length and complexity of Atucha-1 fuel assemblies (See Figure 1). These factors led to a quite high impact of fuel cost on the total operating cost of Atucha-1 NPP. As a result, different lines of activities, developments and projects were initiated in Argentina since several years ago in order to try to lower that impact of Atucha-1 fuel.

Such developments and engineering activities are at present effectively giving their results through the execution of a transition in Atucha-1 reactor from a full Natural-U fuel core (as designed) to a new full 0.85 % Enriched - Uranium (SEU) fuel core, with practically no major modification to the plant hardware and no perturbation to plant availability.

① Identification
② Upper coupling
③ Steel rods
④ Intermediate ring
⑤ Zry-4 tubes
⑥ Tie plate
⑦ Type - 1 spacer grid
⑧ Type - 3 spacer grid
⑨ Bottom spacer grid
⑩ Spring sliding shoe
11Support Zry-4 tube
12Fixed shoe
13Type - 3 spacer sliding shoe

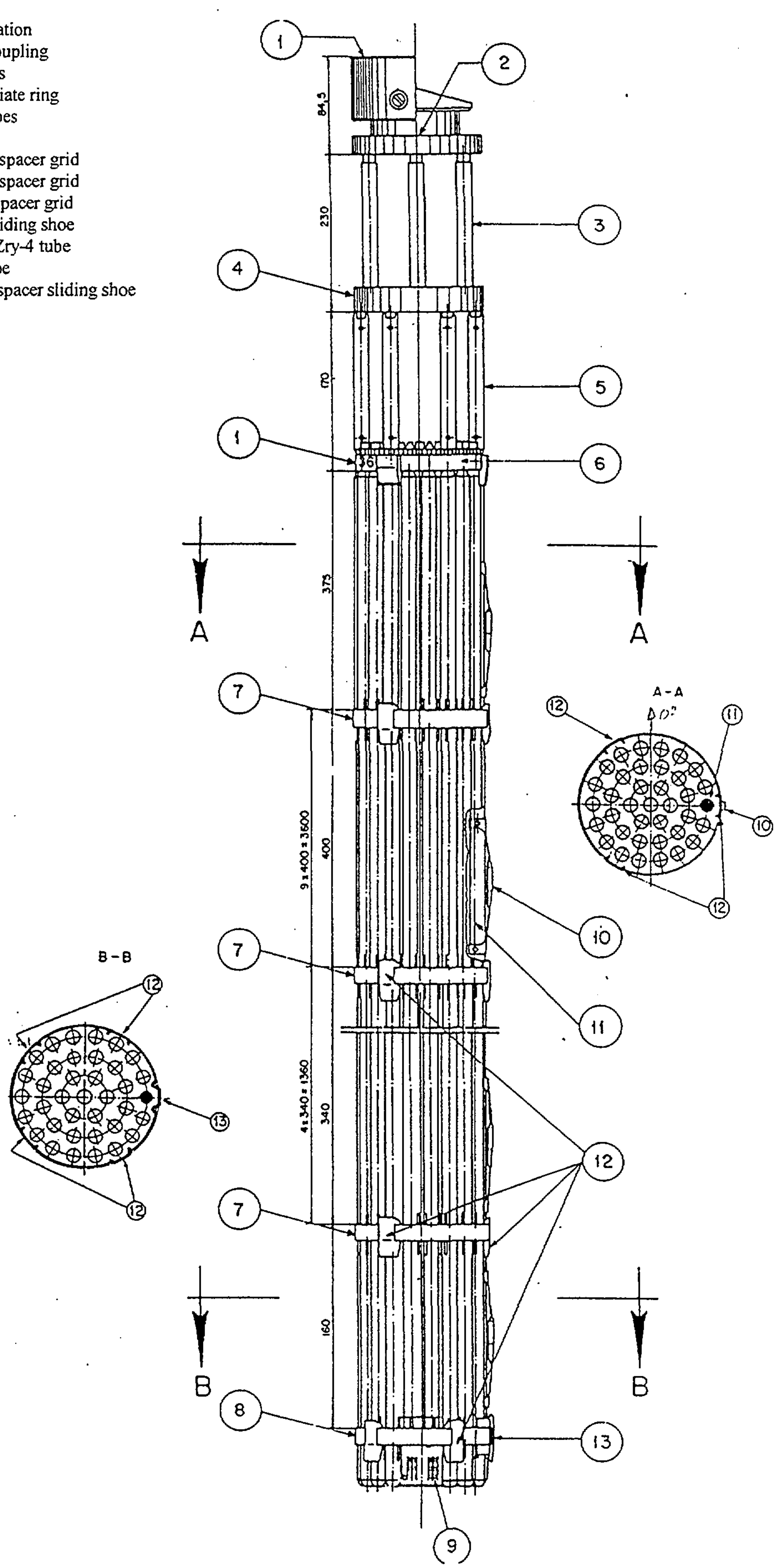

FIG. 1. General view of Atucha-1 fuel assembly.

Meanwhile, the various development lines under way could lead in the future to a possible introduction of SEU fuel also in the CANDU-type Embalse NPP. These developments include, in particular, the CARA Project aimed at unifying manufacturing of fuel assemblies for both operating NPPs in Argentina, which is presented in an accompanying paper.

2. DEVELOPMENTS AROUND THE USE OF SEU FUEL

In this Section certain R&D lines related to the use of SEU fuel in Argentine NPPs are outlined. Due to the possibility of a direct transition in a HWR from a Natural-U to a SEU fuel core, the selected and standard value of U enrichment has been up to now restricted to 0.85 %. Higher values have also been studied but only in exploratory studies oriented to long term schemes.

2.1 Economic Studies.

A wide variety of economic studies have been executed in order to evaluate different aspects. As an example, a particular study is described in this paragraph, summarizing the work presented in Ref. [1].

Studies concerning the impact of SEU fuel as a First Core for Plant Start-up

Due to on-power refueling together with operation flexibility, switching from Natural-U to SEU fuel in HWR-type NPPs has always been considered as a transition; moreover as a very smooth transition with no specific plant shut-down for this change of fuel. This is effectively the case of operating HWR NPPs but, what is the actual situation for a new plant concerning that transition versus a direct use of SEU fuel from the very beginning ?

A new plant like, for instance, Atucha-2 could in principle be started up either with a Natural-U or with a SEU fuel core. However, the startup core, which is normally fully or mainly composed of fresh fuel assemblies, is very far from the subsequent equilibrium core which is composed of high burnup fuel assemblies. This very special situation of a HWR startup core requires a significant use of neutron absorbers in order to compensate for the strong reactivity excess : usually a liquid poison in the moderator and / or a partial load of Depleted-U fuel assemblies. This situation is unique of the startup core since, later, the equilibrium core is progressively attained. This is very different from the case of LWRs with no on-power refueling and operating under burnup/refueling cycles.

The use of SEU in the startup core of a HWR makes the above mentioned unique situation still more intense, leading to a longer transition to the equilibrium core while at the same time exit burnup is smaller. The final and global result is a practically insensitive value of the levelized KWh cost during the plant lifetime, to the use of a Natural-U or a SEU startup core. Using quite conservative assumptions and considering a full-time Natural-U core as the reference case, the levelized KWh cost shows the following reductions for Atucha-2 using a 0.85 % enrichment for SEU fuel.

Table 1.

CASE	KWH COST SAVING (%)
1. REFERENCE (Full-time Nat.-U core)	----
2. Full-time SEU core	27.
3. Startup core : Natural-U fuel Equilibrium : SEU fuel	25.

2.2 Reactor physics investigations

Different studies have been undertaken regarding the potential of SEU fuel to improve neutronic safety parameters, to improve operation performance (especially exit burnup, fuel consumption and final fuel cost) and operation flexibility (especially power limitations and in-core fuel movements). Two examples are summarized below.

Reduction of void reactivity coefficient

A study on the reduction of the void reactivity coefficient is summarized in this paragraph taken from Ref. [2 and 3].

The normally positive void reactivity coefficient of HWRs using standard Natural-U or SEU fuel assemblies can be reduced or even turned negative through an appropiate fuel composition distribution within the annular fuel assembly, using a strong absorber like Dysprosium in the inner rod rings and SEU fuel in the outer rod rings [4, 5]. It has been established [2] that for CANDU-type fuel bundles, the combination of Depleted-U with 1. % Dy in the inner rings and 2. % Enriched-U in the two outermost rings has an almost equivalent behaviour to that of a "Uniform" 37-rod 0.85 % SEU fuel bundle in reactivity evolution with burnup.

Calling "Low Void Reactivity Bundle" (LVRB) to the former bundle and "Uniformly Enriched Fuel Bundle" (UEFB) to the last one, it is observed a higher reactivity for LVRB at very low burnup and a lower reactivity at very high burnup. However, between approx. 2000 and 12000 MWD/tnU, that is most of the usefull region, the bundle reactivity is almost identical for LVRB and UEFB.

Nevertheless, the "Low Void Reactivity Bundle" (LVRB) raises a new problem, namely, inner (radial) power peaking, whose factor changes from approx. 1.1 for the "Uniformly Enriched Fuel Bundle" to approx. 1.4 for the LVRB.

Reduction of Power Peaking

A study presented in Ref. [6] is summarized in this paragraph.

The above mentioned inner power peaking can be flattened through the use, in the outermost rod rings, of holed or annular pellets with an appropiate inner diameter. This concept can be applied either to Candu-type or Atucha-type fuel assemblies, having in both cases similar effects.

The following Table 2 shows a comparison on the Power Peaking Factor (PPF) for Embalse NPP reactor cell in the hypothesis of different fuel types. The minimum and maximum values observed for the whole burnup range of interest are quoted. The last case correspond to the use of 11.% voided pellets in the outermost rod ring, instead of normal pellets.

Table 2.

FUEL TYPE	POWER PEAKING FACTOR (Minimum - Maximum Value)	
Natural-U / standard	1.115	1.13
0.85 % Enriched-U / standard	1.10	1.145
0.85 % Enriched-U / 11.% voided outer pellets	1.045	1.08

For the same three cases, calculations carried out for Atucha-1 fuel cell showed similar effects. The *maximum values* of PPF are respectively : 1.10, 1.11 and 1.04.

Concerning the exit burnup losses due to the use of holed pellets in the outermost rod ring in a Embalse-type fuel bundle, they are very small : around 250 MWD/tnU over a value of approx. 12500 MWD/tnU for Uniform 0.85 % Enriched-U fuel bundle. A very similar situation holds for Atucha-1 fuel : exit burnup losses would be around 160 MWD/tnU over a value of approx. 11000 MWD/tnU for Uniform 0.85 % Enriched-U fuel bundle.

Potential for a combined application

Both for Atucha and Candu types of fuel assemblies the annular configuration of fuel rods is : 1 central rod + 3 rod rings, with respectively 6, 12 and 18 rods.

This number of rings (3) is not very high for satisfactorily accommodating at the same time the LVRB concept (with a central absorber region and an external fissile region) and the holed pellet concept in the outermost or external region. Emphasis in power flattening, through a lower fissile load in the outermost ring would lead to decrease the capacity of the LVRB concept to lower the positive void reactivity coefficient.

The CARA fuel assembly design aimed at being used in both types of plants, and having 60 fuel rods instead of 37, distributed in a higher number of rings, brings much more space for an optimum combination of the LVRB concept and the holed pellet concept.

3. PROJECT "USE OF SEU IN ATUCHA-1 NPP" (1)

3.1 Main features of Atucha-1 Core

The above mentioned 252 vertical fuel channels of Atucha-1 core form a 27.2 cm-pitch trangular lattice, inside the moderator tank. This tank is within the reactor pressure vessel, while the annulus between them forms the coolant down-comer similar to that of a PWR. Each channel is essentially an approx. 2 mm.-thick Zry-4 tube separating the inner D2O coolant (at 280.oC average temperature) and the outer D2O moderator (at 190.oC average temperature). Both fluid systems are connected outside the core and kept at the same pressure (approx. 115 ata); the channel tubes assure a colder moderator separated from the coolant in the core region.

In order to establish a quite uniform exit coolant temperature among the 252 fuel channels at the upper plenum, these channels are lumped into 8 different "Hydraulic Zones" (HZs), each HZ having a different coolant flow selected for approximately matching the radial power profile. The central HZ corresponding to the most rated fuel channels has no flow restrictors, while the 7 outer HZs have 7 different types of throttles located at the entrance of each channel (See Figure 2).

Up to the beginning of 1995, only fresh Natural-U Fuel Assemblies (NU FAs) were loaded and shuffled following a 3-position in-core path. Such a scheme defined three "Burnup Regions" (BRs). Numbering the 3 BRs from the core center to the periphery, they were :

BR 1 : Central BR, with intermediate burnup FAs.
BR 2 : Intermediate BR, entrance region (fresh FA loading) with low burnup FAs.
BR 3 : Outer BR, exit region (FA unloading) with high burnup FAs.

Every FA followed the path :

Fresh FA >> BR 2 (core load) >> BR 1 >> BR 3 (core unload) >> Fuel Pool

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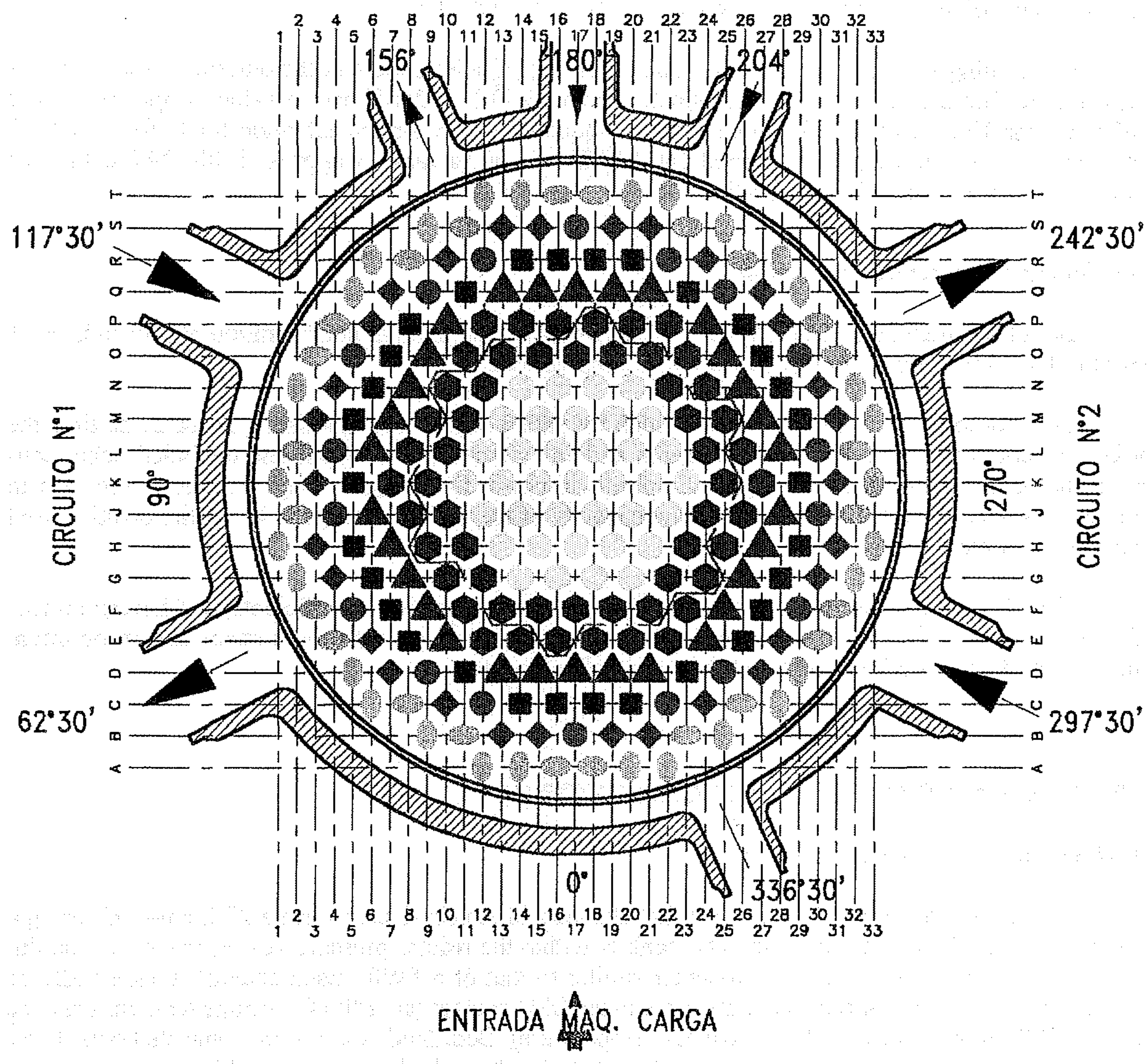
(1) The author is Technical Reviewer of the Project.



TIPO DE ESTRANGULAMIENTO	DIAMETRO EQUIVALENTE mm.	N°DE E.C.	CAUDAL min. kg/seg.(1)	CAUDAL min. kg/seg.(2)	PLANO M20
1	18,6	30	8,54	4,14	405–1
2	21,0	24	11,86	5,43	405–1
3	25,0	30	15,40	7,30	405–1
4	28,4	18	19,14	9,04	405–1
5	34,2	30	23,74	10,96	405–2
6	39,0	30	28,67	13,43	405–3
7	44,0	54	29,41	13,84	405–4
8		37	32,90	16,08	

FIG. 2. View of hydraulic zones in Atucha-1 core.

3.2 Organizational aspects

The Project "Use of SEU in Atucha-1 NPP" is at present carried out by the Utility, Nucleoelectrica Argentina S.A. (NASA), through its Engineering Div., responsible for the Project, and with a relevant participation of Atucha-1 NPP staff.

Other sectors of NASA as well as of the National Atomic Energy Commission (CNEA) provide technical support and execute engineering tasks in specific areas. Manufacturing of Atucha-1 SEU FAs is carried out (as for all other Argentine NPP FAs) by the local manufacturer CONUAR.

3.3 Phases of the Project

This is a Project formally divided into Phases with the purpose of initial 0.85 % Enr.-U FA in-core irradiation and essay, followed by a smooth transition from the full NU FA core to a full SEU FA core. Each Phase has two parts :

1) *Engineering tasks and elaboration of licensing documentation.*
2) *SEU FA Irradiation Program and evaluation.*

At the onset of the Project in 1993, a rather quite number of Phases were foreseen, reflecting a limited knowledge on how SEU FA would work in this HWR. Main concerns were with :

* Atucha-1 FA behavior under a very high burnup (changing exit burnup from 6000 to 11000 MWD/tnU)

* Reactor control system behavior under much higher positive reactivity insertion during FA loading.

* Adequate selection of core channels for fresh SEU FA loading, taking into account quite thin channel power and local power margins even for fresh NU FAs.

* Adequate selection of in-core movement positions for irradiated SEU FA, taking into account channel power and local power limits, as well as Pellet-Cladding Interaction prevention criteria (PCI criteria).

* Overall core behavior, core parameter changes and core response in front of postulated accidents and abnormal transients, under the presence of SEU fuel in the core.

During 1993 and 1994 the engineering tasks of the First Phase were carried out [7] and the first SEU FA was loaded in January 1995. This was defined as follows :

Phase 1 : Initial SEU FA irradiation and essaies. The SEU FA load is limited to a maximum of 12 over 252 FAs in the core. Minimum perturbation of core parameters.

On the basis of both engineering studies and early evaluation of results of SEU FA irradiation during Phase 1, the initial scheme of many Phases was lumped, for the rest of the Project, into only two more Phases, as follows :

Phase 2 : Massive SEU FA irradiation. The SEU FA load was limited to a maximum of 60 and later extended to 99 over 252 FAs in the core.

Phase 3 : Approach to the Full (0.85 % enriched) SEU FA core.

3.4 Summary of Phase 1

A presentation of main results of this Phase was given in [8].

The main outstanding aspects may be summarized as follows :

- All SEU FAs were loaded at 6 selected channels having exit-coolant-temperature thermocouple measurements but located at the outermost channels of a high coolant flow HZ in order to have the maximum possible channel power margin.
- The in-core SEU FA movement scheme was the same as that for NU FAs, though with much higher residence times in each BR and higher transition burnups.
- Excellent behavior of Atucha-1 FAs containing SEU fuel and approaching the target exit burnup for the final core. Most of the 18 SEU FAs irradiated in this Phase 1 reached exit burnups of around 10000 MWD/tnU.
- A special study was done for providing practical and more flexible PCI criteria and a new specification for in-core fuel handling involving SEU FAs was elaborated [7] and applied [8].
- A comprehensive experimental verification of predicted / calculated parameters was executed. This involved especially regulation rod bank movements and coolant exit temperature at fresh SEU FA channels, both during SEU FA loading.

3.5 Summary of Phase 2

The engineering activities, including all the safety studies and licensing requirements are presented in [9].

The most significant aspect of Phase 2, due to its complexity, was the determination of an appropiate in-core refuelling scheme involving a rapid replacement of fresh NU FAs to be loaded by SEU FAs. This was solved through the use of a two-way scheme for SEU and a one-way scheme for NU FA movements within the core.

Phase 2 Irradiation Program was initiated just after the planned annual outage of the plant at mid 1996. It was originally elaborated for reaching a maximum of 60 SEU FAs loaded in the core, nearly at the end 1997. However, due to planification reasons it was decided to consider an extension of the Phase up to a total load of 99 SEU FAs. For that, a more specific study [10] was elaborated on the basis of Ref. [9].

Meanwhile, this Irradiation Program has up to now proceded in the same excellent way as Phase 1. No SEU FA failure attributed to the use of SEU fuel has been observed; FA failure rate remained very low as before the initiation of the SEU Irradiation Program. Core's operation parameters were hardly modified as expected and the safety aspects were adequately covered as mentioned below. The target average exit burnup for the equilibrium full SEU core, namely 11000 MWD/tnU, is already achieved for SEU FAs unloaded during this Phase 2, while a progressive increase in that parameter for NU FAs is also observed.

It is expected to reach the 99 SEU FA load at mid 1998, just before the planned annual outage. After that, Phase 3 would be initiated in order to accomplish the full load with SEU fuel.

3.6 Some relevant aspects of the future equilibrium full SEU core

Main aspects of this future core were already calculated and analyzed. Some of these elements are included in Refs. [8,9,10].

In-core fuel management should be based in a basically 3 BR scheme quite similar to that employed with the former full NU core, using two ways (See Figure 3).

Radial power flattening associated to the use of SEU fuel, would bring larger power margins for the 2 innermost HZ (having the most rated FAs), providing more flexibility for FA shuffling and general reactor operation.

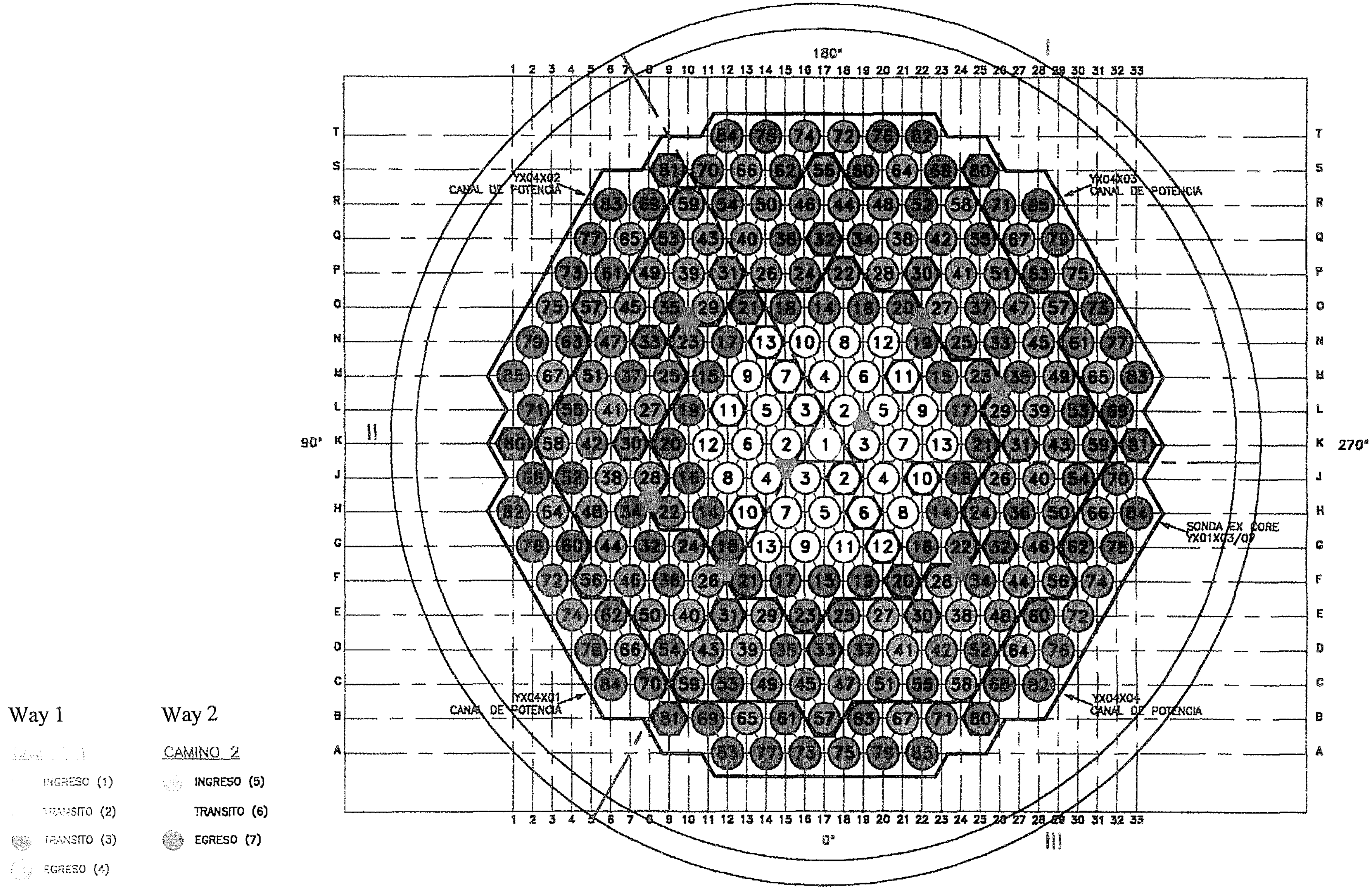


FIG. 3. Scheme of in-core SEU FA management for equilibrium core.

The predicted average exit burnup is 11100 MWD/tnU, representing a saving of approx. 46. % as compared to the former full NU core on total irradiated FAs.

Other similar or significant savings are also expected in terms of use of the fuel loading machine, fuel pool capacity needs, etc., especially savings in the current and levelized fuel costs in the total generation cost, savings situated between 30. and 35. %.

3.7 Safety aspects

Activities in this area encompasses the following for each Phase of the Project, according to the maximum load of SEU fuel for that phase :

* Determination of new reactor-physics core parameters
* Determination of operation systems changes under normal conditions
* Determination of changes in radioactive inventories and releases, operational exposure and dosis to the public through different paths and conditions under conservative assumptions.
* Simulation and analysis of the set of accidents and abnormal transients postulated for the previous full NU core.
* Identification, simulation and analysis of new postulated accidents and abnormal transients associated to the use of SEU FAs.

The most relevant fact to be outlined is the small impact of the replacement of NU by SEU as fuel on all the reactor-physics safety parameters. Such changes though generally in the less-safe sense, are so small that lead to quite insensitive results on the postulated accidents. As an example for Phase 2 the following changes are observed against the former full NU core [8,9] :

Table 3.

REACTOR PARAMETER	CHANGE (%)
Effective delay neutron fraction β	- 1.3
Average prompt neutron half-life Λ	- 1.3
Fuel temperature reactivity-coefficient	- 3.6
Coolant void reactivity	- 0.2
Boron reactivity	- 1.0

3.8 Longer term prospects

The future equilibrium 0.85 % Enriched-U core could be in principle the last stage of fuel strategy por Atucha-1 NPP, since the most significant economic savings could be reached just from the point of view of FA's operating costs.

However, another aspect could then become relevant : the necessity of a new fuel pool for FA irradiated FA storage up to the end of plant lifetime, since the present capacity using this type of SEU FAs is not enough.

One interesting alternative to avoid the expensive construction of a new fuel pool in the plant can be a future transition from 0.85 % Enrich.-U to around 0.95 to 1.0 % Enrich.-U, just after achievement of the full 0.85 % Enrich.-U load in the core. In that case the new gain in exit burnup will reduce the total accumulated irradiated FA inventory towards the end of plant lifetime avoiding the need of a new fuel pool, bringing at the same time an additional saving in the direct FA consumption cost contribution to the total operating cost.

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