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SEU FUEL IN ATUCHA-1 NPP, A VALUABLE EXPERIENCE FOR A CANDU-6 CORE ENRICHMENT

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ABSTRACT

The program to introduce SEU (0.85 % U^{235}) fuel in Atucha-1 NPP started in 1993 and the first SEU fuels were loaded in 1995. Atucha-1 is a PHWR originally fuelled with natural uranium. Fuel Assemblies consist of 36 fuel rods. The active length is 5300 mm.

At the present time 125 SEU Fuel Assemblies were irradiated without failures associated with the extended burnup or unfavorable influences on the operation of the power station. In the present stage of the program 72 % of core positions are loaded with SEU fuel. Mean fuel discharge burnup increased from 5900 MWd/tU to more than 11000 MWd/tU. The impact of the fuel on the cost of operation had an important reduction.

This paper describes considerations about SEU fuel design analysis. The main concerns were related with the internal gas pressure, strains in fuel cladding and PCI-SCC sensitivity in power ramps at high burnup. A new burnup dependent criteria to prevent PCI failures was defined.

The paper also details some aspects of SEU fuel performance data. Among them power ramps, discharge burnup and dwelling time data are discussed. In some cases the cladding axial growth after the irradiation was measured and the data obtained fits with a good agreement with model predictions.

Despite the differences between Atucha-1 and Embalse fuel designs the experience accumulated in this program is encouraging and will be very helpful if a similar program is considered for a CANDU-6 core.

1 Nuclear Power in Argentina

There are two nuclear power stations at the present in Argentina. These power plants are Atucha-1, located 120 km NW of Buenos Aires and Embalse (CANDU-6), located in Córdoba province, 700 km away from the capital of the country. Both power stations are operated by NASA (Nucleoeléctrica Argentina S.A.). Another power plant, Atucha-2, is under construction close to Atucha-1 site.

The commercial operation of Atucha-1 started in 1974. Its gross electrical power is 357 MW_e and the thermal power is 1179 MW_{th}. The reactor is a pressure vessel type designed by SIEMENS (Germany), moderated and cooled with heavy water. The core has 252 coolant channels to contain the fuel assemblies and to separate the coolant from the moderator.

As a natural uranium heavy water reactor, Atucha-1 requires continuous refueling and on-power fuel shuffling in radial direction. Withdrawal and loading of fuel assemblies from and into the vertical coolant channels are performed using one refueling machine located on the top of the reactor vessel. Figure 1 shows a schematic representation of Atucha-1 reactor.

Relevant data for **Atucha-1** is provided in the following table:

Beginning of commercial operation	1974
Reactor Type	PHWR - Pressure Vessel
Thermal Output	1179 MW
Gross Electrical Output	357 MW_e
Coolant And Moderator	D_2O
Fuel Channels	252
Fuel Assemblies	252 (Full Length)
Refueling And Fuel Shuffling	Continuous On-Power
Coolant Pressure	115 Bar
Inlet - outlet coolant temperature	538/573 K
Original Fuel	Natural Uranium
Active Length	5300 mm
Total Uranium Loading	38.9 tU
Core Average Channel Power	4.68 MW
Maximum Channel Power	7.03 MW

2 Main fuel-related operational parameters

The core average linear power density is 232 W/cm and the design limit for the local peak of linear power density under steady state conditions is 531 W/cm. The design limit value for the local peak of linear power density for non-steady state operational fluctuations is 600 W/cm and for hot channel design verifications the linear heat ratio is 690 W/cm.

For natural uranium the FA average discharge burnup is about 5900 MWd/tU with peak pellet burnups about 9000 MWd/tU. The average residence time of the FA is about 195 full power days (fpd), and the average refueling frequency is 1.3 FA/fpd.

Average Linear Power	232 W/cm
Design Limit for Maximum Linear Power:	
Steady state	531 W/cm
Non Steady state	600 W/cm
Average Discharge Burnup (*)	5900 MWd/tU
Refueling Frequency (*)	1.3 FA/fpd
Pellet Peak Discharge Burnup (*)	8400 MWd/tU

(*) For natural uranium

3 Atucha-1 Fuel design

3.1 Fuel Assembly

The fuel assembly for Atucha-1 consists of 36 fuel rods in an array of three concentric rings and one central fuel rod. A supporting tube occupies one position in the outer ring. Zircaloy solid spacer grids keep the fuel rods in their positions. Bearing pads welded to the outer surface of a non-collapsible sheath provide the interaction with the spacer grids. Sliding shoes attached to the spacer grids and to the structural tube are used to set the assembly position in the coolant channel. The fuel rods and the supporting tube are hanging from an upper tie plate which is also made of Zircaloy.

3.2 Fuel Rod

The internal design of the Atucha 1 fuel rod is very similar to a Light Water Reactor fuel rod. Each element has a 5300 mm long stack of UO_2 pellets, isolating pellets, a gas plenum and a compression spring. Both end plugs are welded by tungsten inert gas (TIG) process. The Zircaloy-4 fuel cladding is free-standing (non-collapsible). The fuel rods are prefilled with helium gas at 17 bar .

Figure 2 represents an schematic description of the Atucha-1 fuel assembly and the following table shows fuel relevant data.

Assembly Geometry	Circular Array
Fuel Rods	36
Supporting Tube	1 (Zircaloy-4)
Rigid Spacer Grids	15 (Zircaloy-4)
Tie Plate	1 (Zircaloy-4)
Cladding Material	Zircaloy-4
Outside diameter	10.90 mm
Cladding wall thickness	0.55 mm
Active length	5300 mm
UO_2 sintered pellet density	10.60 g/cm^3
Fuel pellet diameter	10.62 mm
Gas pressure (as manufactured)	17 bar

4 Program for Atucha-1 Burnup Extension Using SEU Fuel

It is well-known that in heavy water reactors, initially designed for natural uranium, a small increase in the enrichment of the fuel produces a significant improvement in the discharge burnup and therefore in the economy of the fuel cycle. This is the central point of the SEU program. As an example, in Atucha-1 an increase of 20% in the degree of enrichment produces an increase in the average discharge burnup of 92%. The advantages of a SEU program have been reported for both, SIEMENS pressure vessel heavy water reactors and CANDU pressure tube heavy water reactors **[1][2]**.

A program to extend the fuel discharge burnup in Atucha-1 was implemented in 1993 and the first SEU fuels were loaded in January 1995 **[3]**.

Clear advantages from using SEU in Atucha-1 are:

- Extension of fuel discharge burnup
- Reduction of spent fuel volume
- Reduction of the fuel component of the cost of generation
- Reduction of on-power refueling frequency

An additional benefit of using SEU is the increase in the discharge burnup of natural uranium fuel during the transition to a full SEU core. Reloading of spent natural uranium fuel assemblies currently stored in pools to extend their original low discharge burnup is also under analysis and might be an additional advantage.

4.1 The program

The program to introduce SEU fuel in Atucha was divided in three stages. During the first stage that started in January 1995, 12 demonstration SEU FA were loaded. The second stage was the transition from 12 to 60 FA, after there was an extension of this stage up to 99 FA. The third stage will be concluded in 2000 – 2001 with the whole core loaded with SEU fuel. At the present 125 FA have completed their irradiation and 181 core positions (72 %) are fuelled with SEU fuel.

4.2 Modifications of Fuel Design

Different aspects of Atucha-1 fuel rod and FA designs were analyzed to consider the influence of the extended burnup. These aspects were: internal pressure, cladding strains and effectiveness of internal compression spring. Also effectiveness of both, bearing pads–spacer grids interaction and elastic sliding shoes-fuel channel interaction to hold fuel rods and fuel assemblies in their positions.

Several changes have been introduced in the design of both, the fuel rod and the fuel assembly to adapt them to the SEU requirements:

- With the aim to provide more volume for gas release the plenum length was increased.
- To assure reliable interaction between spacers and fuel rods during the whole life of the fuel bearing pads with longer contact surfaces were adopted.
- The ductility of the cladding material was increased to reduce the fuel rod susceptibility to PCI failures on power ramps.
- With the same objective, a thin coating of graphite over the internal surface of the fuel sheath is under development to be introduced in the future, if necessary.
- Regarding the fuel assembly design, Inconel 718 was used to replace the original material for spring-loaded sliding shoes (Steel A286) to compensate the higher relaxation produced by the increase in neutron fluence.

Fuel rod calculations were performed to evaluate the new design. These calculations were performed with the CARO-D code. This code was originally developed by SIEMENS for LWR fuel rods with higher burnups than those foreseen for Atucha-1 fuel under the SEU program. To be conservative unfavorable combinations of input data and calibration parameters were selected. Conservative power histories were also selected according to the parameter to be verified.

Calculations in nominal conditions predict that during the long time irradiation up to the SEU discharge burnup almost no mechanical interaction is expected. Only under severe combinations of design conditions the code predicts a low amount of cladding total tensile strain (0.3 - 0.4%). Calculations also show that fuel rod internal pressure is below coolant pressure so no cladding lift-off is expected.

The following table shows relevant data from conservative fuel rod calculations

Maximum central temperature	2260 K
Maximum internal pressure	110 bar
Maximum tensile sheath strain	0.41 %

4.3 PCI Fuel Failure prevention

A new PCI failure criteria was developed as an extension of the existing criteria for natural uranium fuel. The new one was based on the verification of power ramps size considering also the local burnup just before the ramp. Data obtained from fuel management calculations is used for this verification. This criteria is applied to every power ramp during the irradiation like fuel reshufflings, start ups or power cycling . After 3 years of application the results are satisfactory and there was no defect related with PCI.

4.4 Fuel Performance

To evaluate the fuel performance in this stage of the SEU program a data base with local linear power and local burnup distributions was built. This data was obtained from fuel management calculations. To reduce the amount of data only the fuel rod with the highest power in each assembly was considered. To represent the fuel rods 10 axial segments of the same length starting from the lower end are used.

Performance parameters analyzed were the relationship between linear power and local burnup during power ramps, discharge burnup distribution and the spread of dwelling times for different irradiation routes.

Figure 3 shows the power ramps during fuel shufflings to positions with higher power. This data is represented as function of local burnup for all the fuel assemblies analyzed. To simplify the graphic only data for segments 3 to 8 are represented. The distribution clearly shows the application of the burnup dependent PCI failure criteria.

The frequency distribution of FA average discharge burnup is represented in Figure 4. The average discharge burnup for the present stage of the program is a little higher than 11000 MWd/tU. An equivalent graphic for local burnup shows that the mean value is almost 14000 MWd/tU with maximums reaching 15000 MWd/tU. Figure 5 shows the distribution of dwelling times. Without considering two FA that were withdrawn before reaching the discharge burnup, the dwelling time goes from 300 to 500 fpd, almost doubling the corresponding value for natural uranium.

All discharged SEU fuel assemblies were visually inspected in a pool-side station. Some of the FA were measured before and after the irradiation to evaluate fuel rod axial growing. Figure 6 shows the results of this measurements as function of burnup. This data fits well with model predictions.

5 Conclusions

Atucha-1 is the only case of a medium size nuclear power plant with a heavy water reactor in which licensing studies were completed and a program for a gradual transition from a natural uranium core to a SEU core (0.85% U^{235}) is well advanced.

For this program the fuel design was reviewed considering the new conditions associated with the higher burnup. Several modifications were introduced in the fuel design and an extended criteria to prevent PCI failures was established.

The in-pile performance of SEU fuel assemblies at the present stage of the program is encouraging. Particularly the response to power ramps during on-power refueling and fuel shufflings. As was predicted, the operation of the plant showed no unexpected impacts due to the use of SEU fuels. An evaluation of fuel performance data shows that power ramps, discharge burnups and dwelling times satisfy previous estimations. The results of post-irradiation pool-side examinations and fuel rod length measurements are satisfactory and in agreement with previous estimations and models.

Relevant data to point out is the increase of the average discharge burnup from 5900 (natural uranium) to 11300 MWd/ tU and the reduction of the refueling frequency from 1.31 to 0.7 FA/fpd. Fuel consumption was reduced from 402 FA during 1997 to 272 FA during 1998. At the present 72 % of core positions are fuelled with SEU fuel. Based on the favorable experience the number of SEU FA in the core will be gradually increased to a full core in about one year (2000-2001).

6 References

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[3] M. Higa et al, Reducing Operating Costs by Using Slightly Enriched Uranium (SEU) Fuel in the Atucha-1 Nuclear Station. Economic and Technical Aspectos after 18 Months of the Irradiation Program, Proceedings of an International Conference on Nuclear Power Competitiveness in the Next Two Decades, Buenos Aires, Argentina, (November 1996).

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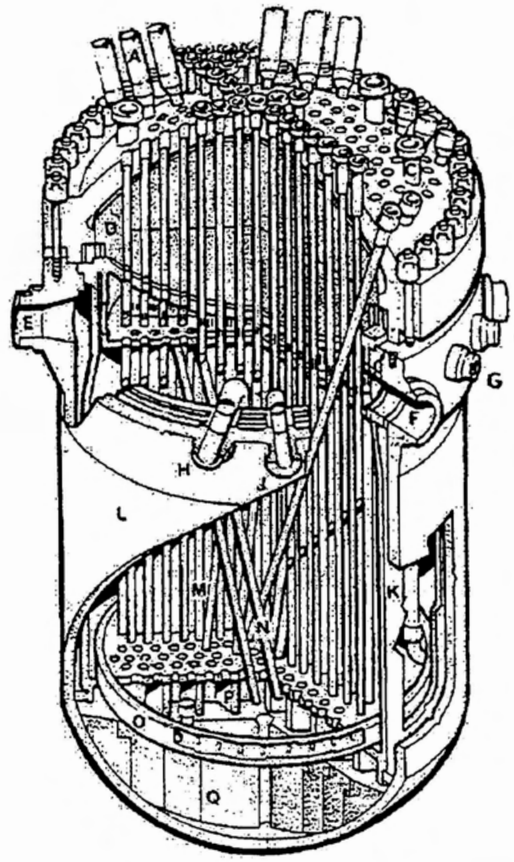
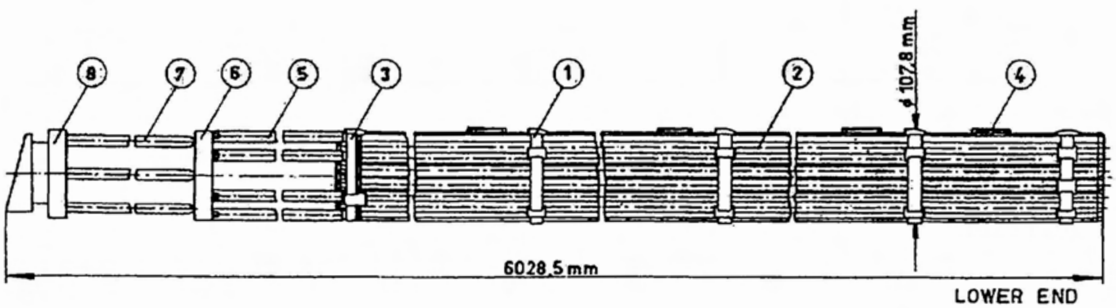


A Control rods
B Channel seal
C Moderator downcomer
D Upper filler piece
E Inlet from coolant pump
F Outlet to steam generator
G Injection line upper plenum
H Moderator outlet
J Fuel element detection system
K Moderator tank
L Pressure vessel
M Fuel assemblies and Coolant channels
N Control rod guide tubes
O Moderator distribution tube
P Support grid
Q Lower filler piece

Figure 1: Schematic representation of Atucha-1 reactor



1. SPACER GRIDS
2. FUEL RODS
3. TIE PLATE
4. SPRING-LOADED SLIDING SHOES
5. ZIRCALOY 4 TUBES
6. STEEL RING
7. STEEL RODS
8. COUPLING PIECE

Figure 2: Description of Atucha-1 Fuel Assembly

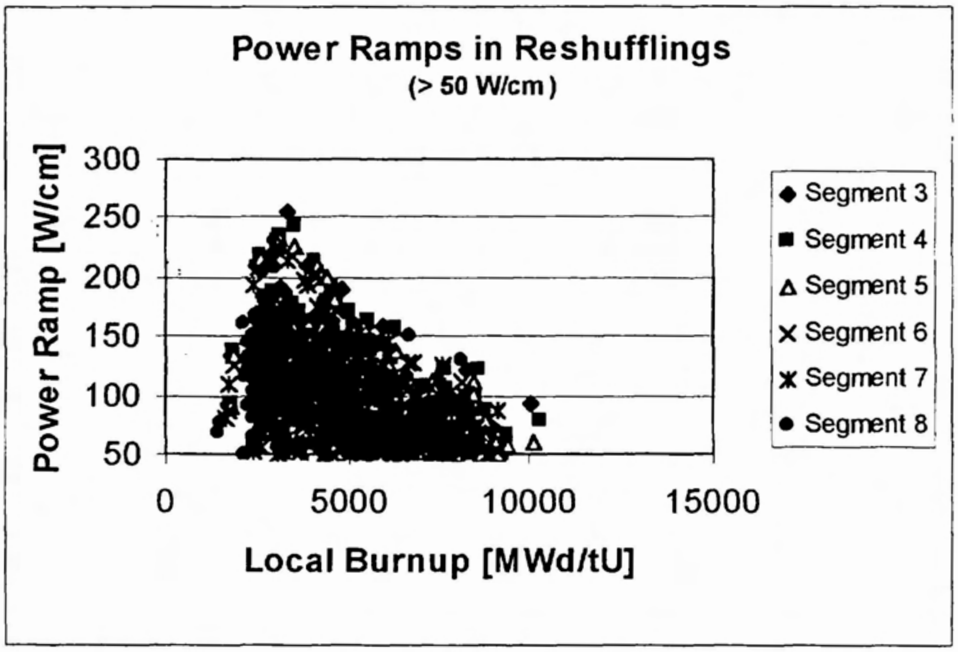


Figure 3: Power ramps during reshuffling for all the fuel assemblies analyzed

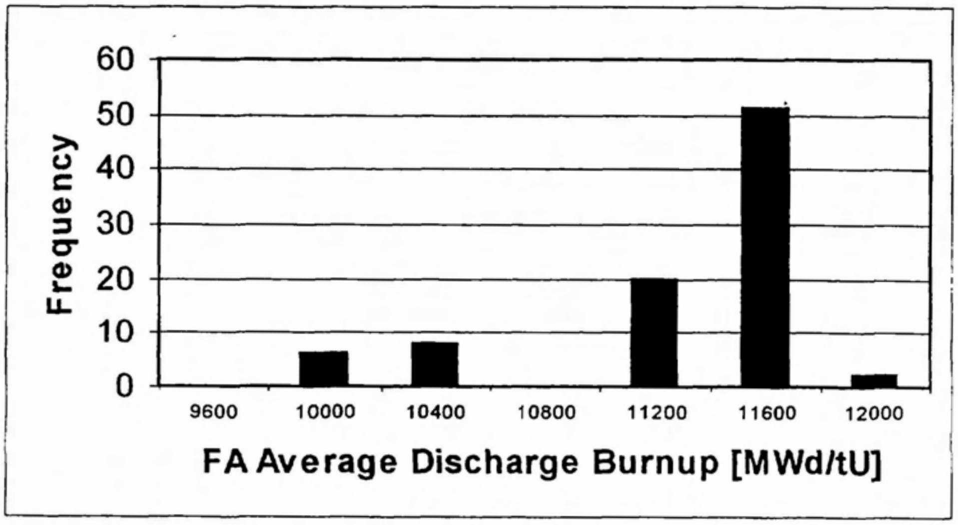


Figure 4: Frequency distribution of FA average discharge burnup

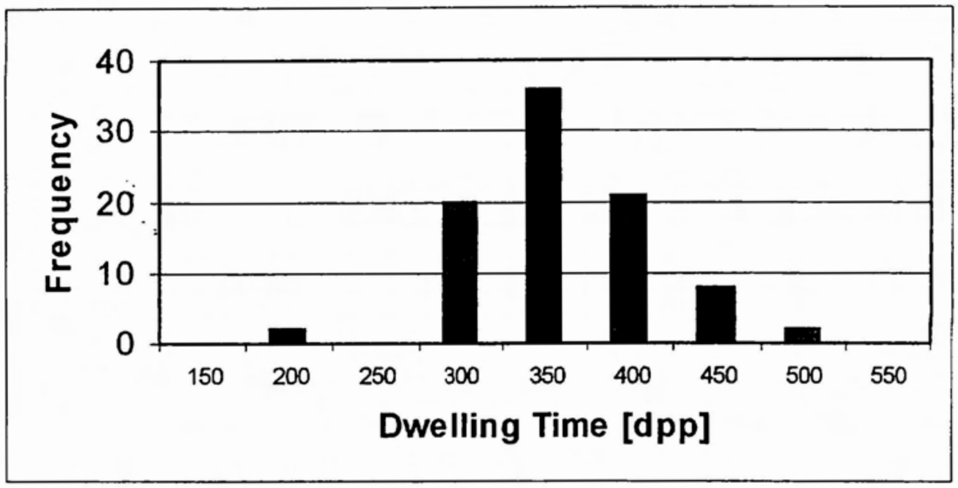


Figure 5: Frequency distribution of dwelling times

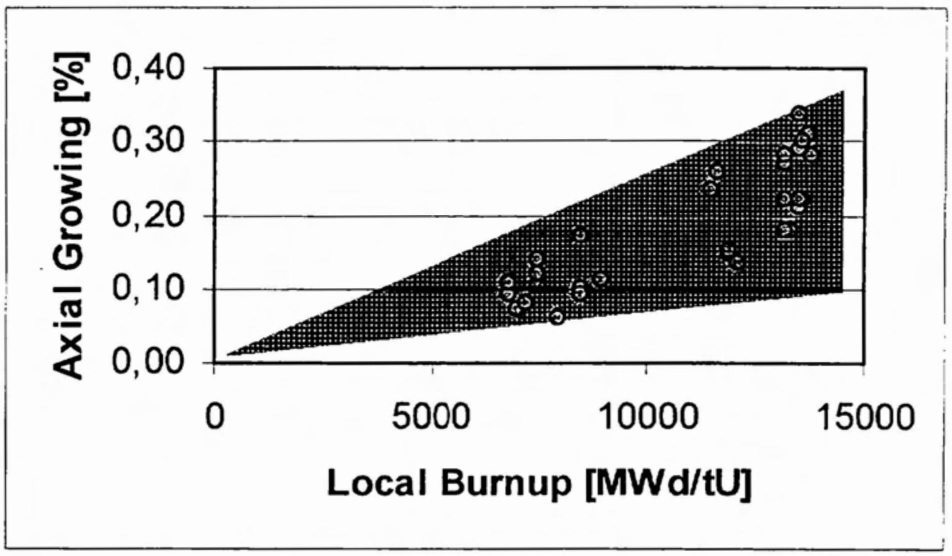


Figure 6: Axial growing measurements as function of burnup