CARA Development: An Argentinean Fuel Cycle Challenge

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ABSTRACT

The CARA is an advanced fuel element for pressurized heavy water reactors (PHWR). The present degree of its development is presented. The design allows extended burnup with good thermal hydraulic margins using a single fuel rod diameter. An additional assembly system enables the use into PHWR vertical channel reactors. The mechanical feasibility for Atucha I and Embalse, and the hydraulic compatibility were checked, verifying that the CARA can fit the Argentinean challenge: a single fuel element for two different PHWR. CARA prototypes are under fabrication with new spacer grid designs and enhanced welding between end plates and fuel rods.

1. INTRODUCTION

Argentina has two Pressurized Heavy Water Reactor (PHWR) Nuclear Power Plants (NPP) in operation (Atucha I and Embalse) since 1974 and 1984 respectively, and one more under construction (Atucha II). Although both of them are cooled by pressurized heavy water and fuelled with natural uranium, they have very different design. Embalse is a standard CANDU-6 [(1)], typical horizontal pressure tubes type reactor. On the other hand, Atucha I has a unique Siemens' design: vertical fuel channels inside a pressure vessel reactor.

In the Embalse NPP (CNE), the fuel element (FE) has a length of approximately 0.5 meter, and the horizontal 6-meter-long channel is filled with twelve fuel elements. On the other hand, the vertical channel of Atucha I (CNA I), has one single fuel element of about 5 meters-long for its active portion, hanged by its upper part [(2)]. These fuels, originally designed for natural uranium, had a discharge burn-up less than 8000

MW·d/ton·UO_2, and after an enhanced program, the Atucha I fuel was increased to 11000 MW·d/ton·UO_2 since 1998 using an enrichment of 0.85 % U-235. Both of them have 37 fuel rods in a cluster array fuel element although very different cladding design, Atucha having self-supporting rods and Embalse having collapsible ones.

The Argentina Atomic Energy Commission (CNEA) is developing the CARA advanced FE for Argentinean PHWR [(3),(4),(5)], specially designed to fit the Argentinean fuel-cycle requirement for Atucha and Embalse NPP´s. The CARA FE can be used in both reactor types, and substantially improves the competitiveness of the nuclear option.

2. CARA DESIGN CRITERIA

The CARA fuel design must keep the same operational conditions for both NPPs. They are the coolant flow and hydraulic channel pressure drop, and the mechanical compatibility of the refuelling machine of the vertical and horizontal channel reactors. The design improves the fuel performance with higher thermal-hydraulic safety margins using a single fuel rod diameter.

The key for the CARA design is a fuel element length (1 meter) twice the present CANDU one, substituting a couple of elements by a single one. This solution is compatible with the CANDU refuelling machine and allows:

- To eliminate the intermediate end-plates and hence its local pressure drop.
- To use this handicap to balance the whole hydraulic restriction at the same time increasing the heated perimeter.
- To use spacer grids instead of classical CANDU spacer pads welded on the cladding to minimize the welding and simplifying the manufacturing process.
- To lower fuel rod diameters, decreasing the fuel centre temperature.
- The lowering of thermomechanic requirement higher burnup can be reached.
- The creation of a new fuel element with many thin rods of a single diameter.
- Eliminating one pair of contiguous plates for each FE, it is possible to increases the uranium mass per unit length, decreases the Zircaloy/Uranium mass ratio, and decreases the number of manufacture operations (welding, end plates, plugs, etc.).
- The mechanical compatibility is reached by using the slighter greater channel diameter of Atucha I (5 mm greater than Embalse, that is 103 mm), in order to assemble five fuel elements within a basket assembly system, compatible with the refuelling machine.
- The hydraulic compatibility with Atucha is reached by tuning the assembly pressure drop with the basket geometry and the angular misalignment of the fuel elements.

3. MAIN CARA FEATURES

The CARA FE has 52 single diameter fuel rods (collapsible under the operational reactor pressure) of about 1 meter length (see Fig 1) in a cluster array, fastened by three self supported spacer grids (see Figs 2 and 3) and welded at both ends to low hydraulic impedance of end-plates (see Fig 4).

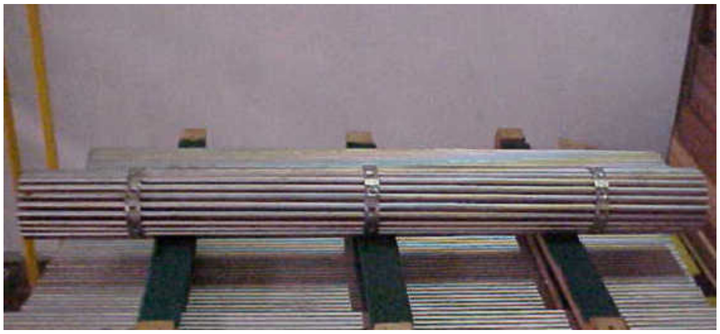

FIGURE 1: CARA FUEL ELEMENT.

FIGURE 2: 1st CARA SPACER GRID SET.

FIGURE 3: 3rd CARA SPACER GRID SET.

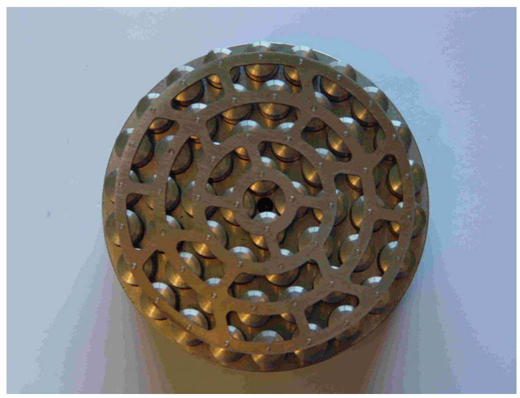

FIGURE 4: CARA END PLATE.

The self-supporting spacer grid has four concentric rounded strips with straight radial bridges connecting them, having dimples and springs to fix the rods, and fasten the cluster of fuel rods tightly. From the mechanical point of view this is very convenient because the self-supporting grids keep the fuel rods in their correct position thus reducing the bending of the fuel rods, since it can be included in the vertical channels. In the pressurized heavy water reactors with horizontal fuel channels, the CARA fuel is simply supported on the pressure tube by several bearing pads on the outer surface of the spacer grids, instead of CANDU bearing pads welded on the fuel rods. In Fig 5 it is shown the geometric comparison of the CARA fuel element with two Embalse designs.

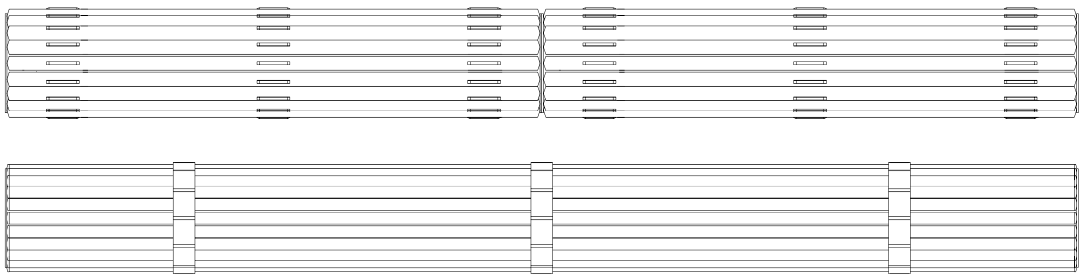

FIGURE 5: CANDU – CARA FUEL ELEMENT COMPARISON.

The geometry and fuel dimensions of the CARA FE are the following:

Number of fuel rods per FE	:	52
Number of spacer grids per FE	:	3
Total length	:	990.6 mm
Fuel element diameter	:	102.5 mm
Clad external diameter	:	10.86 mm
Clad thickness	:	0.35 mm
Pellet radii	:	5.05 mm
Pellet length	:	12.1 mm

The fuel channels in Atucha I are vertical and the fuel elements are suspended from the upper lid of the pressure reactor vessel. To use the CARA FE in Atucha, it is necessary to join five CARA fuel elements using an additional external assembly system, enabling the reuse and improving the fuel burnup by the axial FE relocation.

There are two different designs of the assembly system to be hydraulically tested. In one design the fuel element can be fastened with an assembly system with outer straps as shown in Fig 6. To attach the fuel elements together, a low-pressure drop stopper (Fig 7) is placed at its lower end. In the other end there is an intermediate coupling system containing a spring, which joins the fuel elements together. There is also a coupling body which copy the Atucha fuel upper end, to ensure its adaptability with the Atucha I design, which is also incorporated in the upper part of the channel (see Fig 8).

The other design of the assembly system is an outer supporting tube with windows or openings. It has been designed to support all the fuel elements together and it enables the coolant to circulate lightly through the fuel elements and the channel.

The use of spacer grids, which fix the fuel rods transversally, provides a greater mechanical strength, suitable to withstand the mechanical requirements due to the vertical position. The fuel element is radial supported by the spacer grid bearing pads, which lean at a ring of the assembly systems, and the fuel element is fixed with flexible pads. The assembly system is fixed to the channel by 16 axial supporting planes along its length, each plane having 2 fixed pads and 1 flexible sliding shoe.

FIGURE 6: ASSEMBLY SYSTEM BODY.

FIGURE 7: ASSEMBLY SYSTEM BOTTOM.

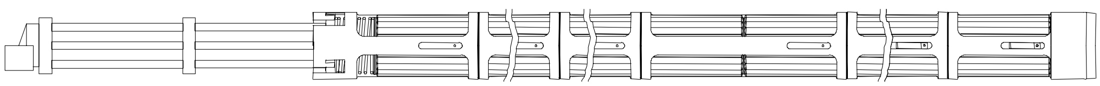

FIGURE 8: COMPLETE CARA ASSEMBLY SYSTEM FOR ATUCHA I.

4. MECHANICAL DESIGN

Based on the current experience of the fuel rod for Embalse and in order to reduce the Zircaloy quantity and to increase the burnup, the CARA fuel rod was designed considering a collapsible mechanical behaviour response under the operational reactor pressure. This thickness is compatible with the mechanical stress and integrity under normal operation conditions and spent fuel management.

Due to the lower inner diameter of the Embalse fuel channel, the external diameter of the CARA fuel element was fixed by this constrain, and the maximum length was fixed taking into account the refuelling machine compatibility.

The higher axial loading of the fuel rods is developed during the refuelling operation in the Embalse reactor. The side stops of the refuelling machine hold the fuel string and 10 external pins are in contact. The design condition for this operation is a maximum compressive load of 7300 N hold by one side stops. A maximum spacer grid distance of 410 mm is obtained as a limit for mechanical buckling stability. This requirement could be solved by means of three spacer grid layers in the maximum deflected points for the first and second transversal modes, considering the mechanical compatibility of the fuel element bending during refuelling operation. One spacer grid is placed in the central position and the others two in 1/6th from each end.

For the CARA FE an enhanced welding has been designed with the purpose to have a simple and complete visual inspection of the fuel rods welding, low end plate pressure drop design, and easy fuel rod placing and accommodation of axial tolerances during assembling [6]. A new design with dimples in the fuel rod end plug for different welding process (GTAW - LAW) is under development [7]. In Figs 9 and 10 are shown prototypes for the CARA end-plate welding.

FIGURE 9: CARA END PLATE

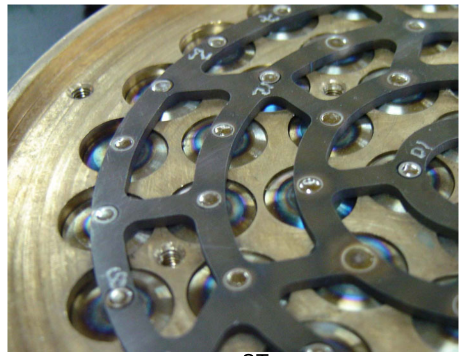

FIGURE 10: 1ST CARA END PLATE WELDING PROTOTYPE.

The assembly system was designed to be loaded by the upper part, and must keep the diameter gap to avoid any interference enabling the reuse. Zircaloy is used to assure low neutron capture. The assembly systems have lateral flexible sliding shoes to fix the relative position with the channel, and inner elastic support to fix the fuel element inside the assembly system.

In the Atucha I reactor channel, the assembly system has different mechanical strains due to axial loading (weight and hydraulic drag forces) and lateral forces due to the elastic interaction with the channel. The 5 CARA string weight is approximately 235 Kg and at the reactor operational condition in the central channel the drag force is 221 Kg. The maximum extraction force was limited according to the present operational limit for the reloading machine.

Vibration induced mechanisms, such as mechanical wear, fretting and fatigue cracking, could produce the fuel rods or assembly failures. The most important vibration mechanism in Embalse and Atucha is the flow-induced vibrations, mainly turbulence. The fluid-elastic instability limit is no reached due to low fluid velocity and stiffness of the fuel rods.

For the CARA fuel in Atucha I and Embalse operating flow conditions, the dimensionless velocities of the fluid-elastic instability analysis [8], considering a conservative case of non collapsible effects on Young module, are 0.46 for Atucha and 0.42 for Embalse. This has shown that this phenomenon will not be present.

The turbulence-induced vibration was estimated with the Paidoussis formula [9] having a zero-peak vibration amplitude of 0.155 mm for Atucha and 0.118 mm for Embalse. The maximum acceptance criterion is 2% in diameter (0.22 mm), and of course this was not exceeded.

The CARA fuel rod was designed to collapse at the reactor operational pressure. The fuel rod natural frequencies change due to the shear stress (friction) between the cladding and the fuel pellet.

Experimental studies were done in order to analyze this phenomenon, using zircaloy cladding and different metallic pellets in order to simulate the collapsible condition (10). Experimental tests have shown that the natural frequency of collapsible fuel rods can be described by the Euler-Bernoulli model (11) with an effective greater Young module, approximately 50% higher, depending on the pellet cladding interaction due to burnup and pellet geometry.

The wearing caused in the space grid and cladding interaction can be wherever neglected by means of setting the appropriate residual forces in the springs. The design of this issue can be reserved for the final design stage, i.e. to the detail engineering of the CARA space grid.

5. HYDRAULIC BEHAVIOUR

Considering that an important pressure drop of the present 37-rods CANDU fuel element is concentrated on the end plates (≈ 30%) (12); and having a CARA fuel element with twice of length of CANDU fuel withdrawing the end-plate junction so reducing the pressure loss, this handicap could be used in order to increase the number of fuel rods, and in this way, to increase the friction loss. Besides, the reduction in the number of end plates (and plugs) gives an uranium credit that could be used to increase the uranium mass in the fuel element.

Due to their concepts, the CARA and present CANDU fuels have different balances of concentrated and distributed hydraulic losses. Since only distributed losses are strongly dependent of the flow regime (that is, Reynolds number), they have different hydraulic performance in reactor conditions (at very high Reynolds numbers) than in low-pressure test facilities (at moderately high Reynolds numbers). Hence, for hydraulic similarity objectives, it is important to model the Reynolds dependence of the fuel hydraulic loss, in order to extrapolate the experimental data obtained at low-pressure facilities.

In the CANDU reactor the fuel string can be loaded with random different azimuthal angle. The end plates junction hydraulic loss depends on the misalignment angle (13). To evaluate the channel average hydraulic pressure drop it is necessary to measure this dependence. This behaviour can be used to tune the channel pressure drop in the Atucha I by fixing their relative angular position with the assembly system.

A rational model of pressure drop for the misalignment angle of junction between neighbours fuels has been developed (14) and tested using published (13) and CNEA experimental data. The excellent agreement between the model and published experimental data for CANDU is shown in Figs 11 and 12.

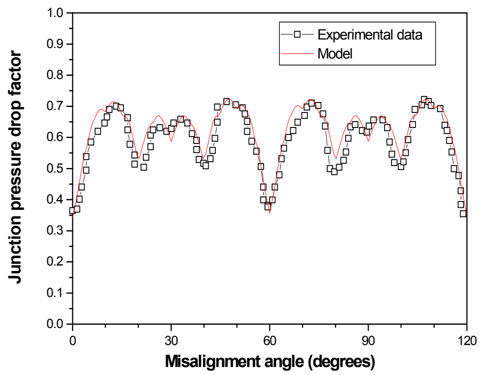

FIGURE 11: CANDU JUNCTION PRESSURE DROP COEFFICIENT.

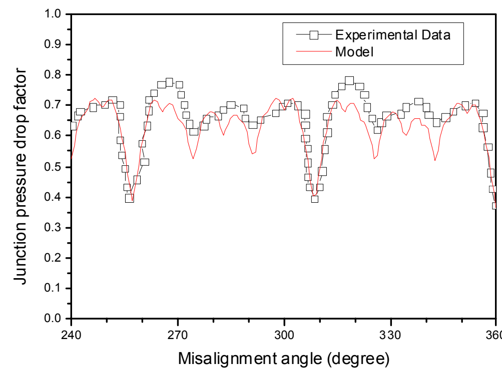

FIGURE 12: CANFLEX JUNCTION PRESSURE DROP COEFFICIENT.

The particular cluster geometry of the CARA fuel element was evaluated by experimental tests. Experiments were carried out with two prototypes in a low-pressure loop. For the hydraulic characterization the CANDU fuel channel was used. The spacer grid hydraulic performance was studied using two CARA prototypes with detachable end plates. In these ones, the fuel rods can be easily dismounted from the end plate using specially designed screw. Several models of spacer grids were tested finding that the design corresponding to a height of 20 mm and a thickness of 0.4 mm is hydraulically compatible for both reactors.

The hydraulic tests were done between 70 % and 130% of nominal CANDU coolant flow. The distributed friction loss along the fuel rods was extracted from experimental data of the channel pressure profile. Thus it can be used for extracting different concentrated friction losses (spacer grids and end-plates junction).

In Fig 14 the distributed friction factor from experimental data is compared with the classical well-known Moody correlation (15) for pipes, and the specific developed correlation for fuel rod PWR arrays (16), showing good agreement within 10% deviation. A new specific cluster correlation using the experimental data was done with less square fitting. In figure 15 the total spacer grid loss coefficient was adjusted from the experimental data showing good agreement (17).

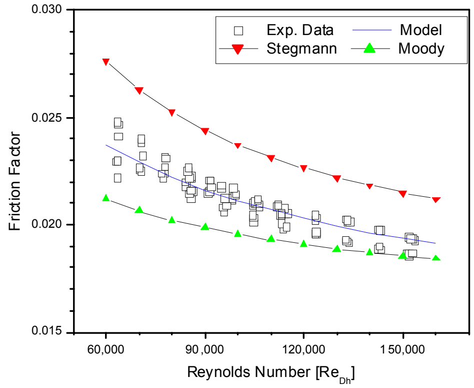

FIGURE 14: DISTRIBUTED FICTION LOSS COEFFICIENT.

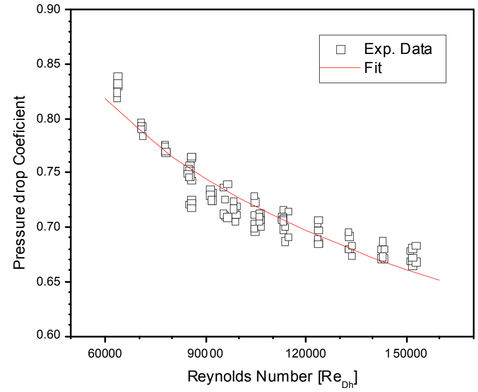

FIGURE 15: SPACER GRID LOSS COEFFICIENT.

The developed misalignment model was used to define the CARA azimuthal junction loss coefficient, and they were selected three relevance angles (minimum, maximum, average estimated). In Fig 17 it is shown the good agreement between the model prediction dependence and the three relevance angle measurements.

Using the previous friction loss models, it can be predicted the CANDU fuel channel pressure drop under nominal operation conditions, by extrapolating to the reactor Reynolds number. Using published acceptance criterion for mono-thermal channels (18) the CARA pressure drop was estimated, finding good results.

The hydraulic characterization and compatibility of the assembly system for the Atucha I reactor are in progress. Preliminary calculations using the developed models show that the compatibility can be reached by means of an assembly system good design. At present two different assemblies were constructed and are going to be tested, both of them being external baskets. The external basket design reduces the effect of the peripheral water bypass due to the radial gap caused by the slightly greater Atucha channel diameter than Embalse one. The assembly system could be designed to be tuned with the Atucha hydraulic loss by setting the properly azimuthal misalignment between CARA neighbours, providing up to 10% margin.

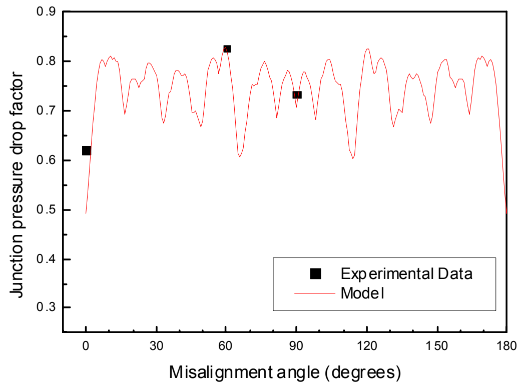

FIGURE 17: CARA JUNCTION PRESSURE DROP.

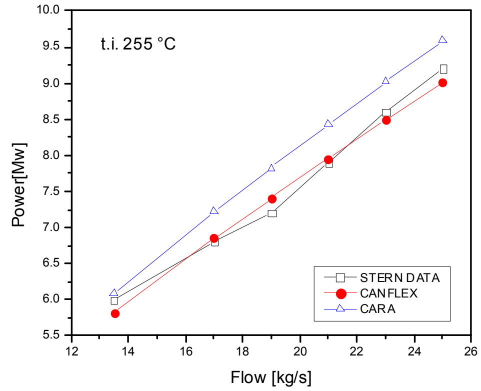

FIGURE 18: DRY-OUT POWERS CALCULATED FOR TI = 255 ºC.

6. CRITICAL HEAT FLUX BEHAVIOUR

One of the main design factors in nuclear fuel elements is the thermal hydraulic aspect. On these, the heating surface is composed of parallel fuel rods cooled by interconnected fluid sub-channels. A way to predict the thermal hydraulic behaviour is to solve the conservation equations of heat, mass and moment on each sub-channel. Examples of this approach can be found in the numerical codes (COBRA, VIPRE, ASSERT, etc.) [19] used at the present.

For PWR and BWR´s fuels, there is a large amount of critical heat flux (CHF) tests compiled in a useful data base [20]. From that report, the accurate test data have allowed to study extensively the sub-channel mixing parameters and so, was constructed a very useful correlation for this phenomenon for COBRA Code calculations, valid from negative qualities (sub-cooled flows, such as in PWRs ones) to high qualities (such as in BWRs ones). Therefore, this correlation could work too for simulating CANDU operating local conditions (qualities up to 2%), when other phenomena do not have major effects.

Despite the fact that the CANDU concept is strongly different from the PWR and BWR ones, it is possible that CANDU cases could be managed by COBRA capabilities in order to calculate dry-out power conditions, since CANDU nominal conditions could be considered intermediate between the PWR and BWR ones.

Critical heat flux margins were calculated using COBRA-IV code [21] and validated [22] with experimental data of dry-out powers for CANFLEX fuel element checked against full-scale experiments. Checking the experimental tests carried out at Stern Lab [13], the dry-out power was predicted by COBRA within a 10% band error for a wide range of conditions. Moreover, for inlet flow parameters close to operational values, a very good accuracy, within a 3% error band, was obtained

In Fig 18 it is shown for a channel inlet temperature nearly the operating reactor conditions, the power dry-out predicted by COBRA (CANFLEX and CARA) and the experimental data for CANFLEX. Using this numerical tool, the CARA fuel design was studied for the same previous conditions, showing a comparable performance respect to CANFLEX. The critical heat flux assessment of the CARA fuel is a qualify test, rather than a developing test, due to improved heated surface (18% greater than CANDU one) with a single rod diameter homogeneous fuel element.

7. FUEL ROD DESIGN

The basis of the fuel rod design was previously presented [5], where hypothetical but realistic power histories were defined for simulation of the BACO code [23], considering the demand conditions of irradiation for a real fuel element. Starting with those power histories it was extrapolated the respective history for the equivalent CARA fuel conditions in a CANDU and Atucha I reactors, corrected by the neutronic cell calculation model. The extrapolation was based on the burnup extension and the adaptation of linear power levels of the CARA fuel. The extension in burnup is 15000 MWd/tonUO2 and the linear power is reduced up to a 72 % of the original value due to the new geometry of the CARA fuel (from 600 W/cm to 450 W/cm for Embalse and for Atucha I, 550 W/cm to 400 W/cm).

The BACO code calculations show: temperature decrease, smallest fission gas release, no restructuring, no central hole and lowest thermal expansion. In particular, BACO calculations for the centre temperature of the UO2 pellet, for a CANDU fuel rod and for the equivalent CARA fuel using its associated power history, allows a decrement of temperature of 500°C at the maximum power level (less than 1300°C). And, for the equivalent CARA fuel element in Atucha I, similar value respect the normal fuel is found. The linear expansion of a CARA fuel at Embalse NPP results in a 25 % of the normal fuel at the same conditions.

The CARA fuel rod design was analysed using BACO[24] parametric and statistical analysis and extreme cases calculations, to know the correct incidence on the manufacturing QA procedure and defining the fabrication uncertainties tolerance limit. It was found the best tolerances of the CARA's dimensional parameters which allow to best and realistic manufacturing tolerances with an improvement in the dishing and shoulder of the pellet, and small plenum, among other parameters [25].

8. CARA FUEL PROJECT

The strong economics advantages of the new fuel, together with the excellent experience of the SEU Atucha program, put incentives for the fuel development up to the commercial level. The project has been divided in phases, each one involving growing complexity and cost with decreasing technology risk.

The following project milestones have been achieved:

- Conceptual and basic design of fuel element.
- First demonstration element.
- First CARA element prototype.
- Low-pressure loop fuel element tests with two detachable end plates.
- Three spacer grids prototypes.
- Design verification (BACO code for thermo mechanic behaviour, COBRA for CHF, Pressure drop models verified with experimental data).
- Detailed design of fuel element.
- Design of fuel rod irradiation test experiments to simulate extreme irradiation conditions (different pellets geometry and filling gases for simulating extreme behaviour conditions).
- Two prototypes of the assembly system for Atucha I

Nowadays the second phase is being carried out with the feedback from the first phase results. Seven CARA fuel prototypes are under fabrication with new spacer grid designs and enhanced welding between end plates and fuel rods. The Atucha I CARA assembly system will be hydraulically characterized and its vibration modes will be tested. The future steps in the project consider fuel element vibrations and endurance test, critical heat flux test and finalization of the irradiation test.

9. CONCLUSIONS

The present development of the CARA advanced fuel element for PHWR was presented, showing the design criteria and the way to reach them. The mechanical solution proposed by the CARA is very innovative (doubling length, few welding on sheaths, spacer grids) in respect to the CANDU fuel element, allowing extended burnup by the use of SEU, with good thermal hydraulic margins using a single fuel rod diameter.

Different CARA fuel element prototypes were hydraulic tested in a low-pressure loop. The experimental validated models shows the CARA hydraulic similarity respecting CANDU in the Embalse NPP. Additional assembly systems enable the use into PHWR vertical channel reactors. The mechanical feasibility for Atucha I and Embalse, and hydraulic compatibility were checked, verifying that the CARA fuel can fit the unique Argentinean challenge: a single fuel element for two different Heavy Water Reactors.

Besides, the mechanical, vibration, neutronic, thermal hydraulic margins and fuel rod performance of the CARA fuel were verified by models and codes, showing a good behaviour. The CARA fuel rod design was analysed using BACO parametric, statistical analysis and extreme cases calculations, to know the correct incidence on the manufacturing QA procedure and defining the fabrication uncertainties tolerance limit. All CARA structural components had been built, and proximately they will be fully tested.

The current results allow us to assure that the CARA fuel can acomplish all the design requirements, and with its implementation, SEU fuel element can be used in the Argentinean NPP´s at competitive values, an essential task for economic production in Argentina.

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