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# EXPERIENCE IN THE USE OF LOW CONCENTRATION GADOLINIA AS A PWR FUEL BURNABLE ABSORBER

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**SUMMARY**

A description is provided of the low concentration gad design being used in the Spanish 3-loop 17x17 fueled PWR's. This design uses a relatively small number of high concentration gadolinia fuel rods (6 and 8 w/o $Gd_2O_3$) with a large number of low concentration gad rods (2 w/o $Gd_2O_3$). The 2 w/o gad rods substitute, in part, the high concentration gad rods, thereby helping reduce the end of cycle reactivity penalty from the residual absorption in the gadolinium. The low concentration gad design is advantageous for long cycles (18+ months) and plant uprating scenarios in that the soluble boron concentration increases that would otherwise result for these situations are avoided. These boron concentration increases could have potentially adverse effects on the plant, since the moderator temperature coefficient (MTC) is made less negative, the effectiveness of the boron shutdown safety systems is reduced, and the safety margins are eroded for some accidents, such as for boron dilution events.

These increases in the boron concentration would also require the plant to operate at higher lithium (Li) concentrations in the coolant in order to maintain the pH level at the desired value. Operation at the higher Li concentrations is undesirable because of the concerns over the potential impact on the fuel assembly material performance (e.g., crud and corrosion).

This paper also reviews the APA nuclear design code system performance for the low concentration gad design. The design system performance for the reload cores that have or are employing this design has been completely satisfactory. The performance and accuracy of the nuclear design methodology is found to be as good for this design as for the reload cores that use exclusively high gad concentrations, or those that use WABA's – the discrete burnable absorber (BA) used prior to its substitution for gadolinium.

The core parameters and core control characteristics of reload cores that employ the low concentration gad design are found to be comparable to those of cores that employ either high gad concentrations exclusively, or that use discrete BA's. The differences that are observed in the core parameters between these alternative BA designs are no greater than the typical variations observed in these parameters cycle to cycle. The low concentration gad design does not adversely affect the core operation and core neutronic characteristics, and does not adversely impact the plant's safety analysis.

Additional on-going effort is aimed at further optimizing the low concentration gad design. One area has, as its objective, to license the use of 2 w/o gad fuel without the need to reduce the $U^{235}$ enrichment in the fuel. The normal design practice is to reduce the $U^{235}$ enrichment to provide a sufficient power margin to compensate for the degraded thermal conductivity of the gad fuel. Elimination of the need to reduce the $U^{235}$ enrichment for the 2 w/o gad fuel can provide a small increase in cycle length and simplify the fabrication of this fuel.

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Another area is looking at optimizing the use of part-length gadolinium with either natural or enriched axial blankets to both provide additional fuel cycle cost benefits and to avoid the core axial power distribution and peaking factor penalties that result from the use of axial blankets. The part-length gad design eliminates the burnable absorber (BA) from each end of the non-blanket fuel column, in the zone immediately adjacent to the blanket. The blanket thickness, height of the non-BA zone next to the blanket, gad fuel column height, and the centering of that column relative to the active fuel length are parameters that are selected to optimize the fuel cycle cost benefits and to minimize the peaking factor impact of the blankets.

**INTRODUCTION**

The need to maximize the utilization of the nuclear fuel, reduce the fuel cycle and plant operating costs, and to extend the pressure vessel lifetime has led the nuclear industry to adopt a number of fuel management improvements, including the move to longer reload cycles (18-24 months), plant upratings, smaller reload batch sizes, increased fuel discharge burnups, and the use of more neutron-efficient low and ultra-low leakage core loading patterns. These changes in fuel utilization/core management have increased the need to use burnable absorbers (BA's). They have also meant higher core peaking factors and the need to use higher fuel enrichments, with a resultant increase in the core excess reactivity, and consequently, in the soluble boron concentration in the early part of the cycle. Other undesirable effects have included a decrease in the criticality margins of the fuel shipping containers and fuel storage racks, and a reduction in the effectiveness of the boron shutdown safety systems of the plant.

The use of gadolinia as an integral BA in the PWR fuel permits the utilization of that fuel to be optimized and to best respond to the current fuel management trends. ENUSA's standard design approach for its PWR fuel is to use a moderate loading of relatively high concentrations of gadolinia fuel in the core. The core initial excess reactivity is controlled by the number of gad fuel rods loaded in the core. The core-wide power distribution and peaking factors are controlled by the judicious placement of the gad assemblies in the core and by means of the gad rod configurations employed. The $Gd_2O_3$ concentration is axially uniform up each gad fuel rod. The $U^{235}$ enrichment of the gad fuel is reduced approx. in the proportion of a 5% relative reduction per w/o $Gd_2O_3$ added to the fuel. This is done to provide a sufficient power margin to adequately offset the thermal conductivity degradation that results from the addition of the gadolinia to the fuel.

The ends of the fuel assemblies may be free of gadolinia to assure a more thorough burnout of the gadolinia in the assembly, since the gad burns out poorly near the ends of the active fuel column. In addition, the gad fuel column may be axially-offset slightly to better shape the core axial power distribution. For axially-blanketed fuel assemblies part-length gadolinia fuel is used. The part-length gad design permits the gadolinia residual absorption penalty to be minimized at the end of cycle (EOC), and the core axial power profile and margins to the core peaking factors to be optimized when axial blankets are present.

ENUSA's standard design approach for its PWR fuel in past reloads has been to use a moderate loading of relatively high concentrations of gadolinia fuel in the core. A typical fresh gad loading for a three-loop 17x17 fueled reload core would consist of 350-400 rods at 6 and 8 w/o $Gd_2O_3$. While reload core designs that employ uniquely 6 and 8 w/o $Gd_2O_3$ are able to control effectively the core power distribution and associated peaking factors, the use of low concentration gadolinia fuel (2 w/o $Gd_2O_3$) to complement and partially replace the higher gadolinium concentrations provides a number of advantages for long cycles (18+ months) and plant uprating scenarios.

In this alternative design, referred to as the low concentration gad design, substantially less use is made of the high concentration gad rods, replacing the majority of these with a large number of low concentration gad rods. For example, 500 or more gad rods of 2.0 w/o $Gd_2O_3$ may be combined with a small number (< 200) of high concentration gad rods (6 and 8 w/o) for a three-loop 17x17 fueled reload core. Multiple gad concentrations are necessarily present in the majority of the feed assemblies, combining either the 2 and 6 w/o, or the 2 and 8 w/o concentrations. Note that the gad concentration is axially-uniform along any given gad fuel rod - that is, multiple gad concentrations are not used within the individual gad fuel rods.

The low concentration gad design offers a number of advantages. The combined use of low concentration gadolinia fuel with high gad concentrations provides an effective way to lower the soluble boron concentration in the coolant in the first part of the cycle (e.g., first 4 GWd/tU of cycle burnup), by up to 300 ppm, without adversely affecting the energy capability of the core and without impacting the power distribution-related peaking factors. The low concentration gadolinia rods are, therefore, very useful for long cycles and for plant uprating scenarios since they effectively offset the boron concentration increases that would otherwise result, and the associated adverse effects that these would have on the moderator temperature coefficient (MTC), shutdown effectiveness of the boron safety systems, and potential negative impact on some accidents, such as boron dilution events.

By offsetting the boron concentration increases, the low concentration gad design also minimizes the adjustments that would otherwise need to be made to the lithium concentration and pH level in the coolant, and avoids concerns as to how these changes might affect the fuel assembly material performance (e.g., crud buildup and corrosion). and the radioactivity dose rate received by the site personnel during the refueling operations.

The use of low gadolinia fuel in the core also permits the number of high concentration gad rods employed to be reduced to the minimum needed to control primarily the power peaking in the core. This helps to further reduce the EOC residual absorption penalty of the gadolinia on the cycle length.

The core parameters and core control characteristics of reload cores that employ the low concentration gad design are found to be comparable to those of cores that employ either exclusively high concentration gad fuel or that use discrete BA's. The differences that are observed in the core parameters between these alternative BA designs are no greater than the typical variations observed in these parameters cycle to cycle. The low concentration gad design does not adversely affect either the core operation or core neutronic characteristics and does not adversely impact the plant's safety analysis.

Figures 1 and 2 depict the typical behavior of the core maximum relative rod power, $\underline{F}_{\Delta H}$, and peak relative local power, $\underline{F}_Q$, as well as that of the core axial peaking factor, Fz, and the core average axial offset for the low concentration gad design. These parameters are useful to help characterize how well the core power distribution is controlled during the depletion of the cycle. These parameters are found to be fully acceptable for the low concentration gad design and are comparable to those of reload cores that use either high gad concentrations exclusively, or that use the WABA discrete burnable absorber. Figure 7, discussed later on, illustrates the soluble boron concentration behavior during the depletion of the cycle for the low concentration gad design. Again, that behavior is completely acceptable.

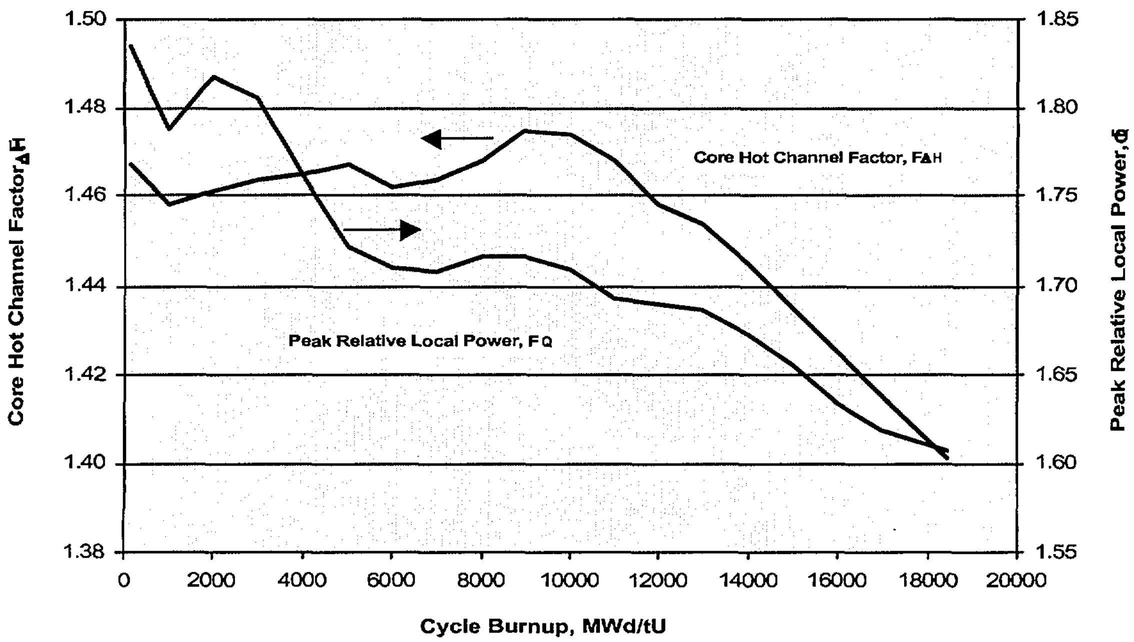

Figure 1. Typical behavior of the core maximum relative rod power, $\underline{F}_{\Delta H}$, and peak relative local power, $\underline{F}_{Q}$, for the low concentration gad design

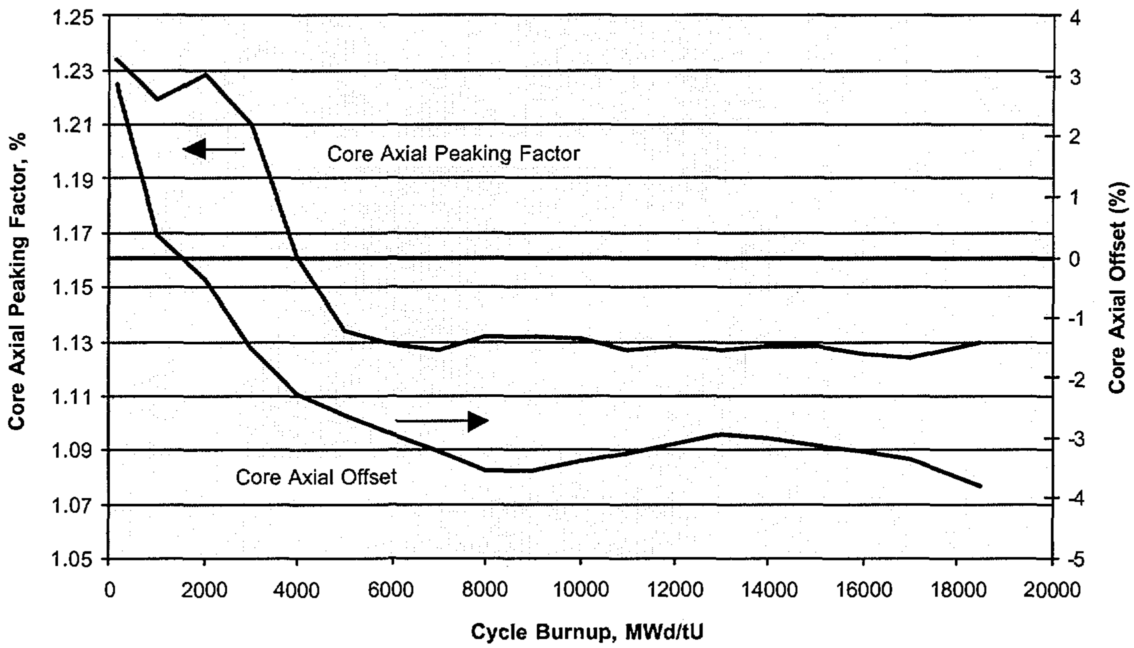


Figure 2. Typical behavior of the core axial peaking factor and axial offset for the low concentration gad design

**EXPERIENCE IN THE USE OF THE LOW CONCENTRATION GAD DESIGN**

In 1998 ENUSA introduced the first reload region of the low concentration gad design in the Spanish 3-loop 17x17 fueled PWR's. As of the end of last year four reloads have used the low concentration gad design, with over 250 fuel assemblies of that design loaded in the 3-loop cores. More than 6,000 gad fuel rods have been loaded, of which more than 2,000 have been of the 2 w/o design.

Westinghouse's licensed APA (ALPHA/ PHOENIX-P/ANC) nuclear design code system is used to model the PWR reload cores. The nuclear design experience accumulated to date for the low concentration gad design confirms that the APA code system is accurate and reliable for this design, and confirms the benefits of the low concentration gad design.

The results of both the startup physics tests and core follow operation (core peaking factors, core axial offset, etc.) at hot full power (HFP) are quite satisfactory and are comparable to the results obtained for core designs that employ exclusively high concentration gad fuel or that employ instead discrete burnable absorbers, such as the Wet Annular Burnable Absorber (WABA) design that was used previously in these cores. As examples of this agreement, Figures 3 to 6 provide comparisons of the prediction vs. measurement agreement from the beginning of cycle (BOC) hot zero power (HZP) startup physics tests. Comparisons are provided for the critical soluble boron concentration, isothermal temperature coefficient (ITC), individual control bank worths, and total all rods in (ARI) bank worth. Finally, in Figure 7, a comparison is provided of the hot full power (HFP) all rods out (ARO) critical soluble boron concentration during the depletion of the cycle. Two predicted boron letdown curves are given to bound the effect of the $B^{10}$ depletion – the first labelled "with $B^{10}$ depletion" corresponds to no recycling of the boron in the primary side during the cycle, and the second, "no $B^{10}$ depletion" assumes continuous recycling of the boron during the cycle. Figures 3 to 7 confirm that the APA design code system provides more than an acceptable level of accuracy for the low concentration gad design.

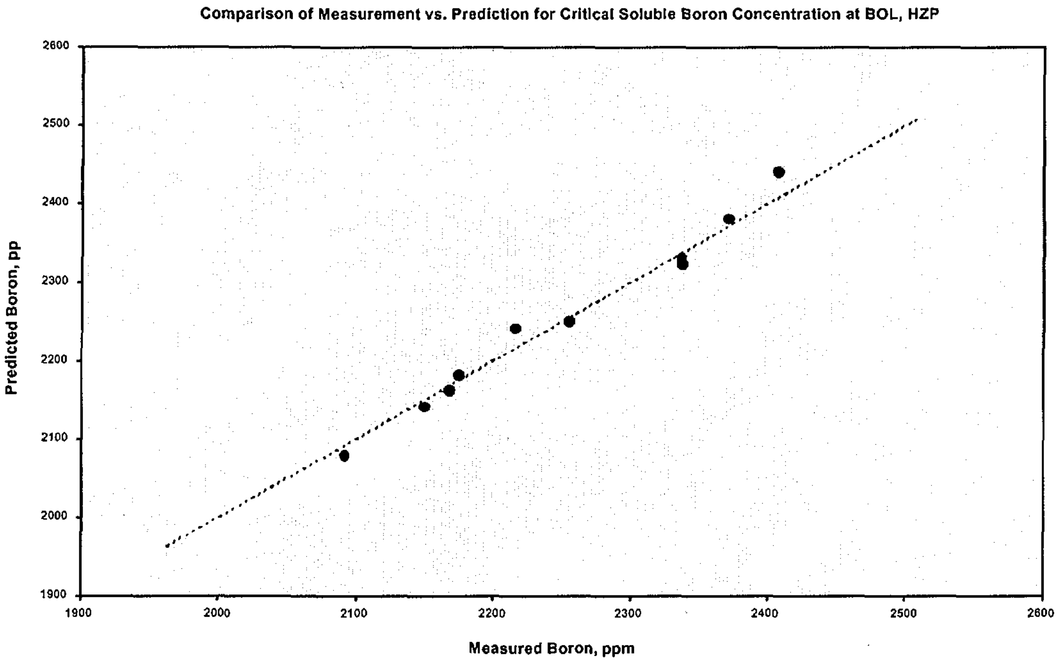


Figure 3. Comparison of the predicted and measured critical boron concentration at BOC, HZP for reload cores employing the low concentration gad design.

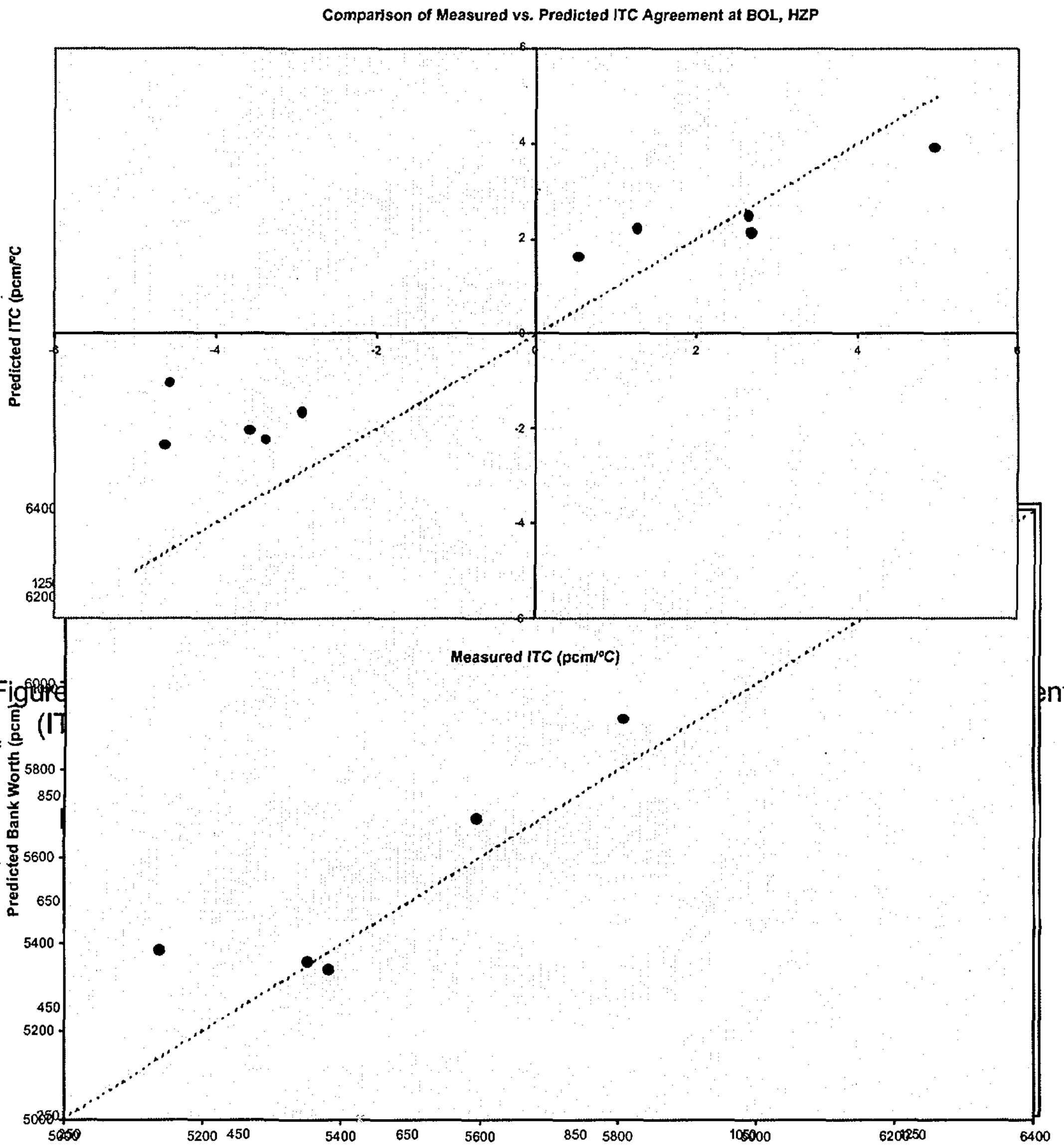

Figure 6. Comparison of the predicted vs. measured total all rods in (ARI) bank worth for reload cores employing the low concentration gad design

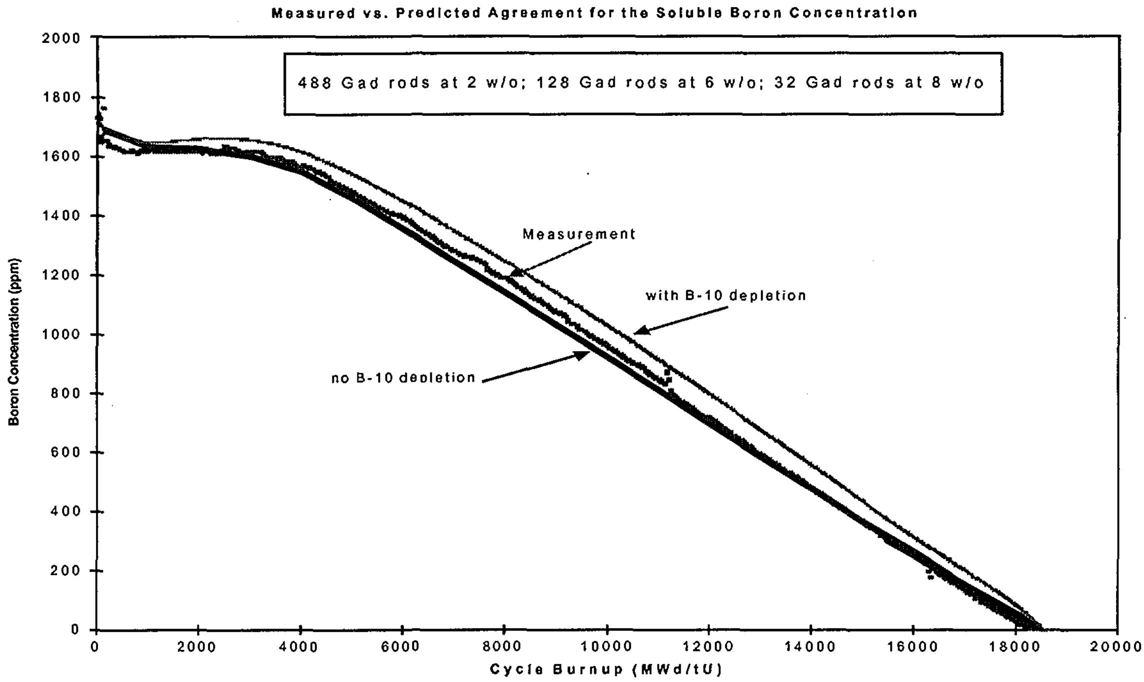


Figure 7. Typical (P-M) agreement for the critical boron concentration at HFP ARO during the depletion of the cycle for a reload core employing the low concentration gad design.

## FURTHER OPTIMIZATION OF THE LOW CONCENTRATION GAD DESIGN

Further improvements to the low concentration gad design are on-going. As commented earlier, for high gad concentrations, the $U^{235}$ enrichment must be reduced to assure a sufficient power margin to offset the degraded thermal conductivity of the fuel that results when the gadolinia is added. This enrichment reduction is small, however, for the 2 w/o gad fuel and a technical basis exists, which has been submitted for approval by the Spanish nuclear regulator, the Nuclear Security Council (CSN), which justifies that, based on the use of a more realistic gad fuel thermal conductivity model and existing design margins, it is unnecessary to reduce the $U^{235}$ enrichment in the 2 w/o gad rods in order to guarantee acceptable fuel and clad temperatures. The elimination of the $U^{235}$ reduction in the 2 w/o gad fuel will permit the core $U^{235}$ loading to increase slightly, yielding a small gain of 1-2 additional days of plant operation, and will simplify the fabrication of that fuel.

The benefits of the low concentration gad design are also being evaluated in combination with the use of axial blankets. With axial blankets, the ends of the active fuel column (typically 6 inch zones) are replaced with either solid or annular fuel pellets of natural or enriched uranium. To offset the increased axial peaking that results from the use of the axial blankets, part-length (P/L) gad is used with the BA column essentially centered along the length of the active fuel length. The adverse impact of the axial blankets on the core peaking factors, primarily on the core axial power peak, $F_Z$, and total core peaking factor, $F_Q$, is eliminated completely with the use of the P/L gad.

The blanket thickness, height of the non-BA zone next to the blanket, gad fuel column height, and the centering of that column relative to the active fuel length are parameters that are chosen to optimize the fuel cycle cost benefit of the axial blankets and to minimize their peaking factor impact.

The introduction of the axial blankets depresses the power near the ends of the core and pushes it towards the core mid-plane, the zone of higher neutron importance. This effect, more pronounced at the beginning of the cycle, increases the core reactivity and thus the critical boron concentration. Again, the low concentration gad design is effective in "absorbing" that boron concentration increase in this first part of the cycle.

The use of the axial-blanketed fuel with P/L gad does not lead to any loss in the nuclear design margins and does not adversely affect either the plant operation, the neutronic characteristics of the core, or the safety margins of the plant.