NEUTRONICS AND SAFETY CHARACTERISTICS OF A 100% MOX FUELED PWR USING WEAPONS GRADE PLUTONIUM (U)

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ABSTRACT

Preliminary neutronics and safety studies, pertaining to the feasibility of using 100% weapons grade mixed-oxide (MOX) fuel in an advanced PWR of Westinghouse design, are presented in this paper. The preliminary results include information on boron concentration, power distribution, reactivity coefficients and xenon and control rod worth for the initial and the equilibrium cycle. Important safety issues related to rod ejection and steam line break accidents and shutdown margin requirements are also discussed. No significant change from the commercial design is needed to denature weapons-grade plutonium under the current safety and licensing criteria.

INTRODUCTION

Westinghouse performed an extensive study where three plutonium disposal reactor (PDR) options were developed for the disposal of excess weapons grade plutonium from returned and dismantled nuclear weapons. This is a part of DOE's Plutonium Disposition Study\textsuperscript{1} launched at the behest of Congress, where denaturing the excess quantities of weapons grade plutonium to a form similar to commercial reactor spent fuel was investigated. The Westinghouse advanced passive PWR of 600 MWe capacity is the state-of-the-art reactor and its plant designs are selected as the basis for the PDR reactor concept, called the PDR600. The following sections describe the core design philosophy and core characteristics of the PDR600.
CORE DESIGN PHILOSOPHY

The basic design objective is to meet the program requirement of denaturing 100 MT of weapons grade plutonium in a reactor as economically as possible using conservative design and proven hardware and software. This objective is, therefore, quite different from a commercial reactor, where fuel cycle cost benefit is a main criterion. The PDR600 requirements necessitate as high a plutonium enrichment as feasible in the core, and consequently a heavy loading of burnable absorbers to hold down the excess reactivity. The end of cycle may contain a higher boron level than ~10 ppm, because the cycle length is limited by the discharge burnup consistent with the objective of denaturing and not limited by the maximum amount of energy that can be extracted from the fuel. In other words, due to higher enrichment, the cycle burnup goal may be reached before the end of reactive life. The discharge burnup is selected such that the Pu-240 content of the discharge fuel will be at least 20%, the denaturing goal.

The basic core characteristics of one-third core MOX fueled PWRs are well-studied and understood. Principally due to higher capture and fission cross sections of Pu-239, the thermal absorption in a MOX fueled reactor is nearly twice that of an equivalent, uranium fueled reactor. This phenomenon, coupled with considerable spectrum hardening, leads to a substantial diminution in boron, xenon, and control rod worth. These effects will accentuate with higher enrichment and full MOX core in PDR600. Therefore, the challenge is to design a core with negative moderator temperature coefficient at all operating conditions, and to increase the number of control rods to compensate for the loss of control rod worth. Efforts are also made to design the PDR600 core under the existing core design and safety envelope of the advanced Westinghouse PWRs so that the licensing effort can be minimized. In addition, the PDR600 has been designed using the standard and proven fuel rod, assembly, burnable absorbers, and control rod system, thereby minimizing testing and deployment time.

CORE DESIGN

The reactor core consists of 145 fuel assemblies arranged in a modified checker board pattern in cycle 1 and employs the out-in shuffling for subsequent cycles. The standard 17x17 Vantage 5-H fuel assembly design is chosen for PDR600. Zircaloy-4 cladding is replaced by 304 stainless steel to maximize plutonium enrichment. The first core loading uses enrichments of 4.5, 5.0, and 5.5 w/o in total plutonium content for regions 1, 2, and 3 respectively. Weapons grade plutonium with an isotopic composition of 93.6%, 5.9%, 0.4%, and 0.1% is used for Pu-239, Pu-240, Pu-241, and Pu-242, respectively. A heavy loading of pyrex burnable absorbers is used to reduce peaking and soluble boron in cycle 1. To further reduce the soluble boron concentration, zirconium diboride coating in the form of integral fuel burnable absorbers (IFBA) with a loading of 1.57 mg/inch is used in all fuel rods. The cycle burnup is kept at 13,300 MWD/MTU consistent with the discharge burnup being 40,000 MWD/MTM. One-third core is discharged every cycle. There are 69 rod control cluster assemblies (RCCA) made of Silver-Indium-Cadmium in PDR600 as shown in Figure 1.

The equilibrium cycle model is developed by using 5.5 w/o (total Pu) enriched once burnt, twice burnt and feed assemblies. Although the 1.57 mg/inch IFBA loading is retained, no discrete glass burnable absorbers are required in the equilibrium cycle for flux flattening or for reducing soluble boron level to provide negative moderator temperature coefficient (MTC).

The core design limits such as peaking factor, shutdown margin, etc., of the Westinghouse advanced PWR are chosen as the initial goal. The moderator temperature coefficient should be negative at all operative conditions. All calculations are performed with the standard Westinghouse design codes.
which were also validated against the operating PWR plant (Beznau Plant in Switzerland) using one-third core MOX fuel, providing additional confidence in critical core physics and safety parameters. All reactor calculations are done with three dimensional core models.

CORE CHARACTERISTICS.

The following sections describe important core characteristics of the initial and the equilibrium cycle of the PDR600. The core description and associated core design limits are given in Table 1. A summary of the core physics characteristics is given in Table 2.

A. CRITICAL BORON LEVEL

The boron level in cycle 1 is 2144 ppm at beginning of life (BOL), hot full power (HFP), no xenon condition. Equilibrium cycle and cycle 1 have almost identical boron levels at BOL, but the equilibrium cycle boron at end of life (EOL) is only 249 ppm as compared to 838 ppm for cycle 1 as shown in Figure 3. The boron letdown with depletion behaves similar to a typical uranium fueled core. The boron concentration reduction with fuel burnup is 108 ppm/GWD/MTM for the equilibrium cycle, which is similar to a uranium fueled core without any discrete burnable absorbers. During the first cycle, the glass burnable absorbers are present, which significantly reduces the boron depletion rate compared to equilibrium cycle. The boron depletion rate is comparable between uranium and 100% MOX fueled cores. This is because the boron worth in PDR600 is very low, but the reactivity loss for the MOX core has a much slower rate due to the formation of fissile Pu-241 isotope. It may be noted that the soluble boron level can be kept within the range of a typical uranium fueled core (~2000 ppm) by the addition of sufficient discrete as well as integral burnable absorbers in order to meet negative MTC criterion.

B. POWER DISTRIBUTION AND PEAKING FACTORS

Assemblywise power distribution for the unrodded core consistent with the boron letdown curve is well behaved. Figure 2 identifies the assemblywise average and peak power. Core average axial power distribution is shown in Figures 4 and 5. The maximum peak hot channel peaking factor \( F_{\Delta H} \) is 1.358 and remains under the design limit of 1.53 excluding the uncertainties. The Hot channel peaking factors are comparable between cycle 1 and equilibrium cycle. The equilibrium cycle total peaking factor \( F_Q \) is 1.72 at HFP, all rod out (ARO), BOL, and 1.57 at HFP, ARO, EOL, while the design limit for \( F_Q \) is 2.4 excluding the uncertainties. Axial peaking factors \( F_Z \) for cycle 1 are 1.39 and 1.21 at BOL and EOL respectively. The axial peaking factors are decreased by about 10% in the equilibrium cycle. These PDR600 peaking factors are, therefore, well within the peaking factor limits of the advanced PWR design.

Since the core is fully loaded with MOX assemblies, there is no spectrum transition at the interface between assemblies, and no intra-assembly zoning is needed. Intra-assembly zoning with different enrichments is, on the other hand, essential in one-third MOX cores.

C. MODERATOR TEMPERATURE COEFFICIENT

The MTC at different ppm and moderator temperatures is shown in Figures 6 and 7. The MTC versus cycle burnup plot is shown in Figure 8. The most negative MTC is found to be \(-28.3\) pcm/{\degree}F at the EOL, HFP, equilibrium cycle. The least negative MTC is \(-4.3\) pcm/{\degree}F at the cycle 1 BOL, HZP
critical boron conditions. The MTC in the equilibrium model is more negative than in cycle 1. Thus the PDR600 MTC values lie within the design basis limit of the advanced PWR (0 pcm °F to -40 pcm °F).

A very important fact of the PDR600 design is that there is enough flexibility to tailor MTC values to suit reactor operation and safety needs. Calculations indicate that MTC values similar to uranium fueled cores can be easily achieved by balancing burnable absorbers and soluble boron, even though at a particular boron and moderator temperature level, the MTC for the PDR600 tends to be more negative than the uranium fueled core. Consequently, the effect of MTC on cool-down accidents is not expected to be more severe than that in a uranium fueled core.

D. DOPPLER AND POWER COEFFICIENT

Doppler-only contribution to the power coefficient (DPC) is shown in Figure 9 as a function of core power. Doppler temperature coefficient (DTC) is shown in Figure 10 as a function of the effective fuel temperature. The effective fuel temperature is lower than the volume-averaged fuel temperature, since the neutron flux distribution is non uniform through the pellet and gives preferential weight to the surface temperature. In general, the Doppler coefficient is more negative which is expected in a 100% MOX fueled core than in the advanced PWR design. The range of Doppler temperature coefficient in the PDR600 varies from -1.9 pcm/°F to -3.5 pcm/°F. The higher negative values of the DPC/DTC are beneficial for accident mitigation and result from spectrum hardening of the PDR600 core.

The combined effect of moderator temperature and fuel temperature change as the core power level changes is called the total power coefficient. The total power coefficient as a function of core power level and at HFP boron concentrations is shown in Figures 11 and 12. These coefficients are calculated using a three-dimensional model; therefore, spatial reactivity effects due to changes in the axial moderator density distribution with power level are implicitly included. The power coefficients are strongly negative under all conditions.

E. BORON COEFFICIENT

The boron worth is noticeably smaller in the 100% MOX fueled core. It varies slightly from -2.8 to -3.8 pcm/ppm at different power and burnup conditions, whereas the boron worth is around -10 pcm/ppm in a uranium fueled core. The inverse boron worth in units of ppm/%Δρ as a function of burnup is shown in Figure 13. The low boron worth is beneficial for boron dilution accidents, and early indications do not reveal any impact of low boron worth on the steamline break accident.

F. XENON WORTH

Like all other reactivity worths, the xenon worth has been decreased by about a factor of two in the PDR600. The xenon worth at HFP BOL and EOL is 1230 pcm and 1500 pcm, respectively, for the equilibrium cycle. Typically, in uranium fueled cores, the xenon worth is around 2500 to 3000 pcm. The low worth of xenon has an important advantage for stability against xenon induced oscillations, making axial xenon transients less severe in the PDR600.
G. CONTROL ROD WORTH

The control rod worth is expected to go down in a 100% MOX core. The control rod worth is also, in general, decreased in the equilibrium cycle, the normal trend. The preliminary control rod pattern developed for the PDR600 is different from that for the advanced PWR, as this core is not designed for load-follow operation. The loss of worth is recovered by replacing 16 gray rods with 16 Ag-In-Cd full-strength rods and also by adding 8 rods on the periphery. The cycle 1 total control rod worth for 69 rods is about 9.5% Δρ at BOL and 10.7% Δρ at EOL and the values goes down by about 0.3% Δρ in the equilibrium cycle. The cycle 1 "5 rod, D Bank" worth is around 600 pcm which is reduced by about 10% in the equilibrium cycle. This D bank worth is similar to an existing PWR having a light D bank.

H. SHUTDOWN MARGIN

The calculated shutdown margin (SDM) varies from 4.9% Δρ in cycle 1 to 4.4% Δρ in equilibrium cycle at BOL and from 5.5% Δρ to 4.7% Δρ at EOL. This represents a relative reduction of SDM of about 10% to 20% at BOL and EOL from cycle 1 to the equilibrium cycle, respectively. But considering the design basis minimum shutdown requirement of 1.6% Δρ for the PDR600 (assumed to be the same as in advanced PWR), a substantial 3% Δρ margin exists in the design.

I. ACCIDENT ANALYSES FOR PDR600

Analysis has been performed for selected transients thought to be most sensitive to certain nuclear design characteristics of PDR600. The reduced delayed neutron fraction led to selecting the control rod ejection event for analysis, while reduced boron worth brought consideration of the main steam line rupture event. The general methods applied to both these accidents are consistent with those long used for standard Westinghouse PWR designs, though the specific analysis models used reflect both the passive plant and plutonium core related features of the PDR600 design.

The rod ejection analysis for the PDR600 considers two representative sets of initial conditions: BOL, HFP and EOL, HZP. Typically, HFP cases are limiting with respect to the peak fuel pellet enthalpy and fuel pellet melt criteria, while HZP cases are generally limiting with respect to peak clad temperature.

To provide bounding results that allow for future cycles, standard Westinghouse rod ejection analyses have typically used conservatively low delayed neutron fraction values of 0.55 and 0.44 percent at BOL and EOL, respectively. For the PDR600 cases, a delayed neutron fraction of 0.30 percent has been assumed for all times in life.

Despite this, the RCCA ejection analysis for the PDR600 core has produced far less limiting results than those for a typical standard plant design. The primary reason is the reduced worth of individual control rods in the PDR600 core, which is offset by an increased total number of RCCAs. The net effect is the reduction of maximum ejected rod worth and associated power peaking, thereby mitigating the overall transient. All applicable licensing requirements for this event are met by the PDR600 analysis, with significant margin to the safety limits still available.

The main steam line rupture analysis for the PDR600 examines a single representative limiting case, intended to assess the impact of the reduced boron worth. Specifically, the analysis considers the
complete severance of a main steam line with the plant initially at no-load EOL condition, with full reactor coolant flow, and offsite power available. The PDR600 passive protection system includes an automatic safety-related signal that initiates reactor coolant pump coastdown in parallel with core makeup tank actuation, which occurs essentially at the outset of the event. Therefore, most of the steam line break transient takes place under natural circulation conditions.

The PDR600 analysis assumes a conservative boron worth of -3.0 pcm/ppm, which is only about one-third of the typical value for a standard PWR. To partially offset the reduced boron worth, the analysis assumes increased core makeup tank and accumulator boron concentrations of 5000 and 3500 ppm, respectively. The specific nuclear model used for the PDR600 employs approximate inputs to model MOX fuel characteristics and the nuclear feedback associated with natural circulation. A PDR600 specific DNB evaluation has not been performed as part of the current steam line break analysis. Instead, the intent of the current analysis is to provide a comparison of the general passive plant design response to a MOX core rather than a standard uranium based core.

The results of this steam line break analysis demonstrate that, with somewhat increased protection system boron concentration, the response of the PDR600 is essentially consistent with that of a uranium fueled passive plant. Based on this analysis, it is expected that a detailed, PDR600 specific steam line break analysis would produce acceptable results that meet all the licensing requirements.

CONCLUSION

A feasible design has been demonstrated that employs a 100% weapons grade MOX core and satisfies all core limit criteria of an advanced uranium fueled PWR. The expected changes in core characteristics with MOX loadings are observed, yet the control rod worths, moderator and Doppler reactivity coefficients and peaking factors are found to be within the realm of normal experience. The lower delayed neutron fraction and boron worth do not impact the safety of PDR600. Thus, a MOX fueled Westinghouse advanced passive PWR is an ideal machine to denature weapons grade plutonium.

REFERENCES


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## TABLE 1

### CORE DESCRIPTION (All Dimensions Cold)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete Burnable Absorber Material</td>
<td>Borosilicate Glass (cycle 1 only)</td>
</tr>
<tr>
<td>Integral Fuel Burnable Absorber (IFBA) Loading, B₁₀</td>
<td>1.57 mg/inch</td>
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<tr>
<td>Power, MWth</td>
<td>1933</td>
</tr>
<tr>
<td>Number of Fuel Assemblies</td>
<td>145</td>
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<tr>
<td>Lattice Configuration</td>
<td>17 x 17</td>
</tr>
<tr>
<td>Clad, Thimble, Grid, Sleeve Material</td>
<td>SS-304</td>
</tr>
<tr>
<td>Fuel Rod Diameter, Inches</td>
<td>0.374</td>
</tr>
<tr>
<td>Enrichments, w/o Pu Total, cycle 1</td>
<td>4.5, 5.0, 5.5</td>
</tr>
<tr>
<td>Enrichments, w/o Pu Total, eq. cycle</td>
<td>5.5</td>
</tr>
<tr>
<td>Fuel Loading, MTM</td>
<td>66.8</td>
</tr>
<tr>
<td>Control Rod Material</td>
<td>Ag-In-Cd</td>
</tr>
<tr>
<td>Number of RCCA Clusters</td>
<td>69</td>
</tr>
<tr>
<td>Hot Zero Power</td>
<td>545.0</td>
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<tr>
<td>Hot Full Power</td>
<td>566.7</td>
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<tr>
<td>Hot Channel Factor Limits:</td>
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<tr>
<td>Total Heat Flux, FT</td>
<td>2.60</td>
</tr>
<tr>
<td>Nuclear Enthalpy Rise, FNΔH</td>
<td>1.65</td>
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<tr>
<td>Average Linear Power Density, kW/ft Fuel</td>
<td>4.1</td>
</tr>
<tr>
<td>Cycle Length, MWD/MTM</td>
<td>13,300</td>
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<tr>
<td>Discharge Burnup, MWD/MTM</td>
<td>40,000</td>
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</table>

## TABLE 2

### SUMMARY OF CORE PHYSICS CHARACTERISTICS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cycle 1</th>
<th>Eq. Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPM, HFP, ARO, BOL/EOL</td>
<td>2144 / 838</td>
<td>2168 / 249</td>
</tr>
<tr>
<td>PPM, HZP, ARO, BOL/EOL</td>
<td>2789 / 1331</td>
<td>2710 / 752</td>
</tr>
<tr>
<td>FAH, HFP, ARO, BOL/EOL</td>
<td>1.38 / 1.32</td>
<td>1.38 / 1.35</td>
</tr>
<tr>
<td>MTC, HFP, BOL/EOL (pcm/°F)</td>
<td>-14.4 / -22.0</td>
<td>-15.5 / -28.3</td>
</tr>
<tr>
<td>MTC, HZP, BOL/EOL (pcm/°F)</td>
<td>-4.3 / -12.4</td>
<td>-5.3 / -17.5</td>
</tr>
<tr>
<td>Doppler only Power Coef., HFP, BOL/EOL (pcm/%P)</td>
<td>-12.9 / -9.2</td>
<td>-12.3 / -8.7</td>
</tr>
<tr>
<td>Doppler only Temp. Coef., HFP, BOL/EOL (pcm/°F)</td>
<td>-2.4 / -1.9</td>
<td>-2.3 / -1.8</td>
</tr>
<tr>
<td>Power Coef., HFP, BOL/EOL (pcm/%P)</td>
<td>-17.3 / -16.5</td>
<td>-17.1 / -18.5</td>
</tr>
<tr>
<td>Boron Worth, HFP, BOL/EOL (pcm/ppm)</td>
<td>-2.8 / -3.4</td>
<td>-3.2 / -3.8</td>
</tr>
<tr>
<td>Total Rod Worth, HFP, BOL/EOL (%Δp)</td>
<td>9.5 / 10.7</td>
<td>9.3 / 10.5</td>
</tr>
<tr>
<td>Available Shutdown Margin, BOL/EOL (%Δp)</td>
<td>4.9 / 5.5</td>
<td>4.4 / 4.7</td>
</tr>
<tr>
<td>Required Shutdown Margin (%Δp)</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>
FIGURE 1. PDR600 - CONTROL AND SHUTDOWN ROD LOCATIONS

FIGURE 2. POWER DISTRIBUTION AT ARO, HFP, EQXE
FIGURE 3. CRITICAL BORON CONCENTRATION VERSUS BURNUP (HFP, ARO, EQXE)

FIGURE 4. RELATIVE AXIAL POWER DISTRIBUTION AT HFP, ARO, EQXE

FIGURE 5. RELATIVE AXIAL POWER DISTRIBUTION AT HFP, ARO, EQXE

FIGURE 6. MODERATOR TEMPERATURE COEFFICIENT AT DIFFERENT PPM AND MODERATOR TEMPERATURE

FIGURE 7. MODERATOR TEMPERATURE COEFFICIENT AT DIFFERENT PPM AND MODERATOR TEMPERATURE

FIGURE 8. MODERATOR TEMPERATURE COEFFICIENT VERSUS CYCLE BURNUP AT ARO, HFP, EQXE, CRITICAL BORON CONCENTRATION
FIGURE 9. DOPPLER ONLY POWER COEFFICIENTS AT BOL AND EOL

FIGURE 10. DOPPLER TEMPERATURE COEFFICIENTS AT BOL AND EOL

FIGURE 11. POWER COEFFICIENT VERSUS POWER LEVEL AT CYCLE 1

FIGURE 12. POWER COEFFICIENT VERSUS POWER LEVEL AT EQUILIBRIUM CYCLE

FIGURE 13. INVERSE BORON WORTH VERSUS BURNUP AT HFP, ARO, EQUILIBRUM XENON