PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Feasibility and Configuration of a Mixed Spectrum Supercritical Water Reactor

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Abstract

Assessment of the feasibility issues and fuel cycle performance of the mixed spectrum supercritical water reactor (MS^2) has been performed. Through pitch-to-diameter (P/D) ratio sensitivity studies, the feasible P/D ratio windows for the thermal zone of the MS^2 core are sought for stainless steel and Ni-based claddings, which is large enough to provide adequate reactivity and small enough to provide an adequate heat transfer coefficient.

By choosing the P/D ratio within the feasible windows, the MS^2 core has been designed and evaluated from safety and actinide management viewpoints. This core has negative moderator temperature reactivity coefficient and the shutdown margin is 1.6% $\Delta\rho$. By recycling Pu, Np and Am in the fast zone, the MS^2 concept is capable of keeping Pu, Np and Am in the reactor fuel cycle and thus eliminating them from the disposed nuclear waste.

KEYWORDS: ***Mixed spectrum supercritical water reactor, Window of feasible operation, Pu, Np and Am recycling.***

1. Introduction

The Supercritical Water Reactor (SCWR) has attracted renewed interests because of its potential for high thermal efficiency and considerable plant simplification. Many concepts of thermal and fast SCWR systems have been proposed; the thermal system has focused on improving economics and the fast one on minor actinide management.[1,2]

A hybrid system aiming at achieving these two goals at the same time has also been proposed.[3] The primary feature of this mixed spectrum supercritical water reactor (called MS^2) concept is the separation of the core into two annular zones, an inner zone operating with a fast spectrum and an outer zone operating with a thermal spectrum. In this concept, the coolant first passes through an outer zone from top to bottom and then an inner zone from bottom to top. The average coolant temperature at the exit of the outer zone is about the critical temperature and it is raised in the inner zone. The high coolant density of the outer zone ensures a thermal spectrum and the reduced coolant density and tight lattice pitch of the inner zone result in a fast spectrum. Thus, by separating the thermal and fast zones radially, the outer and inner zones of the MS^2 core are utilized as a boiler and actinide burner, simultaneously.

For the MS^2 core design, the fuel pin configuration has to be selected appropriately and safety parameters have to be confirmed. For the first item, the pitch-to-diameter (P/D) ratio of the fuel pin should be in the feasible P/D ratio windows that permit both enough moderation and adequate cooling of the cladding. For the reactor safety, the core should have a negative moderator temperature reactivity coefficient and an adequate shutdown margin.

Therefore this paper consists first of P/D ratio sensitivity calculations to determine feasible P/D ratio windows for stainless steel and Ni-based claddings and then the MS^2 core design follows by selecting the fuel pin configuration within the feasible P/D ratio windows. Finally, the safety parameters and the minor actinide management advantages of the MS^2 core are demonstrated.

2. P/D Ratio Sensitivity for Thermal Zones

Even though the coolant remains below the pseudo-critical temperature throughout the downward-flowing thermal-spectrum outer zone, there is a concern of under-moderation. The large enthalpy change as water flows through the critical point results in a lower mass flow rate of water through the core in comparison to a typical LWR. For a comparable P/D ratio, this results in a lower coolant velocity and thus a lower heat transfer coefficient at the cladding. In order to ensure adequate cooling of the cladding, the P/D ratio must be reduced, presenting the possibility of under-moderation despite the near LWR densities in this region. This section demonstrates the existence of a reasonable operating window that permits both enough moderation and adequate cooling of the cladding.

2.1. Methodology

This analysis consisted of first a thermal-hydraulic (T/H) analysis of a single channel followed by a lattice physics analysis of a single assembly. The T/H analysis was based on the preliminary design parameters of the MS^2 reactor: i.e., the coolant mass flow rate is assumed about one tenth of the typical PWR while the fuel diameter is comparable to that of a PWR but with a hexagonal assembly. Since preliminary sensitivity calculations showed that the axial power shape is not sensitive to the P/D ratio, the axial power distribution was determined by the one-dimensional model of the outer zone of the MS^2 core. Using these coolant mass flow rate and axial power distribution, the coolant and cladding temperatures were calculated at 21 different axial locations with the equation of state of supercritical water. The *Jackson heat transfer coefficient correlation* [4] was used to determine the cladding temperature.

The reactor physics analysis was performed using the HELIOS lattice physics software package.[5] Taking advantage of symmetry, a 1/12 assembly model was constructed and analyzed for a hexagonal assembly. For each of the axial locations in the T/H analysis, the appropriate coolant temperature and density and cladding temperature were used in the neutronics analysis to determine the infinite multiplication factor, k_∞, for that axial location. A mean k_∞ value for the whole assembly was calculated by the so-called point reactivity model[6], in which the individual k_∞ value of the each axial node is summed by weighting with the corresponding axial power distribution.

With the fuel diameter and cladding thickness held constant at 0.88 cm and 0.0572 cm, respectively, six P/D ratios were chosen between 1.356 and 1.582, inclusive (Note: these are pitch-to-fuel diameter ratios that correspond to pitch-to-clad diameter ratios of 1.2 and 1.4, respectively).

2.2 Results

The T/H analysis shows that the maximum cladding temperature varies from about 747 K to 1004 K as the P/D ratio varies from 1.356 to 1.582. The limits used for the cladding in this analysis are 873 K for stainless steel (e.g. SS-316) and 973 K for Ni-based alloys (e.g. Inconel 600 or 690).[7] These temperature limits correspond to upper limits on the P/D ratio of 1.492 for stainless steel and 1.563 for Ni-based alloys.

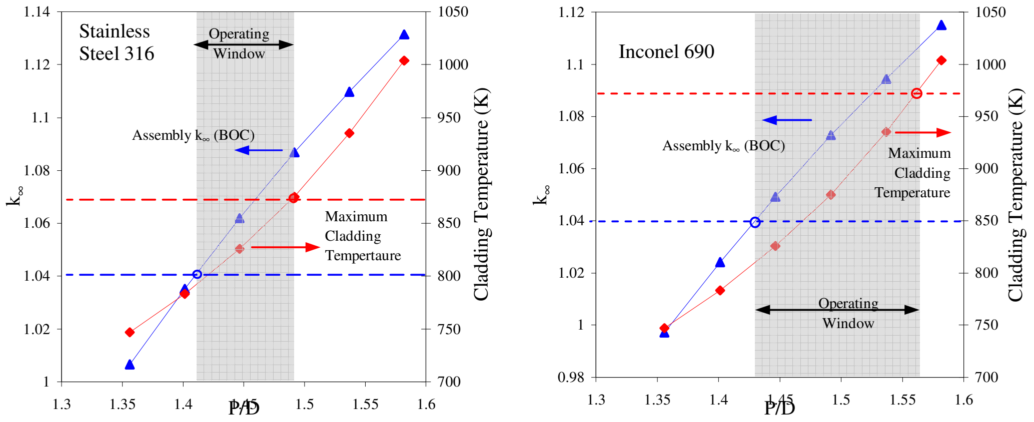


Figure 1. A substantial window of operation is available for both stainless steel (SS316) and Inconel 690 based on the minimum P/D ratio for sufficient moderation and the maximum P/D ratio for sufficient cooling.

The reactor physics analysis was based on a constraint of k_∞=1.04, allowing for a few percent leakage when an entire core is assembled. This corresponds to a lower limit on the P/D ratio of 1.409 for stainless steel, 1.445 for Inconel 600 and 1.429 for Inconel 690. Figure 1 summarizes these results for stainless steel (SS316) and Inconel 690, showing the extent of the feasible operating windows. Although a real reactor design effort would introduce uncertainties and safety margins that would narrow these windows, the operation window for Inconel 690 is likely wide enough to accommodate these effects. While the specific isotopics of the cladding material have an impact on the operating window, the Ni-based alloys show promise for this application. This demonstration of a reasonable operating window provides a basis for a more detailed core design of the full MS^2 reactor concept in the following section.

3. Design of Mixed Spectrum Supercritical Water Reactor

3.1. Design Concepts

Figure 2 shows the layout of the MS^2 core and Table 1 presents the major design parameters, compared to other SCWR concepts and a typical PWR. Like other SCWRs, the MS^2 is operated above the critical pressure and its exit coolant temperatures exceeds the critical temperature (~658 K at 25 MPa) while inlet temperature is below the critical temperature. In addition, the coolant mass flow rate is about a tenth of a PWR due to the high specific heat of the coolant in the operating conditions. Since the MS^2 core separates the thermal and fast zones radially, the effective core radius is larger than those of the other SCWRs or PWR while its active height is shorter. Hence, its volumetric power densities are comparable to others. To ensure the negative void reactivity coefficients by enhancing the neutron leakage, 25 void fuel assemblies exist in the inner zone. Finally, the inner and outer zones are separated by 48 shielding assemblies in the MS^2 core.

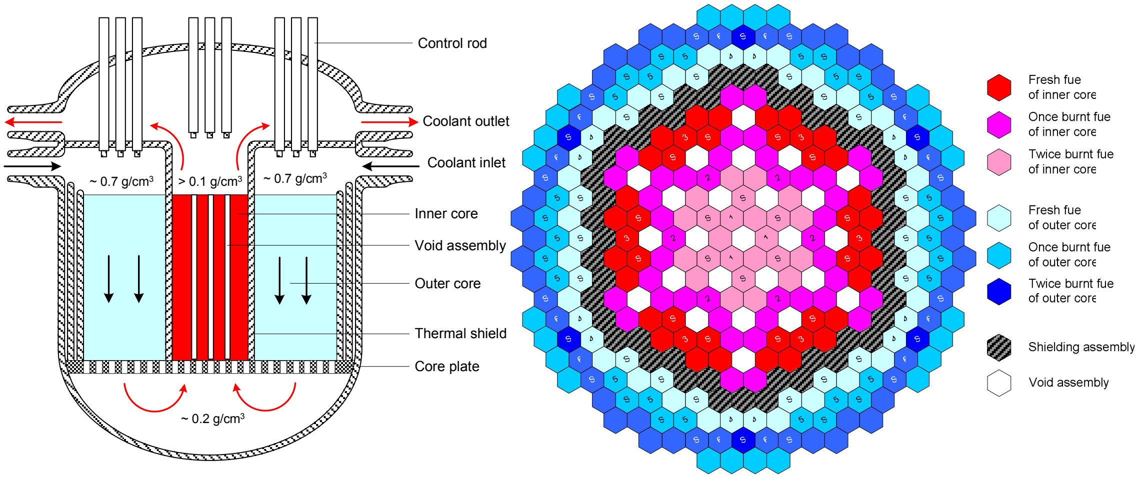


Figure 2. Layout of MS^2 core

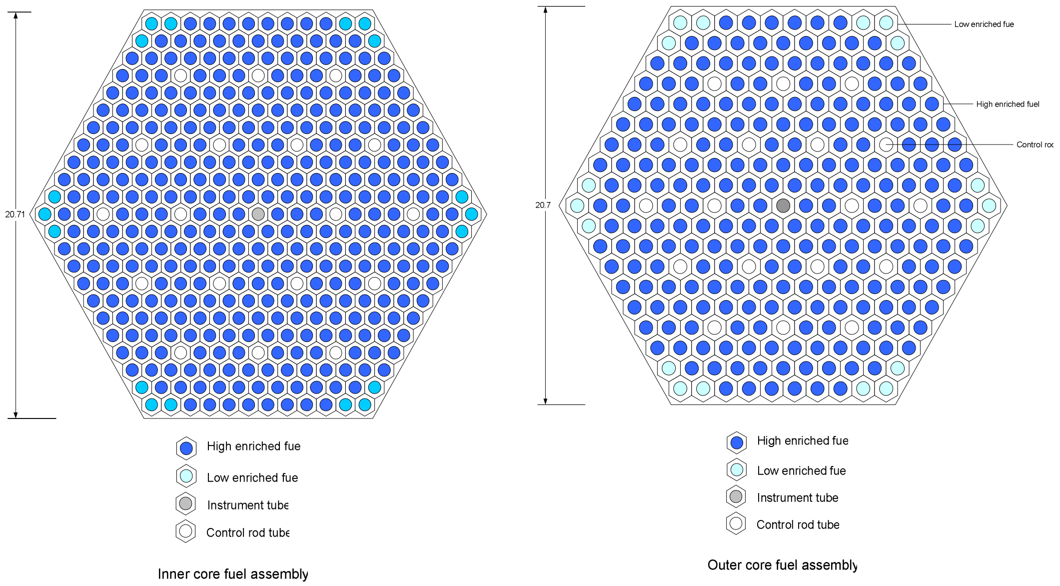
Excess reactivity of the MS^2 core is controlled by burnable absorbers and control rods. The chemical shim (e.g., soluble boron) is not utilized in this core in order to be able to provide the exit coolant to a turbine directly. To compensate for reactivity change during operating and shutdown conditions, typical PWR type control rods are utilized in the MS^2 core. The control rod contains B_4C with 30% enriched B-10. There are 18 and 48 shutdown banks (denoted by *S* in Figure 2) in the inner and outer zones, respectively.

Table 1. Comparison of Design Parameters

		Fast SCWR [8]	Thermal SCWR [9]	PWR	MS^2 SCWR	
					Inner zone	Outer zone
General Core properties	Thermal power, MW	3893	3022	3411	3400	
	Thermal Efficiency, %	44.39	43.51	33.71	44.12	
	System pressure, MPa	25	25	15.5	25	
	Number of fuel assembly	278	121	193	108	168
	Number of shield assembly				48	
	Number of void assembly				25	0
	Active core height, cm	320	427	376	280	280
	Effective radius, m	1.37	1.81	1.83	1.98	
	Power density, MW/m^3	206.0	69.1	104.0	156.7	84.8
	Average linear heat rate, W/cm	221.02	194.97	178.00	154.0	125.0
Fuel and assembly	Fuel form	MOX	UO_2	UO_2	[a] TMOX	UO_2
	Fissile enrichment, %	12	5	4	~11	6.5
	Cladding material	Ni-Alloy	ODS steel	Zr	Ni-Alloy	Ni-Alloy
	Fuel radius, cm	0.4400	0.4470	0.4095	0.4400	0.4095
	Cladding thickness, cm	0.0520	0.0630	0.0572	0.0400	0.0572
	Fuel pitch, cm	1.0100	1.1200	1.2500	1.0000	1.2000
	P/D ratio of fuel pin	1.14	1.25	1.52	1.14	1.47
	Assembly Shape	hexagonal	square	square	hexagonal	
	Assembly pitch, cm	15.66	29.10	21.50	20.71	20.71
T/H	Inlet temperature, °C	280	280	300	387	280
	Average outlet temperature, °C	526	500	332	553	387
	Coolant mass flow rate, kg/sec	1694	1561	17222	2000	

a) TMOX means the thorium-based mixed oxide fuel

Figure 3 shows the fuel assemblies of the inner and outer zones. The assembly pitches of these two assemblies are identical but the P/D ratios are different; the P/D ratio of the outer zone is comparable to that of a typical PWR while it is reduced significantly in the inner zone to achieve a fast spectrum. Thus, the number of fuel pins in the inner zone is about 45% higher than that of the outer zone (397 and 271 pins in inner and outer assemblies, respectively). Note that the P/D ratio of the outer zone was selected around the smallest feasible P/D ratio (i.e., near the left bound of the feasible P/D ratio window in Figure 1) to reduce the maximum cladding temperature.



Inner core fuel assembly

Outer core fuel assembly

Figure 3. Fuel Assembly Configurations

The MS^2 core performances have been evaluated using the WIMS8[10], MC^2-2[11] and SOLTRAN[12] codes. The WIMS8 and MC^2-2 codes generate the assembly-wise microscopic cross sections and the SOLTRAN code solves the multi-dimensional neutron diffusion equations and the depletion equations. Due to the different spectra, the cross sections for inner and outer zones are generated by the MC^2-2 and WIMS8 codes, respectively. Table 2 shows a comparison of the eigenvalues of the inner and outer assemblies calculated by WIMS8 and MC^2-2 codes with the results of the MCNP4C[13] code. The results of the MC^2-2 code are closer to the result of the MCNP4C for the inner zone while the results of the WIMS8 code are closer for the outer zone. Note that WIMS8 and MC^2-2 code are thermal and fast system lattice codes, respectively.

Table 2. Eigenvalues Comparison of Inner and Outer Assemblies

Code	Neutron groups	Inner zone	Outer zone
MCNP4C	continuous	1.18881 ± 0.00044	1.21507 ± 0.00057
WIMS8	28	1.20620	1.22047
	11	1.20557	-
MC^2-2	230	1.18541	0.97296
	11	1.18140	-

The thermal-hydraulic feedback effect is also taken into account in the SOLTRAN code by solving a heat balance equation with a single channel model. Finally, the cladding temperature is calculated by using Jackson's heat transfer correlation at the supercritical conditions.

To evaluate the safety parameters, the startup MS^2 core has been designed and the results are summarized in Figures 4 and 5. The startup core loads one kind thorium-based mixed oxide (TMOX) fuel into the inner zone; 15% Pu discharged from the Advanced Light Water Reactor[14] are mixed with Thorium and 6.0% enriched Uranium. For enhancing the actinide consumption rate and reducing the void reactivity coefficient in the inner zone, about 50% of fertile uranium is replaced by thorium in the inner fuel. Thus, the heavy metal composition of the inner zone is 15% Pu, 42.5% Th, and 42.5% U. On the other hand, 6.5, 5.5 and 4.5% enriched fuels are loaded into the fresh, once burnt and twice burnt locations of the outer zones, respectively. The cycle length of the start-up MS^2 core is about 283 EFPDs.

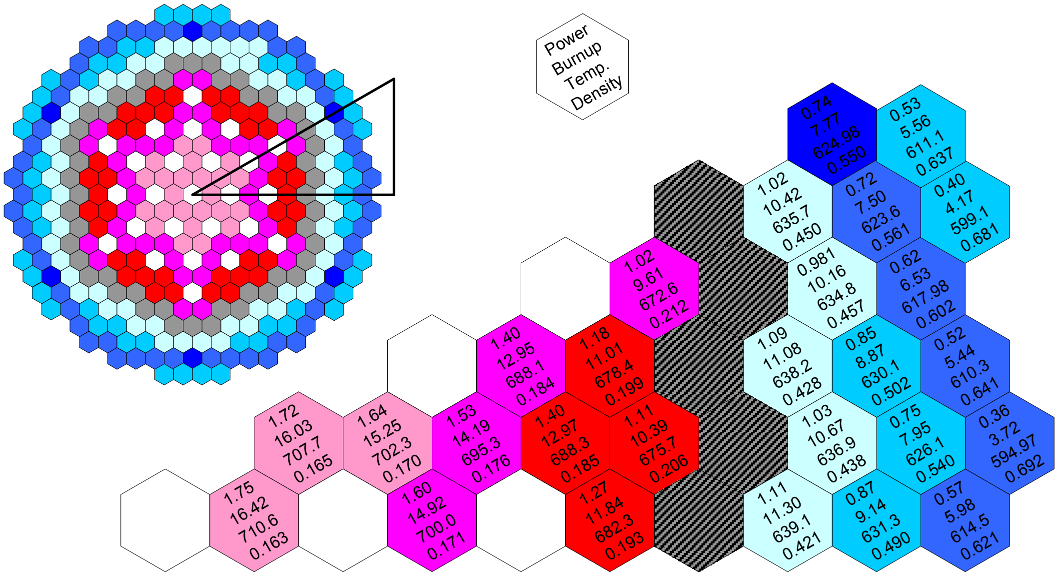


Figure 4. Radial Distribution of Major Design Parameters of MS^2 Core at EOC

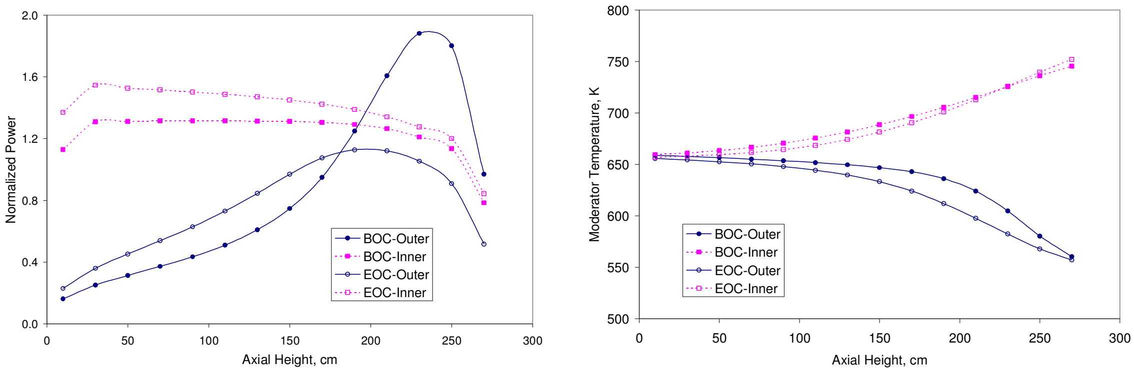


Figure 5. Axial Power and Coolant Temperature of Startup MS^2 Core

In Figure 4, the average coolant density of the outer zone is similar to that of a typical boiling water reactor while it is much lower in the inner zone. The inner zone has a higher power fraction than the outer zone. Figure 5 is very useful to understand the characteristics of the MS^2 core. Since the coolant first passes through the outer zone and then inner zone, the coolant density peaks at the inlet of the outer zone and this results in a power peak near the inlet of the outer zone. On the contrary, the axial power distributions of the inner zone are much flatter than those of the outer zone because of the smaller coolant density variation.

Axially, the coolant temperature increases as power is accumulated. The average coolant temperature at exit of the outer zone is about 660K, which is just above the critical temperature. The exit coolant temperature of the inner zone is about 710 K and the corresponding coolant density is slightly below 0.1 g/cm^3. The maximum cladding temperature occurs at the outer zone at beginning of cycle because of the higher power peaking factor and the smaller heat transfer coefficient, compared to the inner zone. However, the maximum cladding temperature is generally less than the design criteria: the maximum cladding temperature taking into account the axial and radial power peaking factor is 959K at the Xe/Sm equilibrium state.

The moderator temperature reactivity coefficient (MTC) and shutdown margin for the MS^2 core have been evaluated. MTC of the startup MS^2 core are -125 and -99 pcm/K at beginning and end of cycles, respectively. These values are more negative than those of typical PWRs due to the large coolant density variation at the supercritical conditions.

The shutdown control rods should compensate the reactivity changes induced by the operation condition changes. During the operating condition changes from HFP to HZP, a positive reactivity is induced by the so-called *power defect* which consists of moderator temperature defect, Doppler power defect and power redistribution effects. In addition, additional negative reactivity is required to compensate the so-called *Minimum Shutdown Margin.* Typically, the minimum shutdown margin is determined by the uncertainty and safety analyses.

The reactivity changes from HFP to HZP and the control rod scram worth of the startup MS^2 core are summarized in Table 3. Generally, the moderator density effect is positive in LWRs but it is negative in the inner zone because the spectrum softening in the fast zone increases the resonance absorption. The total reactivity change from HFP to HZP is 5116 pcm but the (N-1) control rod scram worth is -6779 pcm. Thus, the control rod scram worth is 1663 pcm more negative than the reactivity change from HFP to HZP. However, further investigations are necessary for the calculation uncertainty and the minimum shutdown margin (derived from safety analysis).

Table 3. Reactivity Requirements and Shutdown Margin

Required Reactivity from HFP to HZP, pcm	Inner zone	Outer zone
Moderator density effect	- 2756	+ 5308
Doppler effect	+ 1336	+ 1228
Total	- 1420	+ 6536
Net reactivity requirement	+ 5116	
Control rod scram worth of (N-1)	- 6779	

3.2. Fuel Cycle Analysis of Mixed-spectrum Supercritical Water Reactor

Figure 6 presents the fuel cycle concept of the MS^2 core. For a given cycle, the outer zone follows the current once-through fuel cycle scheme: i.e., the enriched uranium dioxide fuel is loaded into the outer zone and depleted with three-batch fuel management scheme.

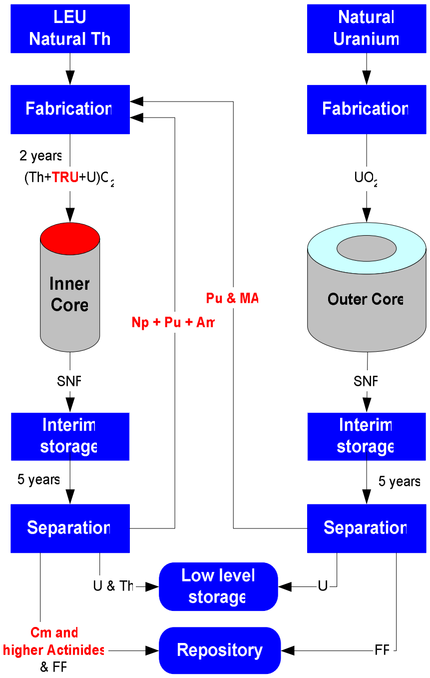


Figure 6. Multi-recycling of Pu, Np and Am in MS^2 concept.

But the fuels of the inner zone are fabricated from external depleted uranium, thorium and the Pu, Np, and Am (simply PNA) extracted from the discharge of the outer zone and previous cycle of the inner zone. Thus, PNA is multi-recycled in the fast zone. Note that recycling of Cm and higher actinides are not considered in the MS^2 fuel cycle because the high decay heat of these nuclides may cause fabrication-handling problems. To minimize the radial power peaking factor, the out-in loading pattern scheme is adopted in the inner zone. In the outer zone, however, fresh (or higher enriched) assemblies are loaded into the innermost part of the outer zone to improve the neutron economy.

A lead-time of two years is assumed from the assembly fabrication to its loading into the reactor. After the assembly is discharged from the reactor, a five-year post-irradiation cooling period is allowed before separation of the discharged fuel. Following the separation, the PNA are recycled to make the TMOX fuel pins, while all fission products and other minor actinides are passed to the repository and uranium is passed to the low-level storage. Thus, the materials to be sent to the repository are minimized by the fission products and Cm and higher actinides.

Table 4 provides the results of the PNA multi-recyclings in the MS^2 core. In order to compensate the degradation of PNA vector, the uranium enrichment of the inner fuel is increased. In Table 4, the fissile content in PNA vector decreases from 64.2% to 57.7% and the uranium enrichment of the inner fuel increases from 6.0% to 6.5% (during the transient cycles, it increases up to 7.0%).

As expected, plutonium is burnt and bred in the inner and outer zones, respectively. The net Pu mass balances (which denote the mass difference between discharge and charge stages) in cycle 5 are -168.9 kg and 206.3 kg in the inner and outer zones, respectively. The net mass balance of Np and Am is constant in the outer zone but it decreases progressively in the inner zone. The total net PNA mass balance is 47 kg in cycle 5, which is negligible to the total PNA mass of the fresh fuel in the inner zone (~3600 kg). Thus, the PNA content is easily stabilized around 15% during the PNA multi-recycling. However, the discharge mass of the Cm and higher actinides increases up to 9.9 kg in cycle 5, which affects the decay heat and radiotoxicity level of the repository for several decades.

Table 4. Summary of Pu, Np and Am Multi-recycling in MS^2 Concept

		Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
U enrich. of outer zone,%		5.28	5.82	6.50	6.50	6.50
U enrich. of inner zone, %		6.0	6.5	7.0	6.5	6.5
PNA content in HM, %		15.0	14.9	14.9	15.1	15.0
Fissile content in PNA,%		64.2	61.1	60.3	59.1	57.7
Net mass balance, kg/Core (inner/outer)	Pu	-228.4 / 287.9	-200.9 / 243.2	-185.0 / 217.8	-179.7 / 200.9	-168.9 / 206.3
	Np+Am	42.2 / 9.2	27.5 / 10.2	15.3 /10.7	5.0 / 9.8	-2.6 / 10.1
	Others	3.5 / 0.0	5.4 / 0.2	6.6 / 0.3	8.6 / 0.3	9.6 / 0.3
	Net PNA	110.9	80.0	58.8	35.9	47.0
Charge vector of PNA	Am241	0.91	3.60	3.81	4.55	5.26
	Am242m	0.00	0.01	0.02	0.04	0.06
	Am243	0.00	0.15	0.30	0.43	0.55
	Np237	0.00	0.08	0.17	0.38	0.50
	Pu238	3.19	2.86	2.75	2.70	2.73
	Pu239	55.15	55.02	54.44	53.88	53.26
	Pu240	25.93	26.44	26.90	27.09	27.50
	Pu241	9.06	6.06	5.80	5.15	4.37
	Pu242	5.70	5.74	5.76	5.73	5.71
	U234	0.05	0.04	0.04	0.04	0.04
	U236	0.01	0.01	0.01	0.01	0.01

4. Conclusions

A pitch-to-diameter (P/D) ratio feasibility study has shown that reasonable operating windows exist to accommodate both sufficient moderation and sufficient cooling in the thermal zone of the Mixed Spectrum Supercritical Water Reactor (MS^2). In particular, a hexagonal pitch fuel assembly can satisfy reactor physics requirements with P/D ratios greater than 1.409, 1.445 and 1.429 for stainless steel, Inconel-600 and -690, respectively. At the same time, with estimated maximum allowable cladding temperatures of 873 K and 973 K for stainless steels and Ni-based alloys, respectively, sufficient cladding cooling is achieved for P/D ratios less than 1.492 and 1.563, respectively. The Ni-based alloys offer the most promising alternative from the standpoint of reactor physics and thermal-hydraulics.

Based on the study for the feasible P/D ratio windows, a mixed spectrum supercritical water reactor has been developed. The high coolant density of the outer zone ensures a thermal spectrum and the reduced coolant density and tight lattice pitch of the inner zone result in a fast spectrum. The core characteristics such as operating conditions, power density, thermal efficiency, etc., are very similar to other supercritical water reactors. But the MS^2 core has 25 void fuel assemblies in the inner zone to enhance the neutron leakage and 48 shielding assemblies exist between inner and outer zones.

Regarding safety parameters, the moderator temperature reactivity coefficient of the startup MS^2 core maintains negative value from beginning to end of cycle (-125 ~ -99 pcm/K). Also, the control rods scram worth is 1.6% $\Delta\rho$ more negative than the required reactivity for the reactor shutdown. However, additional safety analyses are required to confirm that the control rod scram worth is greater than the minimum shutdown margin.

From fuel cycle analysis, it is observed that the MS^2 concept is capable of stabilizing the PNA. During the Pu, Np and Am (PNA) multi-recycling, the fissile content in PNA vector degraded from 64.2% to 57.7% for 5 recycles but the desired cycle lengths were ensured by increasing the uranium enrichment of the inner fuel from 6.0% to 6.5%. As expected, PNA is burnt and bred in inner and outer zones, respectively. The net mass balance of PNA is 47 kg in cycle 5, which is negligible in comparison to the total PNA mass of the fresh fuel in the inner zone (~3600 kg). Thus, the PNA content is easily stabilized around 15%. However, the discharge mass of the Cm and higher actinides increases up to 9.9 kg in cycle 5, which affects the decay heat and radiotoxicity level of the repository for several decades.

Acknowledgements

This work was supported by the U.S. Department of Energy under Nuclear Energy Research Initiative project, DE-FG03-01SF22328.

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