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SUPERPRISM OXIDE AND METAL FUEL CORE DESIGNS

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ABSTRACT

The SuperPRISM (S-PRISM) modular LMR plant is composed of one or more power blocks. Each power block couples two 1000 MWt nuclear steam supply systems (NSSS) that can operate independently, but feed steam to a single superheat turbine generator system rated at 825 MWe (gross). Several power blocks on a common site can share facilities and staff. A full-size plant is rated at 2286 MWe (net) and includes three power blocks. Because each NSSS is a simple, independent, single loop plant, the modular plant offers a capacity factor superior to that of a large, multi-loop, single reactor plant (93% versus 85%).

To accommodate a wide range of potential owners, national infrastructures and commercialization approaches, the reactor must maintain the capability to operate with both oxide and metal fuel and with a large range of breeding ratios. While oxide fuel has the largest experience base, the metal fuel and pyroprocessing development programs and experience have indicated that significant safety and performance improvements may be possible with metal fuel and also that metal fuel reprocessing will be significantly less costly than oxide. With this history, commercialization of LMRs may initially employ oxide fuel and then transition to metal fuel as a supporting database develops. The reactor can also support a range of breeding ratios with either fuel form to implement potential proliferation-related or waste reduction-related missions.

Four SuperPRISM core designs are presented and their performance characteristics are compared. They are interchangeable within a common geometric envelope and satisfy common performance criteria. One pair of cores, one oxide and one metal fuel, has a target breeding ratio of just over 1.0, fissile breakeven, to minimize the initial fuel cycle cost. The other pair of cores, one oxide and one metal, has a target breeding ratio of 1.2, to support a faster LMR introduction scenario and electric power growth rate.

Current results indicate that the geometric and performance envelope of the SuperPRISM reactor core permits both oxide and metal fuel and that the metal fuel shows significant performance advantages over MOX fuel. The high internal conversion ratio achievable with metal fuel reduces cycle burnup swing to near zero, compared to the oxide core at about 1 % $\Delta k/kk'$ (3$) reactivity loss. The cycle average breeding ratio of the oxide core is limited to about 1.17, while the metal core can exceed 1.25. The oxide core requires about a 50% greater fissile inventory than the metal core, however, the allowable MOX fuel burnup (180 MWd/kgHM) is assumed to be greater than metal (150 MWd/kgHM) and thus the specific burnup is more favorable for MOX fuel. Spatial power peaking is lower in the metal core and leads to numerous thermal and fuel performance advantages.

INTRODUCTION

Following the completion of the DOE sponsored program to design an Advanced Liquid Metal Reactor (ALMR) in 1995, GE proceeded with the development of a more advanced modular fast reactor design called SuperPRISM. The thermal rating of each reactor module has been increased and significant improvements have been made to the containment and steam generating systems. The key features of the ALMR that support economical commercialization and passively safe accident response have been maintained:

- Compact pool-type reactor modules for factory fabrication, and affordable full-scale prototype test for design certification
- Nuclear safety-related envelope limited to the nuclear steam supply system (NSSS) within the reactor building
- Passive accommodation of major ATWS events (loss of flow, loss of cooling and overpower)
- Passive shutdown heat removal and post-accident containment cooling
- Core flexibility to support commercialization needs by: 1) use of any available U or TRU fuel source and recycle technology and 2) support of a range of TRU burning or breeding missions

The reference commercial S-PRISM plant utilizes six reactor modules arranged in three identical 760 MWe (net) power blocks for an overall plant net electrical rating of 2280 MWe. Each power block features two identical reactor modules, each with its own steam generator, that jointly supply steam to one of three 825 MWe (gross) turbine-generator (TG) units located in the TG building. Smaller plant sizes can be constructed by eliminating power blocks. With incremental power block construction, early revenue can be produced by operating an initial power block while constructing subsequent power blocks. Figure 1 illustrates the key elements and layout of the nuclear island of one power block.

With support from TEPCO, the Tokyo Electric Power Company, a joint development program is working to adapt the S-PRISM concept to the Japanese needs. Under that program, oxide fuel is the reference form for commercialization. However, the geometric envelope within the reactor permits transparent core interchangeability. The S-PRISM fuel cycle costs can be reduced during initial deployment by using TRU recycled from spent LWR fuel and thus benefit waste reduction, proliferation resistance and LMR startup costs. Under an assumption of ample TRU availability, LMR fuel cycle costs are reduced with a low breeding ratio. Later, as the LWR spent fuel inventory is depleted, the LMR breeding ratio can be increased to support continued deployment. However, this would increase recycle facility mass through-put and hence increase fuel cycle cost. Finally, since safety and economics advantages are projected for the pyrometallurgical recycle process and metal (U-Pu-Zr) fuel, the reactor can be transitioned to the metal fuel after it is fully developed and qualified. Only the control setpoints and the replaceable inlet/orificing modules that control flow to each assembly need replacement to change cores with the S-PRISM reactor design.

Thus, under the joint program, four interchangeable core designs are being developed: 1) a fissile breakeven MOX core, 2) a fissile breakeven metal core, 3) a high breeding ratio MOX core and 4) a high breeding ratio metal core. The requirements and designs of these four cores are discussed below. Results of initial scoping analyses are also compared.

KEY CORE DESIGN REQUIREMENTS

Core power is 1000 MWt, a 19% increase from the ALMR's 840 MWt.

Core inlet and outlet temperatures are 371°C (700°F) and 510°C (950°F), both increases from the ALMR, to support a more efficient superheat steam cycle.

The cores must maintain common control locations and worth requirement limitations, thus the cycle burnup swing has a "soft limit" of 3.4 % Δk/kk' (10$).

To stay within current oxide fuel technology bases, the oxide fuel TRU enrichment is limited to 33 wt% and burnup is limited to 180 MWd/kgHM. The corresponding metal fuel limits are 30 wt% TRU enrichment and 150 MWd/kgHM.

To stay within the ferritic cladding database, peak fast fluence is limited to 4×10^{23} n/cm^2.

To support passive safety accommodation, the breeding ratio target of the fuel cycle cost optimized core is specified to be about 1.03, or approximately fissile breakeven after out-of-cycle losses. A target breeding ratio of about 1.2 is specified for high breeding cores.

Fuel melting is not permitted for design basis events. Peak reactor power is specified to be 113% at scram.

For feasibility scoping analyses, cladding thermal creep strain is limited to 1%, total diametrial growth to 2% and creep rupture cumulative damage fraction to 0.2 to support cladding reliability requirements.

Although not specifically enumerated here, the overall design, performance and passive safety requirements developed for the ALMR are also applicable.

ASSEMBLY DESIGNS

The generic assembly designs developed by the ALMR program are the bases for S-PRISM core designs. Table 1 lists the key assembly cross-section dimensional parameters for the fuel and blanket assemblies. Table 2 lists the axial dimensions. The drawings in Figure 2 illustrate the assembly configurations. Except for the pin bundles and assembly positional discrimination features, the assemblies all use common components, with the exception of the GEMs (Gas Expansion Module). GEMs are special assemblies placed at the perimeter of the core to enhance neutron leakage and negative reactivity feedback upon loss of primary coolant flow.

Fuel and blanket assemblies use sealed pins to contain the fissile and fertile materials and the fission products. Oxide fuel bundles contain 217 fuel pins in a triangular pitch array. Metal fuel bundles use 271 pins because the higher heavy metal fraction in metal fuel allows lower fissile enrichment and better internal conversion than oxide fuel. Thus, the metal fuel core can satisfy nuclear goals with fewer fuel assemblies and a more compact core. Both metal and oxide blanket bundles have 127 pins. The fission gas plenum is located above the fuel column. Upper axial shielding is provided by the long fission gas plenum region and the sodium pool above the core. Lower axial shielding is provided by long pin end plugs. The lengths of the lower end plugs and upper fission gas plena are adjusted between the core designs such that the core midplane elevation remains constant. Because a high fast fluence is required for economical fuel utilization and high temperatures in the core are required for plant efficiency, HT9M is required for the cladding. HT9 is satisfactory for the remaining core components.

Reflector assemblies contain pin bundles of solid HT9 rods. The GEMs also use a short pin bundle of HT9 rods for lower axial shielding. The shield assemblies use large tubes filled with boron carbide for radial shielding. Boron carbide is also used in the control assemblies.

The hexagonal assemblies have an overall length of 4775 mm (188 in). The assemblies are 161.2 mm (6.345 in) across flats at the load pads and allow a 0.25 mm (0.010 in) gap at the load pads. The duct to duct gap is 4.32 mm (0.170 in) along the remainder of the assembly and the duct wall thickness is 3.94 mm (0.155 in).

GEMs include a solid HT9 shield block between the duct and handling socket to define and seal the top end of the gas expansion chamber and to provide holddown weight. Thus, the GEMs have a shorter duct containing the core-region gas expansion chamber and the lower axial shielding rod bundle. The duct is also thicker than in the other assemblies to limit radial strain caused by the higher internal pressure resulting inside an assembly without flowing sodium friction pressure losses. The outer surface shape of the GEM matches that of the other assemblies and only the internal components vary from the other assemblies.

CORE CONFIGURATION AND FUEL MANAGEMENT

Small oxide cores are relatively inefficient from the point of view of neutron conservation. As a result, the ratio of fertile to fissile material in the driver core region must be high. Since the cores are of the radial heterogeneous configuration to minimize fuel fabrication costs, the ratio of internal blanket assemblies to fuel assemblies must be large. As shown in Figure 3, there are 162 fuel assemblies and 73 internal blanket assemblies. The overall core is made up of 541 assemblies. In addition to the driver core region, there are 60 radial blanket assemblies, 138 reflector assemblies, 78 shield assemblies, 18 GEMs, 9 control and shutdown assemblies and 3 secondary shutdown assemblies.

Based on a balancing of the nuclear requirements, the driver core height is specified as 1372 mm (54 in). The resulting cycle length is 24 months and the fuel remains in-core for four cycles.

The metal core layout is shown in Figure 4. There are 138 fuel, 49 internal blanket and 48 radial blanket assemblies. Since the driver core is smaller in diameter, the numbers of reflector and shield assemblies are also reduced. The harder spectrum and smaller core diameter also reduce the required number of GEMs. For the desired balance of nuclear performance characteristics, the core fabricated height is specified as 1016 mm (40 in). For the Pu fraction used, the core axially swells 5% to a height of 1067 mm (42 in) The cycle length is 23 months and the fuel remains in-core for three cycles.

Blanket shuffling is used to reduce burnup swing, flatten the radial power profile and to improve coolant flow orificing and the resulting core temperatures. The shuffle patterns are shown in Figure 5. The oxide core has blanket assemblies with both four and five cycles of residence. Blanket life in the metal core is 4 cycles.

Without axial blanket regions, both oxide and metal fuel cores achieve a breeding ratio close to the breakeven target, 1.03 for oxide fuel and 1.05 for metal fuel. Axial blanket zones are added to the fissile breakeven cores to convert them into high breeding ratio cores. Figure 6 plots the results of sensitivity analyses of breeding as a function of axial blanket height. Because longer blanket zones reduce fission gas plenum volume and add heavy metal throughput to the recycle system along with diminishing amounts of fissile fuel, there are fuel performance and economic incentives to minimize the axial blanket length. Based on engineering judgement, oxide core axial blankets are specified to be 304 mm (12 in) tall, while metal core axial blankets are set at 203 mm (8 in). With the added axial blankets, both cores are close to the high breeding ratio target, yielding cycle average breeding ratios of 1.17 for oxide and 1.22 for metal. The data in the figure also indicate the limited potential to increase the oxide core breeding ratio within the core geometric envelope. In contrast, the metal core can be modified to reach a breeding ratio of 1.3.

CORE PERFORMANCE COMPARISON

S-PRISM core design and analysis is at an early stage. Nuclear, thermal-hydraulic, pin thermal and structural, duct radial dilation and GEM response analyses are used to judge the probable acceptability of these cores. Table 3 summarizes core performance predictions for the cores.

The improved heavy metal fraction in metal fuel reduces the required fissile enrichment, even with the smaller pins, and thus improves internal conversion and cycle burnup swing. The smaller metal core, with a harder spectrum, also has smaller spatial power peaking factors. This allows a higher average pin linear power and less total pin length while maintaining the same peak linear power in both cores. By improving neutronic efficiency, the metal core is smaller and requires significantly less fuel inventory. The fissile inventory of the metal core is only about 65% of that required for the oxide fuel core. The uranium inventory is also reduced by 25% compared to the oxide core.

Given the fuel technology limits selected, the oxide core life is limited by fuel burnup. The harder spectrum and higher flux in the metal core cause it to be limited by both cladding fast fluence and fuel burnup.

Comparison of fissile breakeven and high breeding ratio cores using the same fuel type shows that a large increase in heavy metal and small increase in fissile inventory is caused by the addition of the axial blankets. The average fissile fraction of heavy metal passing through a recycle facility is thus less and the total throughput is greater with the high breeding ratio cores. As a result, the fuel cycle cost would be expected to be greater with high breeding ratio cores.

The four cores show good thermal-hydraulic performance and meet all constraints and criteria. However, the metal core passes the same coolant flow through fewer assemblies with more pins. The metal cores thus have a higher pressure drop. The higher pressure drop improves GEM performance, but increases primary loop pumping power and duct radial creep growth. While there is ample duct creep growth margin remaining at end of life in the oxide core, the metal core duct growth exceeds the conservative screening limit and must take advantage of the experience-based limit that is less conservative.

The reduced spatial peaking factors in the metal core also reduce peak temperatures in the assemblies compared to the oxide cores. This difference benefits the near-core reactor structures with reduced thermal aging and thermal striping (high cycle thermal fatigue) temperatures. Pin cladding performance also improves with the reduced metal core temperatures and the larger gas plena allowed by the shorter metal cores.

The four cores are slightly larger in diameter than the 840 MWt ALMR core. This change increases the flux at the core barrel and the surrounding reactor structures. Shielding analyses are required to confirm acceptability of the designs. Since a large sodium-filled annulus separates the core from the barrel, there is ample room for the addition of removable radial shielding. Thus, the current uncertainty in shielding is acceptable.

Also, the passive safety performance of S-PRISM relies on core reactivity feedbacks. Plant transient analyses of beyond design basis events are required to confirm acceptable safety characteristics. This current performance uncertainty is also acceptable because; 1) the cores and reactor configuration are quite similar to the well-analyzed ALMR design and thus performance is not expected to differ significantly and 2) the passive safety transient performance is not totally dependent upon core reactivity feedbacks. During unprotected loss of flow and cooling events, transient performance is dominated by the GEMs and their performance is shown to be satisfactory with the current thermal-hydraulic scoping analyses. Likewise, the overpower event performance is dominated by the SASS and rod stop systems and is thus not totally dependent upon the core feedback.

CONCLUSIONS

Results to date indicate that both oxide and metal cores for SuperPRISM will show good performance and reliability characteristics. More detailed analyses should be performed. Significant advantages are indicated for the metal fuel form. The fissile breakeven cores show a significantly lower heavy metal inventory and recycle through-put compared to high breeding ratio cores, thus high breeding will be expected to result in increased fuel cycle cost with either fuel form.

Under the imposed passive safety and plant performance requirements, the core geometric envelope accommodates oxide cores with a cycle average breeding ratio ranging from less than 1.0 to about 1.18. Metal fuel cores can span a range from less than 1.0 to about 1.3. Thus, the modular plant concept can support a wide range of core breeding missions as required by the TRU available from the host economy, and can use oxide or metal fuel, depending on availability.

Table 1. SuperPRISM Fuel And Blanket Assembly Cross-Section Dimensional Data

Fuel Type	Oxide				Metal			
Assembly Type	Fuel		Blanket		Fuel		Blanket	
	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)
Assembly Pitch	6.355	161.42	6.355	161.42	6.355	161.42	6.355	161.42
Duct Gap	0.170	4.32	0.170	4.32	0.170	4.32	0.170	4.32
Duct Wall Thickness	0.155	3.94	0.155	3.94	0.155	3.94	0.155	3.94
Load Pad Gap	0.010	0.25	0.010	0.25	0.010	0.25	0.010	0.25
Pin Count	217		127		271		127	
Pin Outer Diameter	0.335	8.51	0.473	12.01	0.293	7.44	0.473	12.01
Pin Cladding Wall Thickness	0.0250	0.635	0.0220	0.559	0.022	0.559	0.022	0.559
Fuel Outer Diameter	0.2779	7.059	0.4236	10.759	0.2156	5.477	0.3955	10.046
Pin Spacer Type	SSWW *		SSWW *		SSWW *		SSWW *	
Spacer Pitch	8.0	203.2	8.0	203.2	8.0	203.2	8.0	203.2
Spacer Wire Diameter	0.055	1.397	0.037	0.940	0.056	1.422	0.037	0.940
Fuel Fabrication Density (% of Theoretical Density)	89.4		95.4		100.0		100	
Fuel Smeared Density (% of Theoretical Density)	85		93		75		85	
Volume Fractions (%, before irradiation)								
Fuel	37.63		51.17		28.30		44.61	
Bond (Fuel-Cladding Annulus)	1.95		1.32		9.43		7.87	
Coolant	34.57		26.54		36.57		26.54	
Structure	25.85		20.97		25.70		20.97	

* SSWW Straight start wire wrap

Table 2. SuperPRISM Fuel And Blanket Assembly Axial Dimensional Data

Core Type	Oxide Breakeven		Oxide Breeder		Metal Breakeven		Metal Breeder	
Assembly Axial Segment	**(in)**	**(mm)**	**(in)**	**(mm)**	**(in)**	**(mm)**	**(in)**	**(mm)**
Upper Handling Socket (Total)	12.00	304.80	12.00	304.80	12.00	304.80	12.00	304.80
(Handling Socket - Duct Overlap)	(0.27)	(6.86)	(0.27)	(6.86)	(0.27)	(6.86)	(0.27)	(6.86)
Duct Standoff	1.75	44.45	1.75	44.45	1.75	44.45	1.75	44.45
Pin - Upper End Plug	1.00	25.40	1.00	25.40	1.00	25.40	1.00	25.40
Pin - Upper Plenum	67.25	1708.15	55.25	1403.35	75.25	1911.40	67.65	1718.30
Pin - Upper Axial Blanket			12.00	304.80			8.00	203.20
Pin - Core	54.00	1371.6	54.00	1371.60	40.00 *	1016.00 *	40.00 *	1016.00 *
Pin - Lower Axial Blanket			12.00	304.80			8.00	203.20
Pin - Lower End Plug	38.00	965.20	26.00	660.40	44.00	1117.60	35.60	904.24
Pin (Total)	160.25	4070.35	160.25	4070.35	160.25	4070.35	160.25	4070.35
(Pin - Grid Overlap)	(0.36)	(9.14)	(0.36)	(9.14)	(0.36)	(9.14)	(0.36)	(9.14)
Support Grid	2.04	51.82	2.04	51.82	2.04	51.82	2.04	51.82
(Grid - Nosepiece Overlap)	(0.68)	(17.27)	(0.68)	(17.27)	(0.68)	(17.27)	(0.68)	(17.27)
Duct (Total)	164.47	4177.54	164.47	4177.54	164.47	4177.54	164.47	4177.54
(Duct - Nosepiece Overlap)	(1.20)	(30.48)	(1.20)	(30.48)	(1.20)	(30.48)	(1.20)	(30.48)
Nosepiece (Total)	13.00	330.20	13.00	330.20	13.00	330.20	13.00	330.20
Assembly Total Length	188.00	4775.20	188.00	4775.20	188.00	4775.20	188.00	4775.20

* Metal core height: 40.00 inches (1016 mm) as fabricated.
5% axial swelling estimated for the Pu enrichment used, results in 42 inch (1067 mm) total core height.

Table 3. SuperPRISM Core Options Performance Comparison

	Cost Optimized MOX	Cost Optimized Metal	High Breeding MOX	High Breeding Metal	Limit
Cycle Average Breeding Ratio	1.03	1.05	1.17	1.22	
Cycle Burnup Reactivity Loss (% dk/kk')	0.98	0.12	0.81	-0.31 (gain)	3.4
Core Inventory at BOC Fissile Pu (kg - kg/MWt) Total TRU (kg) Total U (kg)	 3469.4 - 3.47 5207.7 29718.5	 2336.1 - 2.34 3078.2 23014.2	 3612.2 - 3.61 5341.0 45939.5	 2458.8 – 2.46 3195.9 33052.7	
Feed Enrichment (wt.%, Total Pu in U-TRU)	29.81	21.42	29.61	21.29	33
Supplied Fissile Pu - kg/year - kg/GWDt	411.20 1.32	366.16 1.18	408.40 1.32	363.97 1.17	
Fissile Pu Gain (kg/year)	11.15	19.25	57.10	69.91	
TRU Consumption Rate (kg/year)	-38.60 (gain)	-33.60 (gain)	-85.60 (gain)	-84.63 (gain)	
Cycle Average Spatial Power Peaking Factor	1.54	1.41	1.54	1.42	
Average Linear Power (kW/m, Cycle Average)	15.97	18.90	15.66	18.32	
Peak Linear Power (kW/m) - Fuel - Internal Blanket - Radial Blanket	30.14 27.16 17.76	30.42 40.25 30.70	29.65 26.45 17.33	29.77 38.30 29.80	40
Peak Neutron Flux (10^{15} n/cm^2-s) - Total - Fast	2.38 1.38	3.62 2.47	2.33 1.36	3.49 2.37	
Average Fuel Burnup (MWd/kg) Peak Fuel Burnup (MWd/kg) Peak Fast Fluence, Fuel-Blanket (10^{23} n/cm^2)	116 178 2.96 - 2.44	106 149 3.71 - 3.90	114 175 2.91 - 2.40	103 145 3.61 – 3.79	 180 4.0
Core Thermal Hydraulic Performance Pressure Drop (MPa) Maximum Assembly Outlet Temp. (C) Maximum Subchannel Coolant Temp. (C) Thermal Striping Potential (C) Thermal Constraints Satisfied GEM Full-Core Stroke	Good 0.31 619 678 197 Yes Yes	Good 0.41 595 648 189 Yes Yes	Good 0.31 620 679 197 Yes Yes	Good 0.43 594 648 194 Yes Yes	 0.48 621 887 206
Peak Fuel Pin Steady State Performance (HT9M) Maximum Creep Rupture Damage Fraction Maximum Total Diametrial Growth (%) Maximum Thermal Creep Strain (%) Minimum Power To Melt at Centerline (%) Maximum Power To Melt at Surface (%)	Good 0.0026 0.69 0.37 150	Good 0.00003 0.42 0.07 138 113	Good 0.0023 0.76 0.37 150	Good 0.00006 0.49 0.08 133 113	 0.2 2.0 1.0
Duct Structural Performance (HT9) Maximum Radial Growth (mm)	Good 1.7	Acceptable 2.3	Good 1.2	Acceptable 2.2	2.2 (Cons) 3.2 (Exp)

Cost Optimized Compared To High Breeding

Axial blankets increase Pu and U masses through recycle facility (Increase cost per kg fissile), and increases fissile Pu

Metal Compared To Oxide

Breeding potential in SP2 core envelope: Oxide - approximately 1.17 Metal - greater than 1.22

Metal fuel heavy metal packing fraction improves:
- ***internal conversion***
- ***cycle burnup swing***
- ***fissile Pu requirement***
- ***U requirement***
- ***core diameter and height***
- ***spatial power peaking***

For same peak linear power, lower spatial peaking in metal allows higher average linear power (less total pin)

Oxide core life limited by fuel burnup
Metal core life limited by fuel burnup and cladding fluence

Metal core pressure drop increases with fewer assemblies and more pins per assembly

Both oxide and metal cores require HT9M cladding due to peak cladding temperature. Lower metal core peaking factor reduces peak temperatures and cladding damage.

Metal core has no eutectic melting for all design basis events (up to scram). However, beyond design basis events may be limited by cladding wastage limit of 10% or may require development of barrier cladding.

Metal core higher pressure drop increases duct radial growth beyond conservative limit, towards empirical (experimental) limit

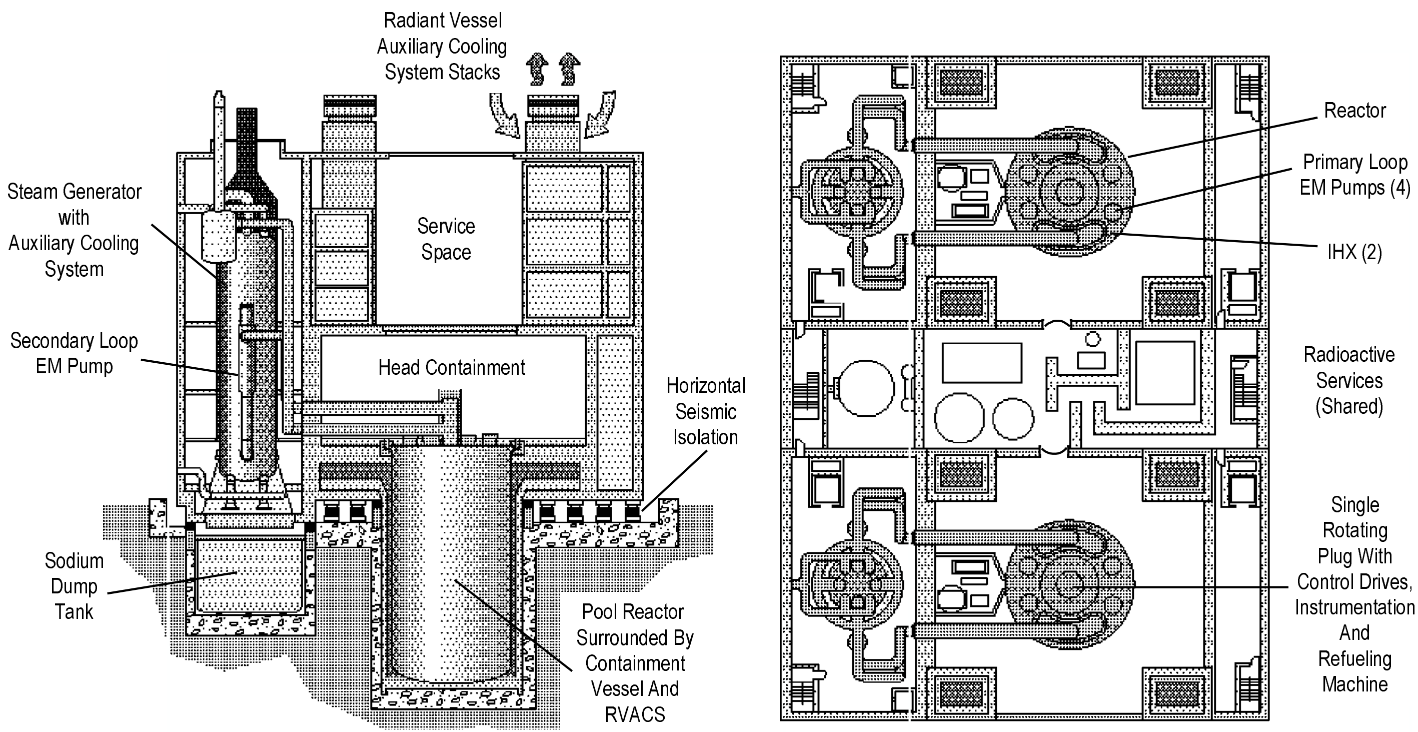

Figure 1. SuperPRISM Power Block Nuclear Island

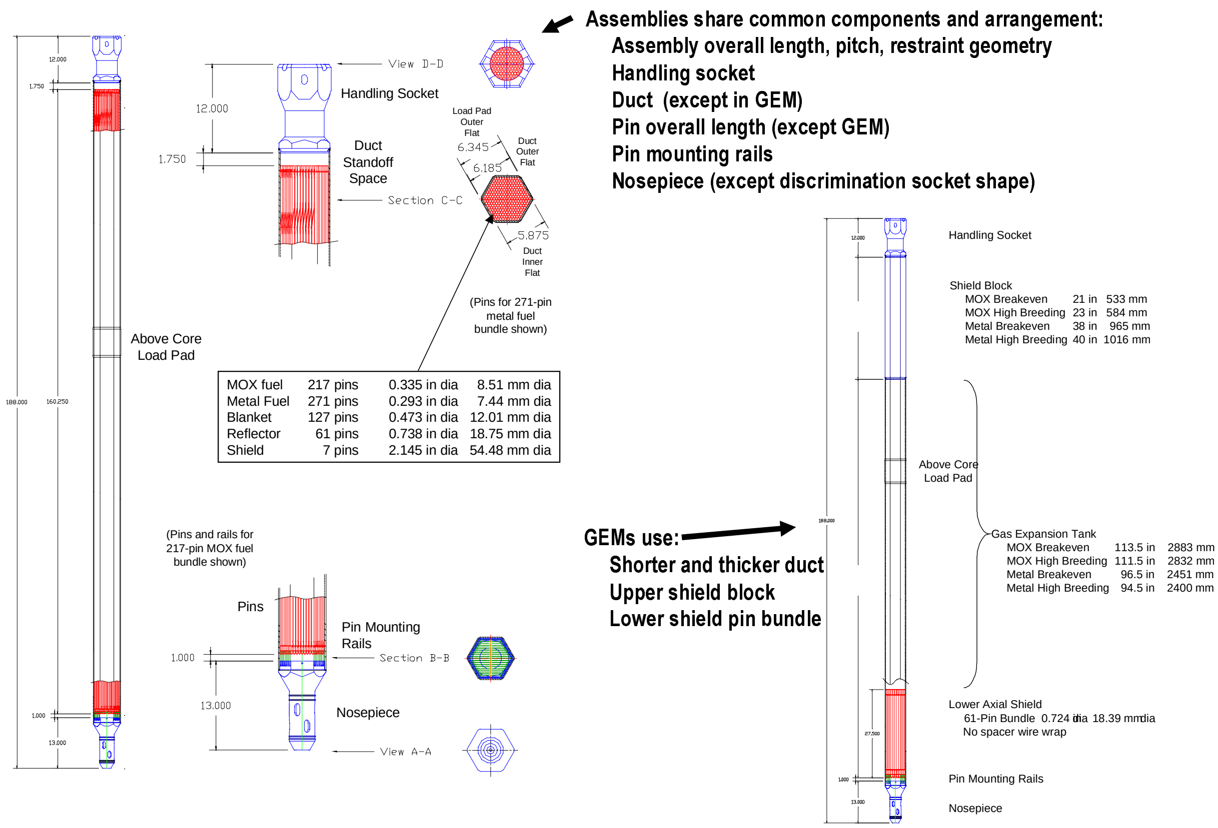

Figure 2. SuperPRISM Core Assembly Drawings

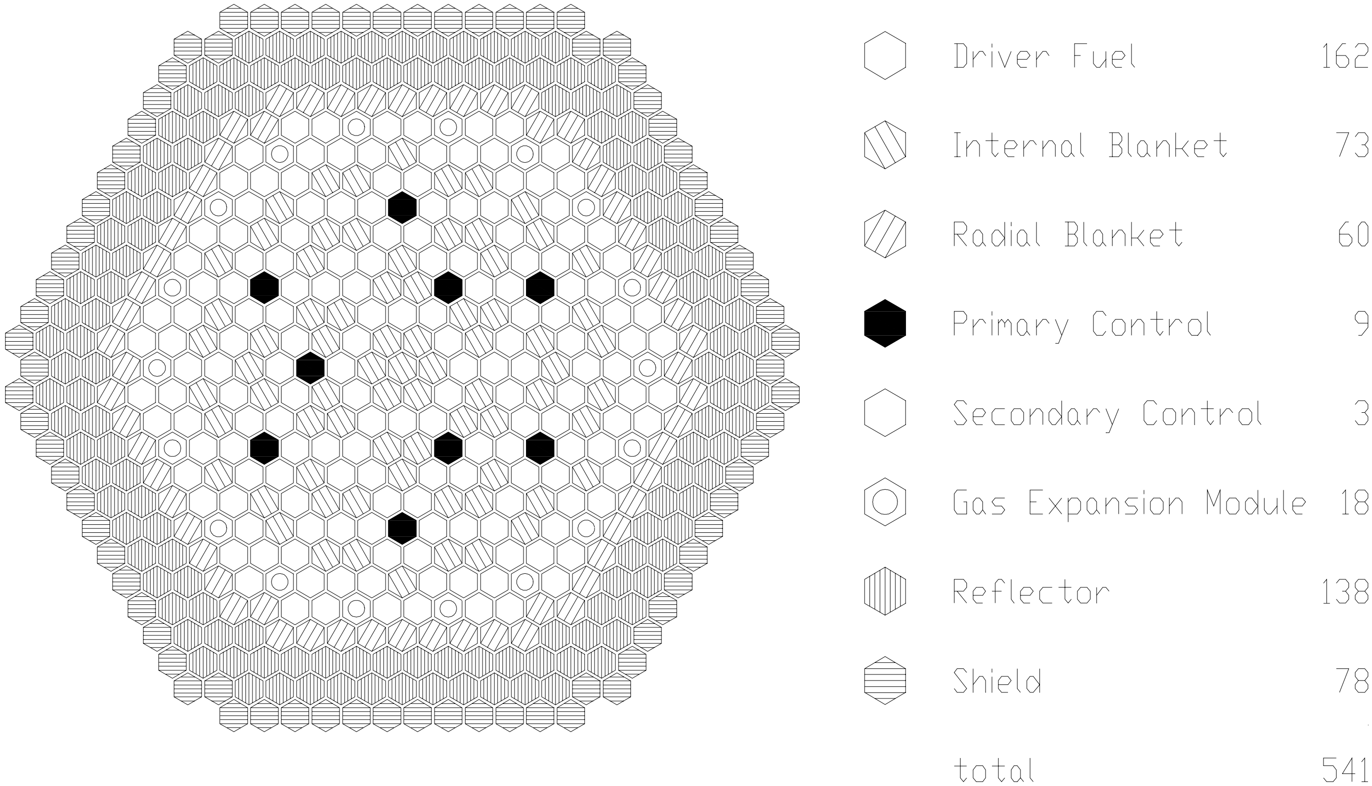

Figure 3. SuperPRISM Oxide Core Configuration

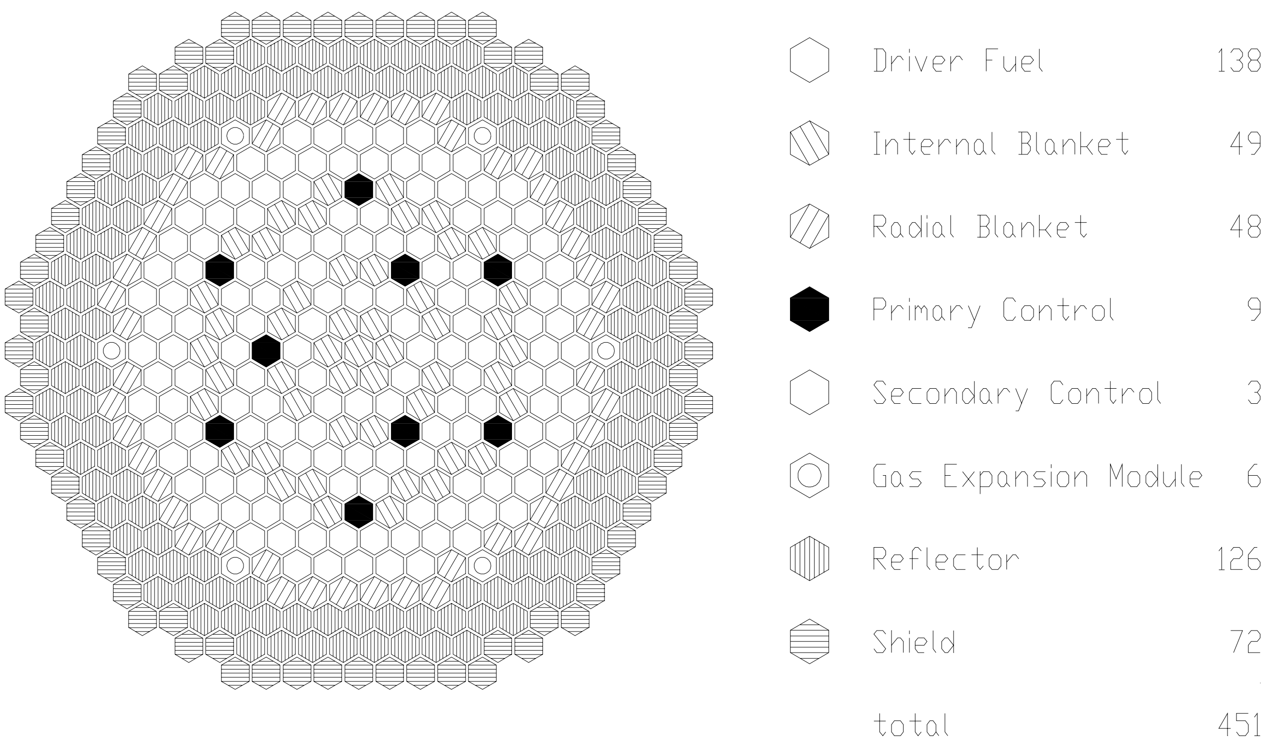

Figure 4. SuperPRISM Metal Core Configuration

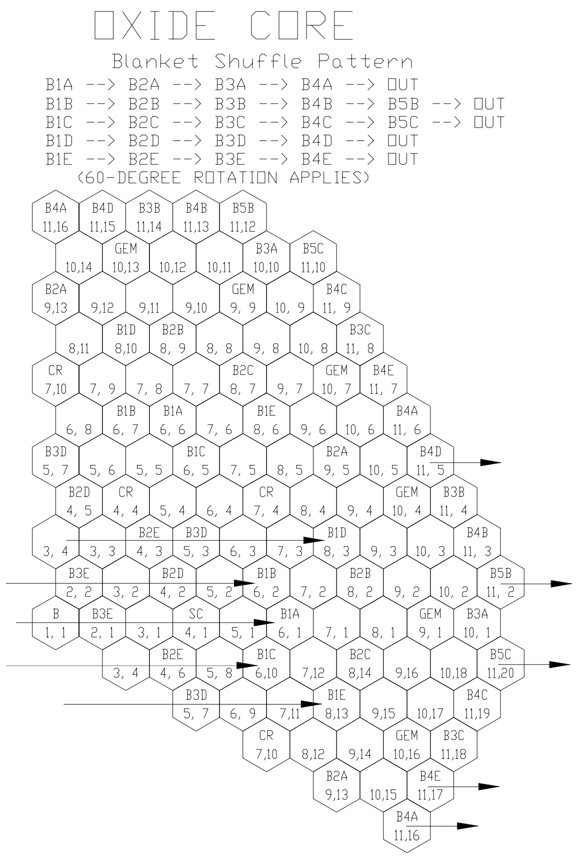

Figure 5. Blanket Shuffle Patterns

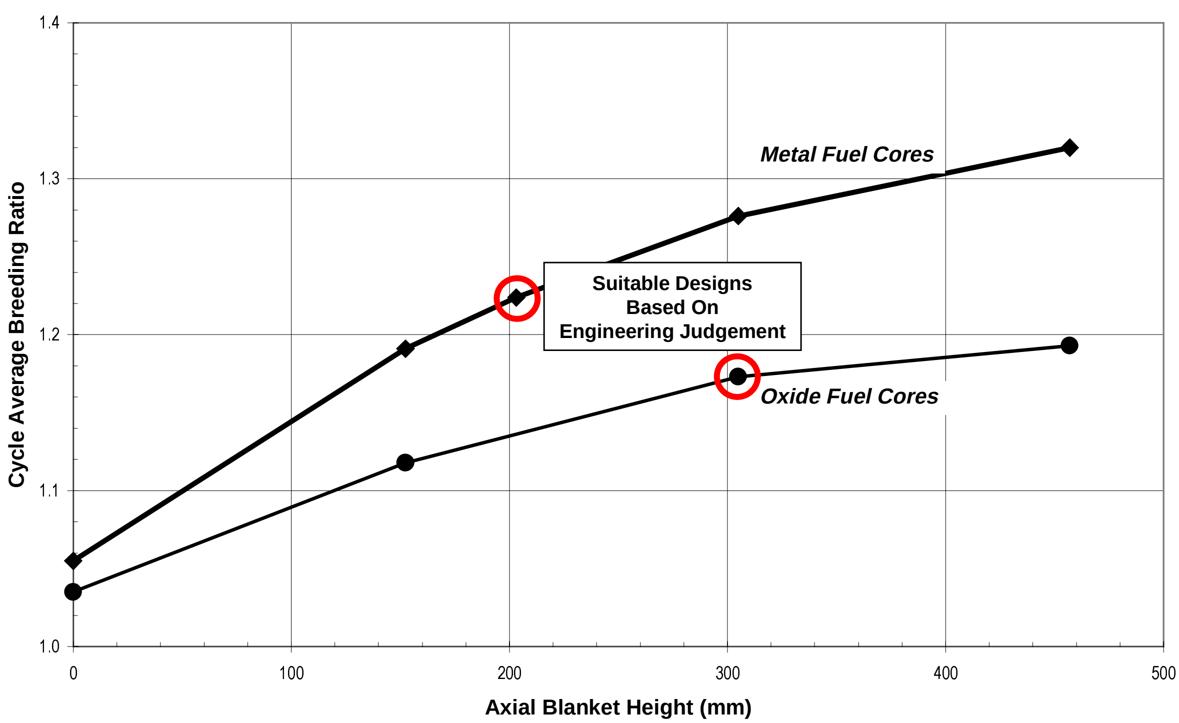

Figure 6. Sensitivity Of Breeding As A Function Of Axial Blanket Zone Length