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PERFORMANCE POTENTIAL OF (Th,U) CARBIDE AND (Th,U) NITRIDE
FUEL IN 1200 MWE LMFBR'S*

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ABSTRACT

An evaluation of the performance potential of thorium-uranium carbide and nitride fuel in 1200 MWe homogeneous and heterogeneous LMFBR's has been completed. Comparisons were done with 9.40 mm outer diameter, 0.38 mm cladding fuel pins at a selected peak (3 σ) linear power of 98.4 kW/m for all cores. Breeding ratios for the homogeneous (Th,U)C and (Th,U)N cores are 1.12 and 1.16, respectively. In the heterogeneous cores the breeding ratios are 0.08-0.09 greater. A comparative breeding ratio of 1.48 results for a sodium-bonded (U,Pu)C homogeneous LMFBR with similar design criteria.

Compound inventory doubling times for the homogeneous and heterogeneous (Th,U)C cores are 82 and 53 years, respectively. The enriched nitride cores, with a higher fuel density, show a large improvement in doubling time for the two core concepts, 53 and 46 years. The (U,Pu)C homogeneous core has a 10 year doubling time.

Additional performance parameters have also been compared, including sodium void worths, specific inventories, fissile material gains, and equilibrium cycle reactivity losses.

INTRODUCTION

An evaluation of the performance potential of thorium-uranium carbide and nitride fuel in 1200 MWe homogeneous and heterogeneous LMFBR's has been completed. Fuel pin dimensions and linear powers previously identified as optimum for uranium-plutonium carbide LMFBR objectives of minimum doubling time, fuel cycle cost and uranium ore requirements have been applied to provide comparable base points for determination of thorium-uranium fuel potential.

*Prepared as an account of work sponsored by the U.S. Department of Energy.

1200 MWe CORE DESIGNS

Core design parameters for the homogeneous and heterogeneous reactors are shown in Table 1. For all cores studied, the fuel pin diameter is 9.40 mm with 0.38 mm CW 316 SS cladding. A sodium-bonded pin design was assumed, with a fuel smear density of 85% T.D. (theoretical density) for the (Th,U) cores and 78% T.D. for the (U,Pu) core. A peak (3σ) linear power of 98.4 kW/m was selected for this pin based on (U,Pu)C optimization studies.¹

With design conditions of 98.4 kW/m peak linear power (3σ), 167°C reactor mixed mean ΔT , and a 7.92 m/sec peak coolant velocity, a fuel pin P/D ratio of 1.192 was required. A 510°C mixed mean reactor outlet temperature results in a 36% thermal efficiency.

With CW 316 SS, a two-year fuel residence time was chosen at a 70% capacity factor for both the homogeneous and heterogeneous cores. Two fuel enrichment zones were applied for radial power flattening in both concepts. In the heterogeneous core, rings of two rows of core assemblies alternate with single rows of internal blanket assemblies. Both the homogeneous and heterogeneous cores have a two-row radial blanket.

Assembly duct and gap dimensions were selected to accommodate irradiation-induced swelling and creep deformations* without assembly interference at end-of-life for the 91-pin assemblies. The minimum fuel cell size configuration was selected from the feasible spectrum of duct designs for each core, therefore maximizing the fuel volume fraction. The lower damage flux levels inherent to heterogeneous cores are reflected in the advantage of a thinner duct wall and smaller inter-assembly gap for the heterogeneous assembly.

Carbide and nitride (fully-enriched N-15) thorium-uranium fuel performance potentials were determined in both the homogeneous and heterogeneous cores. Two uranium feed isotopic compositions with thorium were studied for intercomparisons: 75.2% U-233, 21.1% U-234, 3.0% U-235, and 0.7% U-236, based upon LMFBR thorium fuel equilibrium recycle (FBR U), and 38.0% U-233, 9.2% U-234, 36.5% U-235, and 16.3% U-236, based upon PWR discharge uranium from a once-through thorium cycle.² The PWR uranium feed (PWR U) was evaluated to determine the effect on thorium LMFBR performance of U-233 produced in typical LMFBR's. Since there is no stockpile of U-233, a symbiotic LWR-LMFBR system may be necessary for initiation of a LMFBR closed thorium cycle.

As shown in Table 1, the theoretical densities of the thorium fuels are less than the uranium fuels. Core heavy metal inventories are therefore based on the density of the feed linear combination of required uranium and thorium. As a result, thorium axial blankets, at the same smear density as the core, have a lower heavy metal density than the core,

*CW 316 SS Swelling Revision 5, Creep Revision 3

increasing their neutron leakage relative to uranium fuel designs.

ANALYSIS METHODS

Uncontrolled R-Z burnup studies were completed from clean core conditions through an equilibrium cycle, with 21 group ENDF/B-4 cross sections, for all thorium cores studied. Mass balances were obtained using the following burnup chain:

U-233 and U-235 were identified as fissile materials for thorium fuel breeding performance calculations; Th-232 and U-234 were considered fertile. Pa-233 was not considered a fissile material for reaction rate breeding ratios or enrichments. However, the amount of Pa-233 in discharged fuel was included in equilibrium cycle fissile mass gains, since it would decay to U-233 out-of-reactor.

Doubling times were calculated with the following compound inventory doubling time definition:

$$IDT_C = \frac{.693 \text{ (OPERATING INVENTORY)}}{\text{MASS GAIN-(L) (TOTAL FISSILE DISCHARGE)}}$$

where: Operating Inventory = 3 feed fissile fuel assembly batches
(2 in-reactor, 1 out-of-reactor), kg_{fiss}

Mass Gain = Pa-233 + U-233 + U-235 mass gain per calendar year,
kg/yr

L = fissile reprocessing and refabrication loss fraction

Total Fissile Discharge = Pa-233 + U-233 + U-235 mass discharge
per calendar year, kg/yr

The out-of-reactor time assumed was one year; the fissile reprocessing and refabrication loss fraction was 2%.

Specific inventories quoted are defined as kg_{fiss} per MWe, based on operating inventories.

COMPARISON OF (Th,U) CARBIDE AND NITRIDE LMFBR PERFORMANCE

Core performance parameters for the homogeneous and heterogeneous reactors studied are compared in Table 2. Included is a comparison to

the principal parameters of a sodium-bonded (U,Pu)C homogeneous LMFBR with similar design criteria using PWR once-through plutonium feed material. The thorium-nitride performance is based upon fully-enriched N-15, removing the deleterious absorptions of N-14 while taking advantage of the higher density of nitride fuel.

Middle-of-equilibrium cycle (MOEC) breeding ratios for homogeneous carbide and nitride thorium-uranium cores with FBR recycle uranium feed are 1.12 and 1.16, respectively. In the heterogeneous cores, the breeding ratios are 0.09-0.08 greater for the carbide and nitride fuels, 1.21 and 1.24, respectively. These breeding ratios, while much lower than the value of 1.48 for the (U,Pu)C homogeneous core, are sufficient to provide net gains in fissile fuel. The PWR uranium feed (Th,U)C homogeneous core is not self-sustaining with a breeding ratio of 0.97, less than one due to the large fraction of U-235 in the PWR uranium feed (36.5%)

In the PWR uranium fueled LMFBR, U-233 is retained at the expense of burning out residual U-235 from the initial PWR U-235 enriched thorium.² Although this fuel cycle does not show a net gain in fissile material with burnup, it does produce the most U-233 per cycle of all the cores studied, including the heterogeneous cores (e.g., 234 vs. 87 kg U-233). Use of once-through PWR uranium fuel may be a desirable route to an eventual (Th,U) LMFBR economy as a result of the lack of a U-233 stockpile.

Breeding ratios for the (Th,U) cores demonstrated a strong, non-linear time dependent behavior from beginning to end of equilibrium cycle (BOEC to EOEC):

	<u>BOEC</u>	<u>MOEC</u>	<u>EOEC</u>
Homogeneous (Th,U)C Core	1.091	1.121	1.133
Heterogeneous (Th,U)C Core	1.203	1.211	1.207

Calculation of fissile mass gains from these instantaneous breeding ratios would require consideration of this time dependent behavior as well as consideration of Pa-233 neutron interaction rates. Fissile mass gains were therefore computed by mass balance methods. As shown in Table 2, the mass gain of Pa-233, with its out-of-reactor decay to U-233, is very significant with respect to the total fissile mass gain in these reactors.

Due largely to the high fuel enrichments necessary for the heterogeneous cores (about 60% greater than for homogeneous cores), reactor specific inventories for heterogeneous cores are about 2.3 kg_{fiss}/MWe higher than those for homogeneous cores. The lowest specific inventory for the (Th,U) cores is 15% greater than the (U,Pu)C homogeneous core value. The high thorium fuel fissile uranium enrichments also mean that a high fraction of the total uranium-thorium heavy metal is uranium, 29.8% for the outer zone carbide heterogeneous feed fuel.

Despite their high fissile inventories, the heterogeneous reactors

show lower doubling times than the homogeneous reactors. Compound inventory doubling times for the homogeneous and heterogeneous thorium-uranium carbide cores are 82 and 53 years, respectively. The nitride cores, with a higher fuel density, show a large improvement in doubling time for the two design concepts, 53 and 46 years, respectively. In comparison to thorium fuel performance, the uranium-plutonium homogeneous core, with a lower fuel pin smear density (78% vs. 85%), has a 10 year doubling time. However, since no core design optimization was performed for either the homogeneous or heterogeneous thorium designs, their doubling times may not be exactly representative or characteristic of optimized cores.

The doubling times calculated, as a result of their magnitudes, are very sensitive to methods, models, definitions, and system constants. For the 82 year doubling time homogeneous (Th,U)C LMFBR, variation in the plant capacity factor from 60% to 80% would result in doubling times from 111 to 65 years. Reducing reprocessing losses to 0.5% from the 2.0% level would result in a 51 year compound inventory doubling time, vs. 82 years, with plant operation at the reference 70% capacity factor.

Large equilibrium cycle reactivity swings of about 4% Δk characterize the burnup behavior of the low conversion ratio homogeneous thorium cores. More modest reactivity changes (less than 2% Δk) were observed for the heterogeneous cores. With its high core conversion ratio, the equilibrium cycle reactivity swing of the (U,Pu)C pin is 3.1% Δk smaller than for the comparable (Th,U)C homogeneous core.

Peak damage fluxes, and consequently the damage fluences to structural material, are 30% lower in the heterogeneous than in the homogeneous cores. With the imposed two-year cycle time and a 70% capacity factor, the maximum damage fluence in the homogeneous thorium cores is 1.7×10^{23} n/cm² and 1.2×10^{23} n/cm² in the heterogeneous cores. As shown by the damage flux fractions, the thorium fuel produces a harder neutron spectrum than the uranium-plutonium core. In the homogeneous cores, the peak damage flux level of the thorium cores is 10% less than in the (U,Pu) core.

End-of-equilibrium cycle core sodium void worths were calculated by eigenvalue differences using unmodified cross section data. In contrast to plutonium fuel characteristics, the end-of-equilibrium cycle core sodium void worths of all the thorium-uranium designs, homogeneous or heterogeneous, are negative. The heterogeneous core design concept does not appear necessary with thorium fuel to obtain low sodium void worths.

CONCLUSIONS

Comparison of the thorium-uranium cores studied with the uranium-plutonium carbide homogeneous core, all with similar design criteria and considering only use of a 9.40 mm O.D. fuel pin at 98.4 kW/m (3 σ), shows

the breeding and economic performance of the five thorium cores studied to be far inferior to the optimum sodium-bonded (U,Pu)C concept. With the (U,Pu) fuel homogeneous core, a breeding ratio of 1.48 and a doubling time of 10 years result, while the best thorium values, in a heterogeneous core, are 1.24 and 46 years. This performance difference exists despite core and blanket pin fuel smear densities significantly greater in the thorium than the plutonium core (85% vs. 78%). If thorium fuel pin smear density design limits are less than the 85% T.D. assumed here, extremely long doubling times will result.

With thorium fuel there are large doubling time and economic incentives to improve the total fuel cycle by reducing out-of-reactor fissile fuel losses, reducing out-of-reactor reprocessing time and increasing the reactor capacity factor. The (U,Pu)C fuel performance is much less sensitive to reprocessing sophistication and plant availability.

With the thorium-uranium cycle, use of once-through LWR discharge uranium to fuel LMFBR's in a symbiotic system may be expedient for generation of a U-233 stockpile and initiation of a LMFBR closed thorium cycle, since this combination produces the most U-233 per year of the (Th,U) cores evaluated.

In contrast to plutonium fuel characteristics, core sodium void worths for all of the thorium-uranium fuel designs studied are negative. The homogeneous core worths are more negative than the heterogeneous cores. The heterogeneous core design concept does not appear necessary with these thorium-uranium carbide LMFBR's to obtain low sodium void worths.

Neither the homogeneous nor the heterogeneous (Th,U) cores in this study were optimized for breeding performance, but considered fixed pin and assembly designs. Optimization of fuel pin, assembly, and core designs for alternate fuels, including consideration of thorium-plutonium and U-238/U-233 denatured fuel, should enhance thorium fuel utilization in LMFBR's.

REFERENCES

1. S. A. Caspersson, et al, "Optimization System Design Studies of Advanced Carbide Fuel," Advanced LMFBR Fuels Topical Meeting Proceedings, ERDA 4455 (October, 1977).
2. N. L. Shapiro, et al, Assessment of Thorium Fuel Cycles in Pressurized Water Reactors, EPRI-NP-359 (February, 1977).

Table 1

1200 MWe LMFBR Core Designs for Evaluation of
(Th,U) Carbide and Nitride Fuels

<u>Core Design Type</u>	<u>Homogeneous/Heterogeneous</u>
Fuel Pin Outer Diameter (mm)	9.40
Cladding Thickness (mm)	0.38
Fuel Pin P/D	1.192
Fuel Pins/Assembly	91
Duct Inner FTF (mm)	110.10
Duct Wall Thickness (mm)	3.05/2.79
Inter-Assembly Gap (mm)	4.32/3.30
Core Height (cm)	91.44
Axial Blanket Height (cm)	45.72
Peak Linear Power, 3σ (kW/m)	98.40
Structural Material	20% CW 316 SS
Core Full Power Days	511
Capacity Factor	0.70
Core Refueling Fraction	1/2
Number of Enrichment Zones	2
Number of Assemblies	
Core	666/573
Control	37/33
Inner Blanket	---/307
Radial Blanket	210/234
Reactor T_{out} (°C)	510
Reactor ΔT (°C)	167
Thermal Efficiency (%)	36
Peak Coolant Velocity (m/sec)	7.92
Fuel Theoretical Densities (gm/cm ³)	
ThC; UC	10.6; 13.6
ThN; UN	11.9; 14.3

Table 2

Comparison of 1200 MWe LMFBR Core Performance Data with (U,Pu)C, (Th,U)C, and (Th,U)N Fuel

	<u>Homogeneous Cores</u>				<u>Heterogeneous Cores</u>	
Fuel Type (Sodium-Bonded) Fissile Feed Material	(U,Pu)C PWR Pu	(Th,U)C PWR U	(Th,U)C FBR U	(Th,U)N FBR U	(Th,U)C FBR U	(Th,U)N FBR U
Fuel Smear Densities (% T.D.)						
Core and Axial Blanket	78.0	85.0	85.0	85.0	85.0	85.0
Radial/Internal Blanket	93.0	95.8	95.8	95.8	95.8	95.8
Enriched Fuel Theoretical Density (gm/cm ³)	13.5	11.1	11.0	12.2	11.2	12.4
MOEC Core Average Fissile Enrichment (wt %)	10.4	15.0	12.4	11.7	19.0	18.2
Feed Enrichments (wt %)						
Inner Zone	9.3	14.8	12.1	11.3	19.3	18.4
Outer Zone	11.5	18.4	15.2	14.2	23.3	22.3
Outer/Inner Ratio	1.24	1.24	1.25	1.25	1.21	1.21
Maximum Feed U/U+Th (wt %)	-----	24.7	19.4	18.2	29.8	28.5
MOEC Core Fissile (kg)	3372	4359	3574	3701	4817	5019
MOEC Core Thorium (kg)	27006(U)	22156	23246	25874	18187	20188
Core Heavy Metal (kg HM)	32535	29152	28830	31615	25327	27581
Axial Blanket (kg HM)	32805	27808	27808	30950	23926	26632
Internal Blanket (kg HM)	-----	-----	-----	-----	39422	43722
Radial Blanket (kg HM)	23016	27663	27663	30678	30048	33324

Table 2 (Continued)

	<u>Homogeneous Cores</u>				<u>Heterogeneous Cores</u>	
Fuel Type (Sodium-Bonded)	(U,Pu)C	(Th,U)C	(Th,U)C	(Th,U)N	(Th,U)C	(Th,U)N
Fissile Feed Material	PWR Pu	PWR U	FBR U	FBR U	FBR U	FBR U
MOEC Peak Flux, $E > 0.1$ MeV (10^{15} n/cm ² /sec)	4.2	3.8	3.8	3.9	2.7	2.8
Flux Fraction, $E > 0.1$ MeV	.57	.63	.62	.65	.65	.68
Peak Fluence, 511 Full Power Days (10^{23} n/cm ²)	1.85	1.69	1.70	1.70	1.19	1.22
MOEC Core Conversion Ratio	1.03	.62	.74	.78	.45	.46
MOEC Reactor Breeding Ratio	1.48	.97	1.12	1.16	1.21	1.24
Δk , 256 Full Power Days (%)	-0.8	-3.9	-4.4	-3.8	-1.7	-1.3
Fissile Gain, 256 Full Power Days (kg)						
Pa-233 (Total)	--	58	63	65	63	64
(Core/Blanket)	--	40/18	44/19	46/19	22/41	22/42
U-233 (Total)	--	234	14	43	87	109
(Core/Blanket)	--	-58/292	-284/298	-255/298	-447/534	-433/542
U-235 (Core)	--	-334	13	13	12	12
Total Fissile Gain	387(Pu)	-42	90	121	162	185
Peak Burnup (MWD/kg HM)	72	82	82	77	79	73
Reactor Power (MWt)	3333	3385	3385	3385	3154	3154
Specific Inventory (kg _{fiss} /MWe)	4.2	5.9	4.8	4.9	7.0	7.3
Compound Inventory Doubling Time (yr)	10	∞	82	53	53	46
Sodium Void Δk (%) (Core Voided, EOEC)	>0	-0.9	-1.1	-0.9	-0.8	-0.7