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8. Sodium-Cooled Thorium Cycle Breeder Reactor with Coated Particles, *Yuji Ishiguro (CTA-Brazil), Antonio S. Gouvêa (IPEN-Brazil)*

Merits of sodium cooling and the coated particle fuel are combined in a new type of thorium cycle breeder reactor that may achieve excellent breeding and safety performances. Simplified neutronic analyses show that the reactor doubling time can be about six years at ~600 MW/m^3 power density.

The utilization of thorium has been a subject of much research since the earliest days of nuclear energy. Though recent interests appear to be mainly as a supplement to the plutonium cycle in conventional reactors, breeder reactors for the closed thorium cycle have been of continued interest. Karam[1] proposed two types of breeder reactors for the thorium cycle—the liquid-metal fast breeder reactor (LMFBR) with thin metal pins and the gas-cooled suspended bed reactor (SBR)—which are said to achieve doubling times of ~10 years. Our own calculations confirm that the reactor doubling time (RDT) for a 2500-MW(th) LMFBR with a 4-m^3 core using a fuel element structure similar to the Experimental Breeder Reactor II Mark-II fuel is 10 to 11 years. Here, the RDT is calculated for the initial clean core with k = 1. Several types of reactors, in addition to the LMFBR and the SBR, can potentially be breeders for the closed thorium cycle, such as the molten salt breeder reactor, suspension reactors, and gas-cooled reactors of GBR-2 type.

We propose here another type of breeder reactor for the thorium cycle that may have better neutronic and safety characteristics: the sodium-cooled reactor fueled with coated particles. Fuel element structures similar to that of GBR-2 or the one shown in Ref. 2 are being considered. We believe that the reactor has the following main advantages:

1. the small size of the fuel particles, which combined with sodium cooling, allows a high power density
2. the soft spectrum of the coated particle fuel reduces the core inventory
3. coated particles are easier to reprocess and refabricate by remote control than pin-type fuels
4. excellent safety.

A simplified reactor model is analyzed. Each region is homogenized, no control absorbers are included, and no burnup or excess reactivities are considered. The fuel kernel is a mixture of ^{233}U and ^{232}Th dicarbides. The coating material is normal graphite, and the structural material is iron

TABLE I

Some Characteristics of 2500-MW(th) Sodium-Cooled Coated-Particle-Fueled Thorium-Cycle Breeder Reactors

Coating thickness, fuel kernel volume fraction, enrichment				
T/R	0.20	0.25	0.30	0.30
FVF	0.20	0.16	0.14	0.14
^{233}U/HM	0.11	0.12	0.13	0.12
Critical reactor characteristics				
Core Volume m^3	5.3	5.2	4.1	5.7
BR-core	0.787	0.732	0.683	0.741
BR-total	1.168	1.143	1.127	1.125
^{233}U ton	1.05	0.90	0.67	0.87
RDT yr	6.3	6.3	5.3	7.0
Neutron Absorptions per neutron absorbed in ^{233}U				
Fe	0.075	0.082	0.083	0.088
Na	0.041	0.045	0.043	0.046
Total	2.309	2.292	2.278	2.278
Flux averaged lethargy and corresponding energy[a]				
u	5.25		5.45	
E keV	55		45	

[a] At core center. For the metal-fueled LMFBR and the SBR, u = 3.91 and 5.26, respectively.

with 10% volume fraction. The blanket thickness and composition are not optimized. Criticality, flux, and reaction rate calculations were done by a diffusion code with 25 groups of nearly equal lethargy width covering the 10.5-MeV to 0.215-eV neutron energies. The coating thickness to particle radius (T/R) ratio is taken as a parameter, and the fuel kernel volume fraction (FVF), relative to the core volume, is such that the particle bed volume is ~60% of the core volume.

Some results are shown in Table I. The neutron spectrum is softer than that of the metal-fueled LMFBR, but is not much softer than that of the SBR. The RDT is shorter than for the metal-fueled LMFBR or the SBR. Safety features of the reactor should be excellent. The sodium void and Doppler coefficients are expected to be negative. The high melting points of oxide or carbide fuel kernel and coating materials, together with the small size of fuel particles, add to the safety of the reactor. Natural circulation cooling of the decay heat may also be expected.

The fissile inventory is quite low, and the core breeding (conversion) ratio also is rather low. For the full utilization of the high potential of this reactor, it would be necessary to refuel at short intervals, combined with rapid reprocessing. We envision on-power refueling of several fuel elements per day, maintaining the reactor in a quasi-equilibrium with a minimum control requirement. Should self-sustaining operation be sufficient, the discharge burnup may be extended to utilize the high burnup potential of the coated particle fuel. The low inventory is a positive feature for an easy introduction of this reactor.

If coated particles of metallic kernel and 0.2 T/R coating are feasible, the neutronic characteristics of the reactor are as follows: ^{233}U inventory = 1560 kg, breeding ratio = 1.164, and reactor doubling time = 9.8 years for a 5-m^3 core. In this case, more conventional batch refueling appears feasible with a cycle length of six months to one year. In regard to the fuel temperature, particles 5 to 6 mm in diameter can be used to reduce the coolant pressure drop.

The difficulties of designing efficient breeder reactors with the thorium cycle are well known, as demonstrated by the long doubling times reported in the literature. If one is willing to pay the price in the form of operational, fuel cycle, and/or development costs, however, shorter doubling times are possible. We have proposed a new type of breeder reactor that achieves a doubling time similar to those envisioned for plutonium cycle breeder reactors. The reactor has further merits in enhanced safety and ease of fuel fabrication and reprocessing.

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9. Cell Modeling Influence on ZPPR Criticality Analysis, *P. T. Choong, A. K. Hartman, M. D. Libby, S. L. Stewart (GE, Sunnyvale)*

The data from critical experiments typically are K_{eff}, control rod worths, reaction rates, sodium void worth, and breeding ratio. Even when the power, reactor geometry, and composition are closely simulated in a critical experiment, subtle differences still exist that require careful interpretations. For instance, the plate arrangement of a critical experiment representation of a fuel assembly is significantly more heterogeneous than is the pin assembly in the power reactor.

In Zero Power Plutonium Reactor (ZPPR) Assembly 7 Phases B and C, which were benchmark configurations of a demonstration-size heterogeneous liquid-metal fast breeder reactor (LMFBR) representing the clean beginning (BOC)- and end-of-cycle (EOC) core loading conditions, the calculated critical eigenvalues are different by ~0.6% Δk/k (Ref. 1). Translating this difference into the uncertainties for the eigenvalue bias and the cycle burnup reactivity would result in costly design penalties. The phenomenon persisted in the analysis of ZPPR-11 (Ref. 2), another heterogeneous core mockup. Examination of prior ZPPR analysis results[3,4] revealed that this critical eigenvalue uncertainty is most pronounced in a heterogeneous core. Further evaluations found that this phenomenon is not sensitive to multiregion resonance treatment model, elastic removal cross-section correction model, or basic cross-section sets. The transport effect seemed to improve the discrepancy modestly.[4] Unlike the Argonne National Laboratory results[5] for ZPPR-7, the eigenvalue difference between BOC and EOC after transport correction is still 0.4% Δk/k. However, there is strong evidence from the results of Ref. 6 that the observed large critical eigenvalue differences between BOC and EOC in ZPPR-7 and ZPPR-11 are due to the inadequate spatial treatment. It is inferred from the results of Ref. 6 that the optimal cell configuration should be multidrawer to reasonably simulate the loading in the core zone of interest. Furthermore, the transverse leakage should be modeled by means of energy-group-dependent critical buckling. Following these criteria in principle, the criticality of ZPPR-7 and ZPPR-11 was reanalyzed using a combination of two-drawer and three-drawer models for spatial heterogeneity treatment. Current practices of ZPPR core analysis were followed, i.e.,

1. ENDF/B-IV cross-section-based 50-group GMUG library
2. multizone f-factor adjustment for resonance self-shielding of all cross sections of all isotopes
3. spectral adjustment of elastic removal cross section based on spectrum seen by each isotope
4. spatial homogenization based on fluxes from accurate integral transport solution
5. zone-wise, condensed nine-group cross sections for core analysis
6. criticality calculation by four-mesh-per-drawer XY diffusion theory solution using group- and zone-dependent transverse buckling input from RZ diffusion solution.

The consistency of the criticality results is summarized in Tables I and II. Principally,

1. The large eigenvalue discrepancy between BOC and EOC conditions is significantly reduced.

TABLE I

Summary of ZPPR-7 Criticality

	ZPPR-7B	ZPPR-7C	C/E Discontinuity
Experiment[a] (E)	1.0005	1.0012	
One-drawer (C)	0.9855	0.9922	
Energy dep. B^2 (C/E)	0.9850	0.9910	0.0060 (0.0048)[b]
Multidrawer (C)	0.9884	0.9890	
Energy dep. B^2(C/E)	0.9879	0.9878	−0.0001

[a] Excess reactivity adjusted to 300 K through measured temperature coefficient.

[b] Comparable RZ/XY diffusion theory results extracted from Table I of Ref. 5.