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BREEDER REACTOR DESIGN FOR ENHANCED PERFORMANCE AND SAFETY CHARACTERISTICS

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ABSTRACT

A fast breeder reactor design has been created which offers a considerably extended fuel cycle and excellent performance characteristics. An example of a core designed to operate on a ten-year fuel cycle is described in some detail. Use of metal fuel along with a moderator such as beryllium oxide dispersed throughout the core provides both design flexibility and safety advantages such as a strong Doppler feedback and limited sodium void reactivity gain. Local power variations are small for the entire cycle; control requirements are also modest, and fuel cycle costs are low.

INTRODUCTION

The Extended Fuel Cycle FMSR [(EC)FMSR] is a new breeder reactor concept which offers the potential for excellent performance and lower fuel cycle costs, in addition to providing attractive nuclear weapons proliferation resistance and resource utilization advantages. It has a strong Doppler feedback and limited sodium void reactivity gain. Local power density changes are small over the long fuel cycle, as are the reactivity changes. As in the Centrally-Moderated FMSR,[1] metal fuel is used to take advantage of its high density of fertile atoms as well as its excellent burnup characteristics. The MARK-II fuel concept used in EBR-II reactor operation is utilized in order to achieve extensive fission gas release, and thereby, excellent burnup performance. In addition, a moderator, presently BeO, is used for design flexibility. The reactor is sodium cooled.

The principal design strategy is to exploit the inherent high conversion ratio of metal-fueled breeders while adding sufficient moderator, in this case BeO, so that the reactivity gain resulting from breeding new fissile material just balances reactivity losses due to fission product buildup. Under these conditions there is a very small reactivity swing over a very long fuel cycle. A long fuel cycle has immediate advantages to the operating utility and leads to lower fuel cycle costs.

Major safety advantages of this design approach which result from employment of some moderator are a relatively low sodium void reactivity worth

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and a significantly larger (approximately a factor of three higher than for conventional LMFBRs) Doppler feedback coefficient. These two factors are expected to enhance the safety of the plant without compromising either performance or economics.

The (EC)FMSR design reported in this paper is only one of the many design options that can be achieved through the judicious use of metal fuel and moderator. Primary emphasis in the design studies reported here was directed toward achieving a design which had excellent physics and thermal-hydraulic performance, low fuel cycle costs and enhanced safety features.

The (EC)FMSR was designed to achieve as far as possible the following objectives:

a. an extended fuel cycle (10 years),

b. a small reactivity change over the fuel cycle,

c. small power density changes over the fuel cycle, locally and regionally,

d. competitive fuel cycle costs,

e. low sodium void reactivity gain,

f. strong Doppler effect feedback safety coefficient,

g. proliferation resistance through use of only three core loadings over the plant lifetime, and

h. conventional breeder reactor technology used as far as possible. The balance-of-plant should be compatible with conventional LMFBR plants. The metal fuel should operate in the manner of the MARK-II fuel used in EBR-II. Scaleup to prototypical 1000 MW(e) reactor fuel dimensions represents a concern which will be resolved by experimental testing.

DESCRIPTION OF THE (EC)FMSR

Since the primary objective of the (EC)FMSR was to obtain as long a fuel residence time as possible, several design decisions had to be made with regard to achievable power densities, core volume, fuel to moderator atomic ratio and subassembly design. Since metal fuel has roughly twice the density of fertile atoms as comparable oxide fuel, the amount of total power generated for the same fraction of heavy metal burnup in a given volume of the core is twice that obtainable with oxide fuel. The higher burnup and lower fissile enrichments of the (EC)FMSR lead to lower fuel cycle costs. In addition, there is valuable flexibility in designing the reactor within size constraints.

The core radius was kept close to that of a typical 1000 MW(e) heterogeneous oxide-fueled reactor so that an (EC)FMSR core could be considered as a potential replacement core for such a reactor. In addition, the capital costs reflected by core and vessel diameters would be the same. The (EC)FMSR core height was increased, however, as the means to achieve added core volume. This had some small effect on reactivity losses due to axial streaming during a loss of sodium accident. By running the reactor at modest power densities with a nominal sodium volume fraction, the core mid-height pressure was correspondingly low, thereby reducing duct distortion under creep, even for the long residence times.

Another key design objective from a thermal-hydraulic performance point of view was a radially flat power distribution. Furthermore, this power distribution remained constant over the cycle, thereby greatly reducing control requirements. Details of this design follow.

CORE DESIGN DATA

Design of the (EC)FMSR fuel and subassembly followed, as closely as possible, conventional LMFBR designs. The (EC)FMSR core, however, was designed for a very long fuel cycle, somewhat higher burnups and significantly higher fast neutron fluence than conventional LMFBRs. The smeared density of the metal fuel was taken to be exactly that used in the MARK-II design employed for the metal driver fuel in EBR-II. The MARK-II fuel has already demonstrated that irradiations of 100,000 MWD/MT are attainable through irradiations of about 1000 pins to or beyond this limit.

Moderator material (BeO) was dispersed uniformly throughout the core. This moderator was placed in the center of every fuel subassembly and occupied about 25% of the total volume. The core layout is shown in Fig. 1. Future (EC)FMSR designs may employ subassemblies which contain either fuel alone or BeO. Two enrichment zones were used.

Core and fuel subassembly design data are summarized in Tables I and II along with comparable data for a typical heterogeneous LMFBR design.[2]

The fuel subassembly design contains 240 fuel pins with an outer diameter of 0.776 cm and a cladding thickness of 0.035 cm; the fuel pins are wire wrapped with a wire thickness of 0.13 cm. The outer subassembly wall thickness is 0.318 cm and the inner duct, surrounding the moderator zone, is 0.250 cm. The fuel was 75% of theoretical density, consistent with the MARK-II fuel. This density provides the means for extensive fission gas release and corresponding reduction in fuel swelling. In the design, the need to cool the moderator was taken into account. A sintered block of BeO is anticipated for purposes of helium gas release and thermal conductivity. If the temperature of BeO can be kept above about 900°C by means of a large temperature drop across the helium bond to the moderator duct wall, it is anticipated that BeO will exhibit excellent irradiation stability.

CALCULATIONAL METHODS

The 1DX code[3] was used to generate the required multigroup cross-section sets from the LIB-IV cross-section library[4] based on ENDF/B-IV data. These cross-section preparation calculations were performed in cylindrical geometry for a two-region "unit-assembly" cell. The "unit-assembly" cell

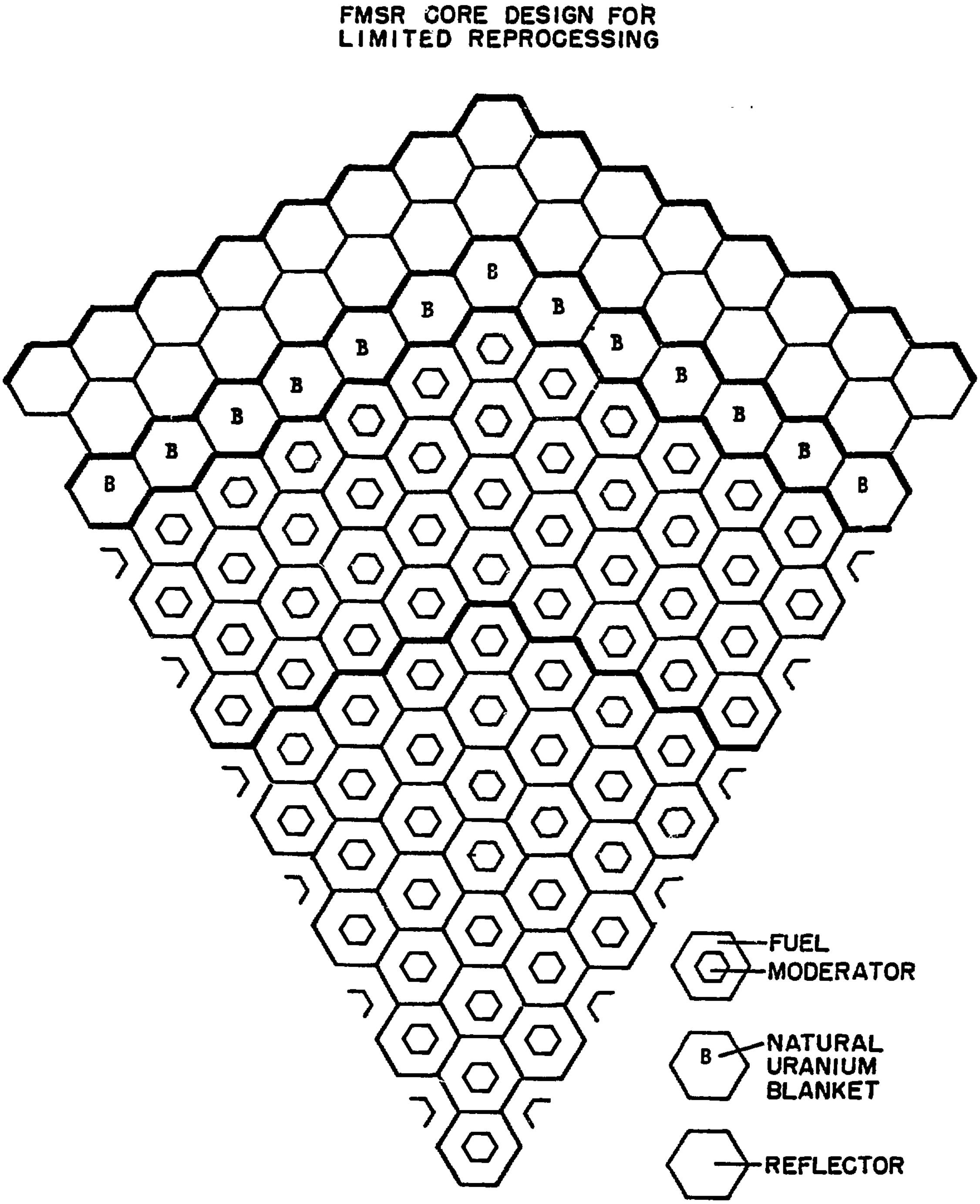

Fig. 1. Core Layout

TABLE I

Core Parameters

	(EC)FMSR	Heterogeneous LMFBR (TC-CC40-36)
Power, MW(e)	1000	1000
Number of rows in core and radial blanket	14	17
Initial fissile inventory (Pu-239 + Pu-241), kg	7262	4268
Core height, cm	160	81
Core radius, cm	243	254
Fuel volume fraction, %	43	44
Steel volume fraction, %	20	19
Sodium volume fraction, %	37	37
Number of fuel subassemblies	468	354
Number of radial blanket subassemblies	78	210
Number of internal blanket subassemblies	None	169
Total:	546	733
Number of control rod positions	42 (tentative)	24
Moderator volume fraction, %	25*	None
(BeO) moderator density, % T.D.		
Inner Core	65	
Outer Core	57	

*Except first 4 rings of subassemblies which have moderator volume fraction 35%.

TABLE II

Subassembly Parameters

	(EC)FMSR	Heterogeneous LMFBR (TC-CC40-36)
Subassembly pitch, cm	18	15
Duct wall thickness, cm	.318	.282
Sodium gap between subassemblies, cm	.800	.500
Number of fuel pins per subassembly	240	271
Fuel pin OD, cm	.776	0.711
Fuel pin pitch, cm	.910	0.839
Pitch/OD ratio	1.17	1.18
Fuel density, % T.D.	75	88
Fissile fraction, % fissile Pu		
Inner Core	7.4	17.7
Outer Core	7.8	18.1
Moderator duct thickness, cm	0.25	-----

dimensions were chosen to represent a single hexagonal subassembly with an inner moderator region. Reflective conditions were imposed on the left and right boundaries of the cell. Heterogeneous corrections were introduced to take into account "pin-cell" heterogeneity and "assembly-cell" heterogeneity. The "inverse fuel" correction, with moderator inside and fuel on periphery, was introduced into the 1DX code, following Ref. 5.

A 20-group library was used for the burnup calculations, while for the sodium-void reactivity and Doppler coefficient calculations, a 50-group library without collapsing was generated by the 1DX code for the fuel and moderator regions. A separate cross-section set was generated for the blanket fuel composition. In addition, cross-section sets were generated for different fuel temperatures (465 K and 1400 K), as well as for fuel compositions under voided sodium conditions.

The principal neutronic calculations were carried out with the 2DB code[6] using both R-Z and x-y geometries. Hexagonal geometry calculations were needed in order to obtain the critical plutonium concentrations and radial power shapes within the subassembly. One-twelfth of the core was represented (30° option); each hexagonal subassembly was divided into 24 triangular mesh points. Duct material and stagnated sodium (between subassemblies) were smeared over the fuel region, and the duct surrounding the moderator was smeared over the moderator region. An R-Z representation of the core is necessary for depletion calculations, where the axial component of the power distribution is important, as well as for sodium void effect calculations.

Fuel and moderator zones in the hexagonal core must be properly modeled by the arrangement of fuel and moderator in the circular rings used in the R-Z model of the core. As a means of defining the moderator and fuel ring dimensions, the fuel and moderator from every hexagonal ring were projected on the R-axis and separated into rings while conserving their respective volumes. All fuel and moderator ring thicknesses are approximately the same, except the first moderator ring. In order to avoid overmoderation of the central part of the fuel as a result of the thick moderator zone, that moderator ring was split into two rings. It was observed that the zonal conversion ratio, as calculated in hexagonal geometry, followed a spatial dependence corresponding to the spectral shift from the center of the core (harder) to the periphery of the core (softer). This same effect was also achieved in the proposed ring geometry utilized in the R-Z model. The conversion ratio and power fraction values at the inner core, outer core and radial blanket, as calculated by the hexagonal and R-Z geometries, were compared to assure a close match between the two representations. Comparisons between effective multiplication factor calculations showed differences of up to 0.5% ΔK; these are attributed to the use of a fixed geometrical buckling in the determination of the axial leakage.

The fission product cross sections used were those available in LIB-IV. This is a treatment provided by Garrison and Roos for water reactors. Recent work in this area at BNL has indicated that these cross sections are overly absorptive in an LMFBR by perhaps as much as 30%.

RESULTS FOR (EC)FMSR CORE PERFORMANCE

One of the important advantages of the (EC)FMSR core design is its very low reactivity swing over the long fuel cycle. The design of control systems is proportionately simplified if the reactivity swing is small; and if local reactivity changes are kept proportional over the fuel cycle, then control problems are further reduced. Table III shows the change in K_{eff}, regional conversion ratio, and fissile plutonium inventory over the 10-year fuel cycle. The change in K_{eff} is less than 1% over the fuel cycle. Preliminary design studies not reported here indicate that simple B_4C rods in control tubes within the BeO distributed across the core could readily provide this control.

A second major advantage of the (EC)FMSR is its exceptional stability with regard to local and regional power distributions over the very long fuel cycle. It was found that in order to achieve a flat power shape across the core at the beginning of life (BOL), the initial fissile plutonium enrichments (Pu-239 and Pu-241) should be 7.4% HM and 7.8% HM for the inner and outer cores, respectively. The fissile inventory of the discharged fuel after 10 years of operation has increased by 2000 kg, (the initial fissile inventory has increased by ∿28). The plutonium isotopic composition for the initial fissile loading was that of discharged LWR plutonium.[7]

In addition to the requirement of a flat radial power profile across the core, another design objective was to minimize the power swing in each subassembly over the 10-year fuel cycle. The larger the change in subassembly power, the greater the penalty in the thermal performance of the reactor due to overcooling during the low power density portion of the fuel cycle. It

TABLE III

Multiplication Factor, Fissile Inventory and Conversion Ratios as a Function of Time

Full Power Days (Years)	K_{eff}	Conversion Ratios				Fissile Pu Inventory (239 + 241), kg				
		Inner Core	Outer Core	Radial Blanket	Axial Blanket	Inner Core	Outer Core	Radial Blanket	Axial Blanket	Total
0	1.0104	1.303	1.230	-----	-----	3152	4110	-----	-----	7262
550(2)	1.0072	1.277	1.199	21.2	14.0	3340	4190	94	178	7802
825(3)	1.0072	1.194	1.185	14.6	9.6	3416	4226	138	264	8044
1375(5)	1.0072	1.139	1.158	9.2	6.1	3534	4286	220	426	8466
1650(6)	1.0072	1.117	1.146	7.9	5.2	3578	4312	258	504	8652
2200(8)	1.0057	1.079	1.123	6.2	4.1	3640	4356	332	654	8982
2750(10)	1.0027	-----	-----	-----	-----	3672	4390	404	796	9262

was found that a trade-off exists between the flatness in the power shape across the core and the minimum power swing in each subassembly. Flattening of the power shape is achieved by increasing the fissile fraction of the fuel in the outer core. This increase leads to a lower conversion ratio in that part of the core. In order to avoid a decrease in power density with time due to the lower conversion ratio, the moderator density in the outer core was decreased, increasing the conversion ratio. A low power swing was obtained in the inner and outer core; the maximum power density change for any individual subassembly is about 11% with most of the subassemblies experiencing power swings of less than 10%. The power shift during the 10-year fuel cycle is shown in Fig. 2, which presents the radial power shape for BOL, mid-life (5 years), and EOL as calculated in R-Z geometry.

Cumulative fuel burnup and fast fluence damage across the core follow the spatial power distribution and the spatial spectrum shift. The peak burnup level at the center of the core, for a 10-year fuel cycle, is about 150,000 MWD and the peak fast fluence is 3.4×10^{23} n/cm^2 sec (E>0.1 MeV).

The Doppler reactivity coefficient was calculated by performing K_{eff} calculations for two different temperatures. The temperatures chosen were 875 K and 1400 K. The results of the calculations are summarized in Table IV for BOL and EOL fuel compositions, as well as for the sodium voided core.

Table IV

Doppler Coefficients $\left(- T \frac{dK}{dT}\right)$

Core Condition	BOL	EOL
Sodium In	0.0270	0.0175
Sodium Out	0.0180	0.0110

The significant decrease of the Doppler coefficient for the EOL composition is due to the higher fraction of absorptions in fission products as well as the replacement of U-238 atoms by the fission product atoms. At EOL about 16.5% of all absorptions occur in fission product atoms. The Doppler coefficient for the (EC)FMSR is significantly larger than that of conventional LMFBRs, even at end-of-life.

Calculations of the sodium void reactivity effect were performed in R-Z geometry by voiding all of the sodium from the core, radial blankets and axial blankets. It is important to note that in the present calculations the stagnated sodium between the subassemblies was smeared with flowing sodium over the fuel region and also removed during the sodium void calculation. It is common practice in voiding calculations that only flowing sodium is removed from the core. Therefore, the present calculations overestimate the sodium void reactivity shift relative to this procedure. Results of the calculations are presented in Table V, where $\Delta K_{Na.V.}$ is the reactivity shift due to sodium voiding.

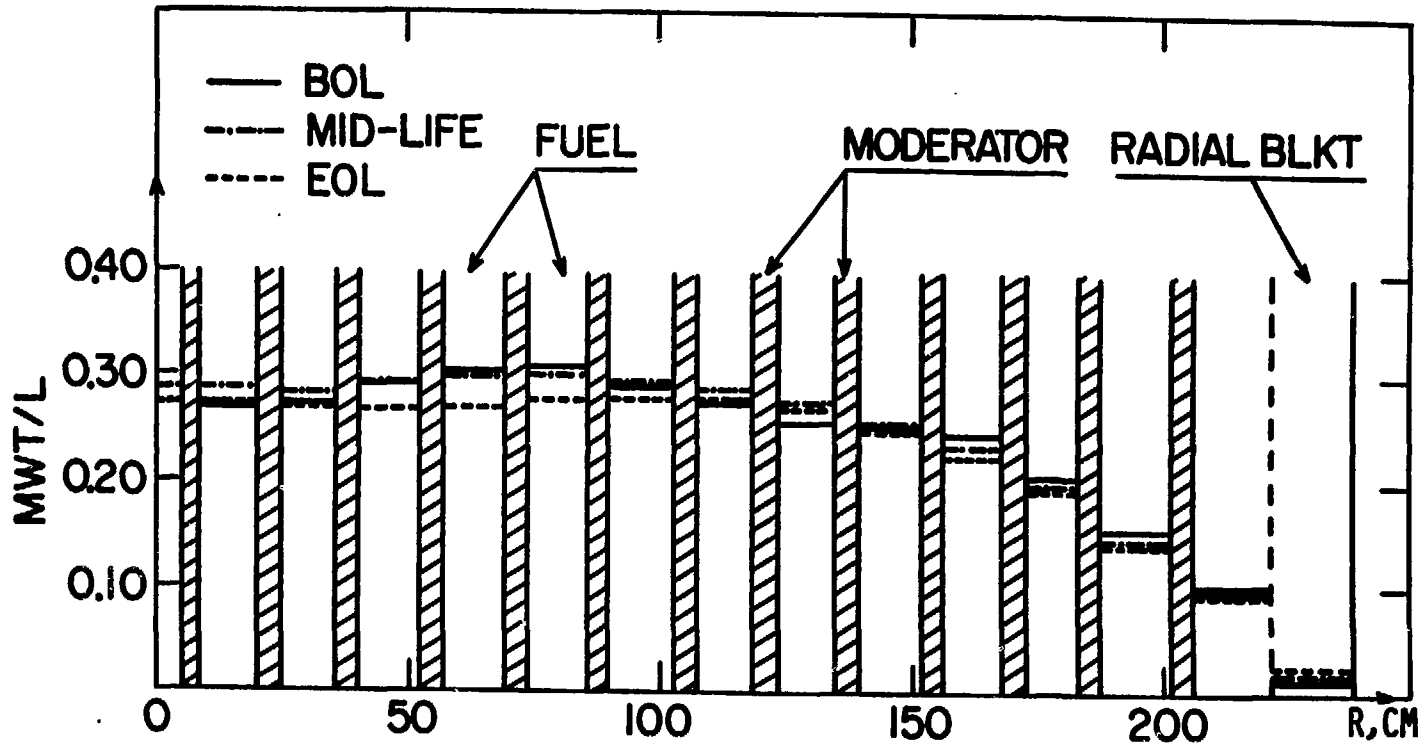

Fig. 2. Radial Power Shape at BOL, MOL and EOL

Table V

Sodium Void Reactivity Effect as a Function of Time
($1 = 0.4% ΔK)

	Sodium Void Effect $\Delta K_{Na.V.}$
BOL	$1.8
MOL (5 years)	$3.7
EOL	$5.0

These calculations are preliminary. More intensive studies, which have only recently been started in this difficult area, indicate that these numbers may be reduced if a more adequate fission product treatment is used. Modest design changes may also mitigate the sodium void effect.

THERMAL-HYDRAULIC ANALYSIS

The thermal-hydraulic design of the (EC)FMSR is very much like that of a conventional LMFBR except for the need to treat the characteristics of metal fuel. The most limiting constraint was the criterion recommended by Argonne National Laboratory that the maximum hot spot temperature at the fuel-clad interface should not exceed 625°C. Two dimensional heat transfer analyses using the COBRA-IV code have been performed for the subassembly design of Configuration B, with the BeO moderator in the center of the subassembly. These have shown that because fuel pins adjacent to any surface such as a wall are always overcooled, the fuel near the fuel-moderator interface is actually overcooled even though this is a location of highest power density.

COST EVALUATION

Cost studies have been performed for the (EC)FMSR on a 10-year fuel cycle in cooperation with MIT. A discounted cash flow analysis procedure[8,9] was employed which showed that the most sensitive parameter was the price to be assigned to plutonium. Using an "indifference price" of $27/gm, fabrication costs of $650 and $150/kg of fuel and blanket, spent fuel shipping charges of $90/kg and reprocessing charges of $450/kg, the fuel cycle cost for the full (EC)FMSR core comes to 4.2 mills/ kwhr. Use of comparable parameters for a typical oxide-fueled heterogeneous LMFBR would lead to a corresponding fuel cycle cost of approximately 7.3 mills/kwhr.

CONCLUSIONS

A sodium-cooled breeder reactor has been designed which can operate very satisfactorily over a long fuel cycle, 10 years in the present case. The reactivity and power density histories over this long cycle are very small. The peak burnup of the metal fuel is high but not unacceptably high and should be reduced in future designs. The fluence damage of the steel may be found acceptable for near-term D-9 steel and more readily in the acceptable range for new ferritic steels. The feedback Doppler effect is unusually strong. The reactivity gain on sodium voiding is now under evaluation. It appears to be low and is subject to control through design flexibility available to the (EC)FMSR concept.

ACKNOWLEDGMENTS

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