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FUEL MANAGEMENT STUDIES OF SMALL METAL AND OXIDE LMR'S

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ABSTRACT

Fuel-cycle analyses performed at Argonne National Laboratory to evaluate and compare the neutronic performance characteristics of small oxide- and metal-fueled LMR's are described. Specific consideration is given to those analyses concerned with optimization of core and blanket configurations, selection of fuel residence time and refueling interval, determination of control rod worths and requirements, development of in-core fuel management strategy, and evaluation of performance characteristics both for startup cycles and for the equilibrium state reached via repeated recycle of discharged fuel. Differences in the computed performance parameters of oxide and metal cores, arising from basic differences in their neutronic characteristics, are identified and discussed. Metal-fueled cores are shown to offer some important performance advantages over oxide cores for small LMR's because of their harder spectrum, superior neutron economy, and greater breeding capacity. These advantages include smaller fissile and heavy metal loadings, lower control-system requirements, and greater adaptability to changes in fuel management scenarios.

INTRODUCTION

The changing emphasis in the development of fast reactors from maximizing breeding capacity to enhancing safety, improving public acceptance, and minimizing investment risks has motivated some new approaches to liquid-metal reactor (LMR) design and fuel management. In particular, small, modular plants have received attention[1,2] because of flexibility in generating capacity and the potential for shop fabrication of components and subsequent transportation to the plant site. In addition, the interest in metallic fuel has been renewed as a result of advances in metal fuel design[3,4] allowing irradiation at elevated temperatures to high burnups and in reprocessing technology[5] permitting a compact, diversion-resistant, integral fuel cycle. Also, the physical and neutronic characteristics of metal fuel (particularly its high thermal conductivity) provide important safety advantages,[6] which further enhance the degree of passive safety achievable with a pool-type LMR having a large heat capacity and a low-pressure coolant with natural circulation capability for shutdown heat removal.

While metal fuel thus has a unique and very attractive potential, oxide fuels are more highly developed, and for this reason, small cores (power < 500 MWe) utilizing both fuel types are currently being investigated at Argonne National Laboratory (ANL). This paper summarizes fuel cycle analyses carried out to address some key issues in the management of oxide and metal fuels that affect the performance and safety characteristics of small LMR cores. These analyses have been performed for equilibrium and non-equilibrium cycles of metal and oxide core designs and provided a basis for intercomparing their performance.

The equilibrium-cycle calculations were used to optimize the core and blanket configurations, to investigate the effects of fuel residence time and refueling interval, and to quantify global performance characteristics and isotope mass flows for the equilibrium cores. The non-equilibrium (discrete-cycle) calculations were employed to optimize the in-core fuel management strategy, to compute detailed performance parameters, and to analyze startup and transition cycles. Differences in computed performance characteristics between oxide and metal cores, resulting from basic differences in fuel characteristics, are identified and discussed.

COMPUTATIONAL METHODS AND PROCEDURES

The fuel cycle analyses described in this paper were carried out using the REBUS-3 code,[7] which solves the static neutron diffusion equation in conjunction with isotope transmutation equations that determine isotope concentrations for each neutronics calculation. The neutronics calculations were consistently performed for three-dimensional (hex-z) reactor representations using eight neutron energy groups and a nodal diffusion theory approach.[8] The composition-dependent, broad-group cross sections were determined from the ENDF/B basic nuclear data using the MC^2-2[9] and SDX[10] processing codes developed at ANL.

Two different types of depletion analyses were done: equilibrium-cycle calculations, which approximate reactor characteristics after many cycles of operation subject to a fixed, repetitive fuel management strategy,[7,11] and discrete-cycle calculations, which explicitly treat a sequence of burn cycles.[7,11] Generally speaking, the equilibrium-cycle analyses provide good estimates of integral parameters, mass flows, and global characteristics of a reactor after attaining an equilibrium state, while the discrete-cycle analyses are needed to calculate reactor behavior when not in equilibrium (e.g. during the first several cycles) and to determine accurately local quantities such as peak power densities and detailed flux and reaction-rate distributions.

DESCRIPTION OF THE CORE DESIGNS

Metal and oxide core designs have been developed as a basis for comparing the characteristics of small LMR's utilizing the two fuel types. The two cores were designed to comparable degrees of optimization (of equilibrium-cycle performance) subject to the constraint that they fit into approximately the same geometric and thermal-hydraulic envelopes. The general reactor specifications to which the metal and oxide cores were designed are presented in Table I. The same planar core layout (shown in Fig. 1) was used for both fuel types. Basic differences between metal and oxide fuel (e.g. the higher peak linear power sustainable by metal fuel and the higher fast fluences of metallic cores) were compensated by differences in core height and in fuel-pin and assembly design.

TABLE I. Reference Reactor Specifications

Reactor Power, MWth	900
Reactor Outlet Temperature, °F	950
Reactor ΔT, °F	275
Primary Coolant Flow Rate, lb/h	3.66×10^7
Maximum Assembly Pressure Drop, psi	50
Core Concept	Heterogeneous
Fuel Residence Time, Cycles	
Driver	4
Internal Blanket	4
Radial Blanket	4
Cycle Length, days	365
Capacity Factor	80%
Fissile-Fuel Composition	
Initial Core	U-235
Reload Cores	LMR Recycle

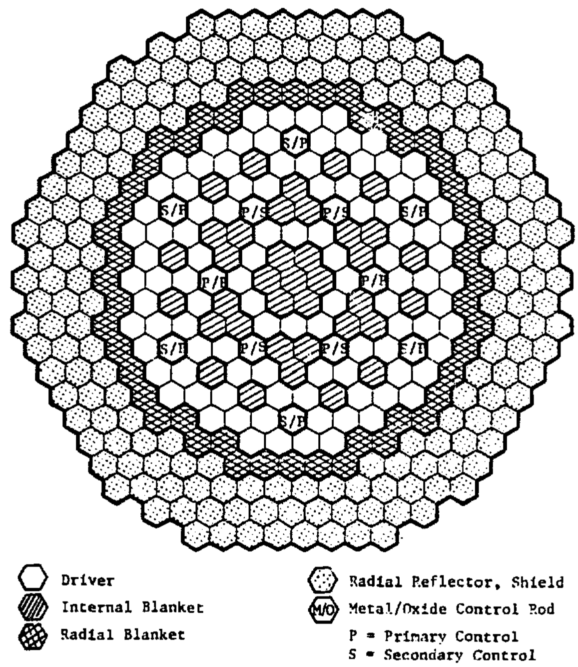


Fig. 1. Core Layout for Metal and Oxide Fuel

Some of the metal and oxide core design parameters are summarized in Table II. The choice of these parameters was not based on any single criterion, such as minimizing doubling time, but rather on a balanced consideration of issues affecting reactor cost, fuel-cycle economics, and safety.[12-14] Note that for both cores, the initial fuel loading is assumed to be enriched uranium, while the fuel composition for the equilibrium cycle utilizes plutonium, recovered by recycle of discharged fuel, as the fissile source. For metal fuel, this fueling approach, in the context of an integral fuel reprocessing facility, has a number of important advantages over the traditional approach of relying on large central facilities for fuel reprocessing.[5,6] However, the practicality of the integral fuel cycle concept for oxide fuel is still being evaluated.

A more detailed description of the design features and the performance characteristics of the metal and oxide cores is presented in a companion paper;[12] The remainder of this paper focuses on three types of fuel management studies performed for the two cores:

TABLE II. Core and Assembly Design Parameters

	Metal Fuel	Oxide Fuel
Fuel Material		
Driver	U-Pu-10%Zr	$(U-Pu)O_2$
Blanket[a]	U-10%Zr	UO_2
Cladding and Duct Material	HT-9	HT-9
Fuel Smear Density, %T.D.		
Driver	75	82.5
Blanket	75	93.3
Active Fuel Height, in.		
Driver	36	40
Blanket	44	52
Axial Blanket Thickness, in.	0.0	6.0
Number of Pins per Assembly		
Driver	271	271
Blanket	169	169
Fuel Pin Diameter, in.		
Driver	0.285	0.290
Blanket	0.392	0.400
Pin Pitch/Diameter Ratio		
Driver	1.18	1.18
Blanket	1.09	1.09
Cladding Thickness, in.	0.022	0.022
Duct Wall Thickness, in.	0.14	0.13
Interassembly Sodium Gap, in.	0.15	0.10
Assembly Lattice Pitch	6.06	6.09

[a]Refers to internal and radial blanket.

1. equilibrium-cycle studies that provided input to the basic core designs and fuel cycle parameters

2. discrete-cycle analyses (utilizing the equilibrium, Pu-based fuel composition resulting from repeated recycle of discharged fuel) to determine an optimum batch refueling scheme and to evaluate detailed equilibrium-cycle reactor characteristics

3. discrete-cycle analyses of startup cycles with initial loadings of enriched uranium and of transition cycles utilizing fuel compositions determined by recycle of previously discharged core and blanket fuel.

EQUILIBRIUM-CYCLE ANALYSES AND THEIR IMPACT ON THE DESIGNS

Fuel Residence Time and Refueling Interval

Equilibrium-cycle analyses were used to examine the effects of fuel residence time and cycle length. Residence times of three and four years have been considered. For the metal core, the peak discharge burnup and peak fast fluence were found to be 109 MWd/kg and 2.32×10^{23} n/cm^2, respectively, for the three-year residence time. These values increase to 143 MWd/kg and 3.45×10^{23} n/cm^2 when the residence time is increased to four years. The corresponding oxide values, for the four-year case, are 162 MWd/kg and 2.55×10^{23} n/cm^2, and thus the burnup-to-fluence ratio is significantly higher for oxide fuel. Although the four-year values are currently beyond the ranges of burnup and fluence for which fuel pin performance data are available, and are therefore fairly aggressive, these values are nevertheless believed to be achievable in view of recent advances in oxide[15] and metal[16] fuel design. Thus to take advantage of the decrease in fuel cycle costs with increasing discharge burnup, the four-year irradiation time was selected for both oxide and metal fuel. Because of its favorable swelling behavior at high fluences, the ferritic alloy, HT-9, was chosen as the cladding and assembly duct material.

Refueling intervals of one year and two years were investigated, with the total residence time fixed at four years. Intervals longer than those considered are probably inadequate from a maintenance perspective, while shorter intervals excessively reduce availability. The major neutronic effect of increasing the cycle length was found to be an increase in the reactivity loss Δk resulting from fuel depletion. Table III compares, for

TABLE III. Comparison of Control Requirements for One-Year and Two-Year Cycle Lengths

	One-Year Cycle		Two-Year Cycle	
	Oxide	Metal	Oxide	Metal
Burnup Reactivity Decrease, %Δk	1.80	1.16	4.01	2.61
Maximum Control-System Requirements, %Δk ($)				
Primary System	4.97 (15.4)	3.58 (10.6)	7.51[a] (23.3)	5.25[b] (15.5)
Secondary System	1.99 (6.16)	1.39 (4.11)	1.99[a] (6.16)	1.39[b] (4.11)

[a]Values exceed achievable control rod worths with fully enriched (92% B-10) B_4C, even if the central blanket assembly is replaced by a control rod assembly.
[b]Requirements can be satisfied using 50% B-10 enrichment.

the oxide and metal cores, the values of Δk and of control system requirements for one-year and two-year cycle lengths. Since oxide fuel has a larger Δk because of its lower core conversion ratio, the value of Δk with a two-year cycle was found to be excessive for the oxide case in view of the limited number of suitable control assembly positions available in a small core. Moreover, for both fuel types, the increase in Δk has the undesirable safety consequence of increasing the reactivity vested in the primary control rods and potentially available to a rod-ejection accident. In addition, the longer refueling interval would require more in-vessel storage locations for discharged assemblies since the batch size is larger. These drawbacks of a longer cycle length were judged to overshadow the benefit of the increase in capacity factor, and thus the one-year cycle length was selected for both metal and oxide designs. However, because of its lower burnup reactivity loss, the metal fuel clearly permits greater flexibility in the choice of cycle length.

Determination of Control Rod Worths and Requirements

The control rod worths, requirements, and critical positions for the equilibrium oxide and metal cores were estimated with the aid of equilibrium-cycle analyses of the reference core designs. An equilibrium-cycle calculation was first done for each core with the control rods withdrawn. In this calculation, an iterative search procedure[11] was employed to determine the core fuel enrichment (i.e. the relative amounts of fissile-containing Pu and depleted U) that yields a minimum keff of 1.0 over the duration of the equilibrium cycle. The cycle decrease in keff, Δk, was determined from this calculation and used in computing the excess reactivity component of the control-system requirements shown in Table III.

Nominal values of the integral control rod worths were evaluated at the beginning of equilibrium cycle as a function of B-10 enrichment in the active control material, B_4C, and for different designations of primary and secondary rods. The primary and secondary rods were then selected and their minimum enrichments determined by requiring the computed worths of each control system (allowing for failure of its most reactive rod) to exceed the control system requirements. It was found that the metal core required a lower enrichment for the control rods, primarily because of its lower burnup reactivity swing, but also because of the smaller magnitude of the reactivity associated with core temperature changes.

Given the required enrichment of the primary rods, their differential worth was evaluated and used in conjunction with the burnup reactivity variation to predict the critical position of the primary rods at any time during the (equilibrium) cycle. The accuracy of the predicted positions was checked by repeating the equilibrium-cycle analysis with the primary control rods inserted to their critical depths and verifying that keff = 1.0 throughout the cycle. The maximum worth for ejecting a control rod from its critical position was then computed. For the metal core, this worth was found to be \$0.68, compared to \$1.18 for the oxide core. The lower reactivity available to a potential rod-ejection accident represents a potentially important safety advantage for metal cores.

Blanket Design and Fuel Management Studies

Since reprocessing cost is a strong function of the heavy metal input to the reprocessing facility, an important design goal for both oxide and metal cores was to minimize the blanket volume by tailoring excess breeding to an amount which compensates for anticipated losses during reprocessing. However, somewhat different approaches to blanket design and fuel management were utilized for the two cores because of the higher breeding capacity of metal fuel and because of probable differences in the reprocessing schemes applicable to the two fuel types.

For the metal core, the proposed pyrometallurgical technique for fuel recycle (in which a different sequence of steps is needed to reprocess core and blanket fuel[5]) creates a strong incentive for eliminating the axial blanket in order to avoid the step of mechanically separating it from the active driver fuel. The superior breeding capacity of metal fuel makes it possible to eliminate the axial blanket, while maintaining adequate breeding for a self-sufficient (equilibrium) cycle with respect to fissile mass. However, to satisfy the minimum breeding requirement, a heterogeneous configuration was needed, as well an increase in the height of the internal and radial blanket columns relative to the active core height (36 in.). Table IV summarizes the results of a tradeoff study done to determine the required blanket height. Note that for the 90% U-10% Zr blanket composition at a 75% smear density (which is conservative with respect to the four-year residence time[17]), a blanket height of 44 in. is adequate and results in an annual fissile gain of approximately 7 kg; this gain is equivalent to about 2% of the annual fissile loading.

With oxide fuel used in the same heterogeneous layout (see Fig. 1), it was found that a six-inch axial blanket was needed above and below the core to satisfy the minimum breeding criterion. Table V provides a comparison of equilibrium-cycle breeding parameters and mass flows for the oxide and metal cores, based on a single 900 MWth reactor. Note that while both cores have similar breeding ratios (slightly greater than unity), the metal core offers the advantages of a smaller annual fissile loading and a smaller annual discharge of heavy metal. It should be emphasized, however, that no attempt was made to maximize breeding, and that the objective was limited to achieving a self-sustaining fuel cycle.

DISCRETE-CYCLE CALCULATIONS WITH THE EQUILIBRIUM FISSILE COMPOSITION

In addition to assuming an equilibrium state (resulting from a repetitive sequence of fuel management operations), equilibrium-cycle analyses are based on flux solutions that are

TABLE IV. Variation of Breeding Ratio, Net Fissile Gain, and Heavy Metal Inventory With Blanket Size and Composition for Metal Core Without an Axial Blanket

Blanket[a] Height, in.	Smear Density, % of T.D.	Zirconium Content, wt%	Reactor Breeding Ratio	Heavy Metal Inventory, kg	Fissile[b] Gain, kg/yr
36	85	0	1.123	20942	32.8
36	75	0	1.080	19406	20.7
36	75	6	1.027	17957	7.1
36	75	10	0.970	16448	-7.9
44	75	10	1.028	18351	7.4
50	75	10	1.062	19778	16.4
64	75	10	1.113	23109	29.9

[a]Internal and external (radial) blanket.
[b]Fissile = $U^{25} + Pu^{49} + Pu^{41}$

TABLE V. Comparison of Equilibrium-Cycle Breeding Parameters and Mass Flows for the Oxide and Metal Cores

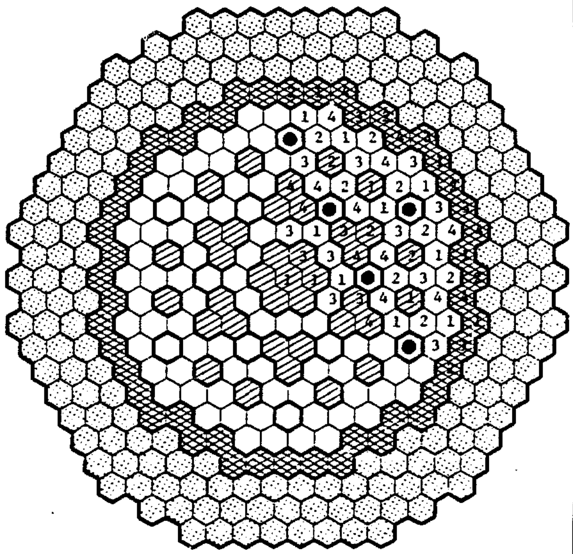
	Oxide Fuel	Metal Fuel
Breeding Ratio		
Core (driver)	0.392	0.460
Internal Blanket	0.348	0.348
Radial Blanket	0.080	0.216
Axial Blanket	0.218	0.0
Total	1.038	1.024
Annual Fissile[a] Loading, kg		
Core	412.4	368.1
Internal Blanket	2.4	2.3
Radial Blanket	3.1	3.0
Axial Blanket	1.1	0.0
Total	419.0	373.4
Annual Heavy Metal Discharge, kg		
Core	1522.1	1752.0
Internal Blanket	1159.8	1102.4
Radial Blanket	1536.7	1454.2
Axial Blanket	535.7	0.0
Total	4754.3	4318.6

[a]Fissile = $U^{25} + Pu^{49} + Pu^{41}$

derived by first averaging the isotope densities in each spatial region over the distinct cycles making up the repeating sequence of cycles.[11] Thus in computing the flux at a given stage of the equilibrium cycle, the fuel composition in each region is approximated by an average of the various fuel compositions occupying that region at the same stage of the successive cycles in the repeating sequence. Although the different compositions are then treated explicitly in solving the isotope transmutation equations, the cycle-averaging approximation used to compute the flux may not permit accurate determination of detailed flux and power distributions.

Discrete-cycle calculations, in which each burnup cycle is explicitly analyzed, are thus needed both to calculate reactor behavior when not in equilibrium and to determine accurately reaction-rate distributions and peak power densities. In this section, we consider the latter problem for the oxide and metal cores in the equilibrium case after their transition from the initial uranium loadings to the high-fissile-content (recycled) plutonium fueling is complete. While these discrete-cycle calculations are thus concerned with an equilibrium state, they treat explicitly each of the n unique cycles of a fuel loading pattern that repeats every n cycles. These calculations were used to optimize the fuel assembly batch refueling scheme and to compute detailed reactor performance parameters.

Figure 2 shows the common assembly batching scheme developed for the metal and oxide cores. Although this scheme was optimized for the metal core, the optimum oxide scheme is likely to be very similar because of the nearly identical core geometries. The scheme, which involves no fuel shuffling between cycles, was designed to minimize cycle-to-cycle variations in mass flows and global parameters, as well as to achieve the lowest core power peaking factors. Note that the scheme has a repetition interval of four (i.e. cycle N+4 is identical to cycle N for sufficiently large N) and that it exhibits 120° symmetry. The reduced symmetry relative to core layout (which is 30°-symmetric) allows greater uniformity in the number of assemblies discharged at the end of each cycle and consequently in reactor characteristics.



(n) Assembly in Batch n; Batch n Discharged at End of Cycle N+n (N = 0,4,8,...)

Fig. 2. Batch Refueling Scheme for the Metal and Oxide Cores

Discrete-cycle analyses of the oxide and metal cores were carried out for a sufficient number of cycles to establish the repetitive sequence. These calculations were done with the primary control rods withdrawn; earlier equilibrium-cycle analyses had shown that fairly accurate predictions of performance parameters can be determined in this manner. Table VI provides a comparison of the performance characteristics of the oxide and metal cores. This table shows that the metal core has somewhat lower power peaking factors and discharge burnups, while the peak flux (and therefore fast fluence) are lower for the oxide core.

Currently, the discrete-cycle analyses are being repeated with the primary control rods inserted to their critical positions. However, the performance parameters given in Table VI are not expected to change significantly, and the various trends exhibited by the results should not be affected.

ANALYSIS OF STARTUP AND TRANSITION CYCLES

In addition to discrete-cycle analyses done for the oxide and metal cores using the equilibrium Pu fuel, discrete-cycle calculations were also carried out for startup cycles, in which the cores were fueled with enriched uranium, and for transition cycles in which the fuel composition was derived from recycled core and blanket discharge. The evolution of the fuel composition over reactor lifetime was deduced from these calculations, as well as non-equilibrium performance characteristics and isotope mass flow data. In addition, the self-sufficiency of the oxide and metal designs with respect to fissile mass regeneration during the transition cycles was examined.

A number of simplifying assumptions were made in these calculations. For example, the same cycle length, thermal output, and assembly batching scheme were assumed for the startup

TABLE VI. Performance Characteristics of the Metal and Oxide Cores

		Metal				Oxide			
Discrete Cycle[a]		N+1	N+2	N+3	N+4	N+1	N+2	N+3	N+4
Burnup Reactivity Swing, $Δk		1.26	1.15	1.10	1.27	1.87	1.71	1.66	1.89
Peak Linear Power, kW/ft									
Core	B[b]	14.3	14.2	14.2	13.8	13.3	13.1	13.1	13.0
	E[c]	12.9	13.2	12.9	12.9	11.7	11.9	11.8	11.3
Blanket	B	10.8	11.1	10.9	10.9	10.6	10.8	10.5	10.5
	E	11.9	12.3	12.8	12.3	11.6	11.8	12.1	11.6
Core Power Peaking Factor									
	B	1.61	1.60	1.61	1.56	1.69	1.67	1.67	1.65
	E	1.56	1.59	1.57	1.55	1.61	1.63	1.63	1.55
Peak Core Flux, $\times 10^{15}$ n/cm^2-s									
	B	5.16	5.17	5.06	5.19	4.57	4.51	4.50	4.47
	E	5.31	5.35	5.17	5.20	4.50	4.46	4.45	4.36
Peak Discharge Burnup, MWD/kg		140	143	139	143	160	163	160	162

[a] N = 4, 8, 12, ...
[b] B denotes beginning of cycle
[c] E denotes end of cycle

cycles as for the equilibrium cycle. Thus at the end of the each cycle, approximately one-fourth of all subassemblies were discharged (see Fig. 2) and reprocessed. A one-cycle reprocessing/refabrication interval was assumed. The initial core and first reload were fueled with enriched uranium, while the core loading beginning with the third cycle was determined from reprocessed core and blanket fuel. In reprocessing, material losses were neglected, and complete removal of all fission products was assumed. The Pu recovered from the blankets was added to the U/Pu mixture recovered from the core to determine the fissile isotopic mix of recycled fuel.

In these startup and transition cycle analyses, a numerical search was performed for each cycle to determine the critical mass of the fissile fuel (initially U-235 and subsequently recycled fuel). This fissile mass was compared to that actually available from reprocessing to calculate the fissile surplus or deficit for the cycle. In the current version of REBUS-3, a fissile deficit in one cycle cannot be compensated by the net surplus from preceding cycles. Instead, a fixed makeup fissile source (e.g. U-235) was employed to satisfy a fissile deficit when encountered.

Because of the particular batch refueling scheme selected for the metal and oxide cores, the odd-numbered transition cycles were characterized by a fissile surplus, while the even-numbered ones had a fissile deficit. Moreover, for both designs, the magnitude of the fissile deficit decreased with time, while the surplus gradually increased to the equilibrium value of approximately 7 kg/cycle. At the end of 18 cycles, the net fissile deficit was approximately 180 kg for both the metal and oxide cores. While these deficits accumulate at a decreasing rate, it is clear that minor design modifications that augment breeding are required to eliminate the need for fissile makeup during the transition cycles.

Figure 3 illustrates the variation in the isotopic makeup of the fissile source used in fueling the metal core. Note the transition from U-235 to Pu-239 as the predominant fissile isotope and the significant U-236 concentration at the end of 17 cycles. The relatively slow rate at which the U-236 is depleted will probably make it desirable to eliminate uranium from the discharged core fuel once the U-236 to U-235 concentration ratio exceeds some specified value.

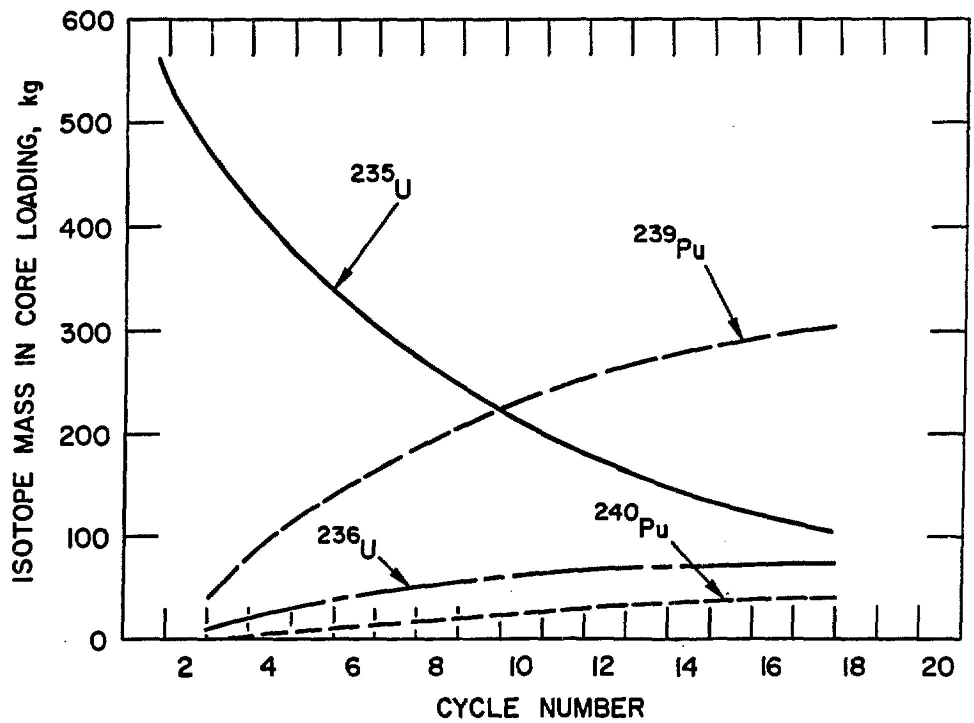


Fig. 3. Variation of the Isotopic Makeup of the Fissile Fuel for the Metal Core

CONCLUSIONS

Our fuel management studies have shown that a number of performance advantages result from use of metallic fuel for small LMR cores. The greater heavy metal density and the harder neutron energy spectrum characteristic of metal fuel lead to improved neutron economy and a larger core conversion ratio relative to oxide fuel. These metal fuel characteristics permit a smaller fissile loading and a reduced blanket volume to achieve a specified minimum breeding ratio. As a result, the fissile and total heavy metal inventories and the heavy metal throughput to reprocessing are lower in the case of metal fuel. The metal fuel characteristics also lead to a lower burnup reactivity loss, and therefore to reduced control system requirements and costs, as well as to a decrease in the reactivity available to a potential rod-ejection accident.

The performance advantages of metal-fueled cores indicate that metal fuel is likely to be more adaptable to changing design constraints and fuel management scenarios. Although a greater uncertainty exists in the actual performance achievable with metal fuel than with oxide, our fuel management studies indicate that metal-fueled cores, in the context of an integral fuel cycle, have some attractive characteristics that may address many of the concerns raised in the current U.S. debate regarding the building and operating of nuclear plants.

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