

To be Presented at The International Conference on Fast Reactors and Related Fuel Cycles, Kyoto, Japan October 28 - November 1, 1991

LMR Design Concepts for Transuranic Management in Low Sodium Void Worth Cores

ANL/CP--72183

DE91 018645

R. N. Hill  
Reactor Analysis Division

Argonne National Laboratory  
9700 South Cass Avenue  
Argonne, IL 60439  
(708) 972-4865

**DISCLAIMER**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

\* Work supported by the U.S. Department of Energy, Nuclear Energy Programs under Contract W-31-109-ENG-38.

**MASTER**

db

**LMR DESIGN CONCEPTS FOR TRANSURANIC MANAGEMENT  
IN LOW SODIUM VOID WORTH CORES**

R. N. HILL

Argonne National Laboratory  
9700 S. Cass Avenue  
Argonne, Illinois 60439-4842, USA

**ABSTRACT**

*The fuel cycle processing techniques and hard neutron spectrum of the Integral Fast Reactor (IFR) metal fuel cycle have favorable characteristics for the management of transuranics; and the wide range of breeding characteristics available in metal fuelled cores provides for flexibility in transuranic management strategy. Previous studies indicate that most design options which decrease the breeding ratio also allow a decrease in sodium void worth; therefore, low void worths are achievable in transuranic burning (low breeding ratio) core designs. This paper describes numerous trade studies assessing various design options for a low void worth transuranic burner core. A flat annular core design appears to be a promising concept; the high leakage geometry yields a low breeding ratio and small sodium void worth. To allow flexibility in breeding characteristics, alternate design options which achieve fissile self-sufficiency are also evaluated. A self-sufficient core design which is interchangeable with the burner core and maintains a low sodium void worth is developed.*

**I. INTRODUCTION**

The key features of the IFR concept include a pool plant layout, U/Pu/Zr metallic alloy fuel, high internal conversion ratio core designs, and pyrometallurgical fuel reprocessing with remote injection casting fuel refabrication. The IFR concept addresses safety by providing for inherent processes to bring the core to a safe shutdown condition and to remove decay heat in response to off-normal conditions, and addresses competitive fuel cycle economics by employing a closed fuel cycle based on pyrometallurgical processing and injection casting re-fabrication in a compact fuel cycle facility (which can be collocated with the reactor plant if desired). Two proposed core designs for the IFR concept are PRISM<sup>1</sup> and SAFR;<sup>2</sup> these core designs will be referred to as conventional IFR designs throughout this paper.

In the ongoing evaluations of IFR technical options, trade studies on several key IFR design features are being performed. In particular, alternatives in the **core size, transuranic management, and sodium void worth** characteristics of conventional IFR cores are being investigated. Conventional IFR cores are small, modular designs. The requirement that the vessel remain rail or barge-shippable places a severe constraint on the core diameter. In addition, the small size tends to yield favorable surface-to-volume ratios conducive to passive decay heat removal. However, the small unit size requires construction of many modules to achieve significant power production. Thus, the LMR development community is per-

forming trade studies to determine the optimum power rating per module. In this paper, a 1575 MWt (600 MWe gross) power output is targeted, although 900 MWt size cores are utilized in some of the trade studies to illustrate the key design trade-offs.

Various transuranic management strategies can be used in an IFR fuel cycle. Since the geological repository has received increased attention in recent years because of various siting difficulties, the usefulness of transuranic burning is again being evaluated. Transuranics dominate the long-term toxicity of LWR spent fuel; thus, it may be desirable from a waste management viewpoint to "burn" (fission) them. Various concepts for burning transuranics, ranging from accelerators to thermal reactor recycle, have been proposed. However, the IFR closed fuel cycle offers a number of favorable features regarding management of man-made actinides. The pyrochemical processing techniques and hard core neutron energy spectrum facilitate transuranic burning as described in Ref. 3. Therefore, a fuel cycle which is a net consumer of transuranics (low breeding ratio) may be desirable; this is a significant departure from conventional IFR designs with their high internal conversion ratio.

Recent investigations have also focused on design options for reducing the sodium void worth of LMR cores. Although large margins between the peak coolant temperature and the sodium boiling temperature have been demonstrated for various unprotected transients, there remains a non-zero probability of at least a limited amount of sodium boiling in a LMR. Large-scale voiding, in response to extremely unlikely events, would introduce substantial reactivity (\$4 to \$6) in conventional IFR designs and may present a significant licensing issue because of the potential for severe reactor damage and of the resulting risk to the public. For this reason, there remains a strong incentive to minimize the reactivity that can be added when sodium voids (ideally to a negative value) and, thus, to minimize the consequences of voiding in the extremely unlikely event that it takes place. Various techniques for reducing the void worth were analyzed in Ref. 4; to obtain a significant void worth reduction, substantial modifications of conventional IFR cores are required.

In this paper, various design options for achieving a low sodium void worth in cores capable of a wide range of breeding characteristics are evaluated. The focus of this paper is the neutronics performance of the proposed core designs with the realization that other design issues (i.e., thermohydraulic performance, vessel commodities, etc.) remain to be evaluated. The calculational methods for the neutronic performance evaluations are briefly described in Section II. In Section III, the design of low void worth burner cores is addressed; and a flat, annular burner design is developed. In Section IV, the design of an interchangeable self-sufficient core is addressed.

## II. CALCULATIONAL METHODS

Although the low void worth designs analyzed in this paper vary somewhat from conventional IFR designs, it was assumed that previously generated conventional IFR multigroup constants are adequate for performance comparisons. Fine group constants were generated using the *MC<sup>2</sup>-2<sup>5</sup>* code for a conventional IFR ternary fuel composition with ENDF/B-V.2 data. For sodium-in and sodium-out cases, the group constants were spatially collapsed using the *SDX<sup>6</sup>* code for a conventional IFR radially heterogeneous model. The group constants were spatially collapsed into a 9 group structure for the depletion calculations and a 21 group structure for the void worth calculations.

The equilibrium-cycle neutronic performance was analyzed using the *REBUS-3<sup>7</sup>* fuel cycle analysis code. In the equilibrium model, batch-averaged compositions are used in each depletion region. The fuel cycle iteration searches for a transuranic enrichment, in the charged fuel, which maintains criticality throughout the cycle. The transuranics in the fresh fuel come from an external feed of reprocessed LWR transuranics and depleted uranium is used as a fertile feed. Some cases preferentially reload the discharged IFR transuranics and use the LWR transuranics as fissile make-up; these cases are referred to as infinite recycle calculations since they model the equilibrium achieved after repeated recycle. The analysis was carried out in hexagonal-Z geometry using a nodal diffusion approach<sup>8</sup> and 9 group cross

section data. Nuclear transmutations for isotopes ranging from U-234 to Cm-246 are modeled.

The sodium void worth was calculated using exact perturbation theory. The DIF3D<sup>9</sup> code finite-difference diffusion theory option is used for the eigenvalue calculations; the 21 group cross section data is utilized. The total void worth is calculated for voiding of the flowing sodium in the active core and upper plenum zones. The perturbation calculation allows the void worth to be broken down into reaction components (i.e., spectral component and leakage component) and regional contributions.

### **III. DESIGN OF TRANSURANIC BURNER CORE**

The core physics aspects of transuranic consumption in the IFR cycle were investigated in Ref. 3. The actinide behavior in self-sufficient IFR fuel cycles which "store" transuranics, and alternatively, pure burner (no U-238 present) IFR fuel cycles which "burn" transuranics was analyzed. These core designs exhibit the limiting behavior for transuranic management strategies ranging from storing to "pure" burning. The pure burner designs in Ref. 3 utilized exotic fuel compositions; the absence of fertile U-238 leads to high plutonium concentrations and corresponding low heavy metal fractions. Thus, the fuel composition and assembly design of "pure" burners will vary significantly from conventional IFR core designs. The goal in this paper is to achieve transuranic burning with prototypic assembly and fuel characteristics; in particular, fuel enrichments in the range supported by the current IFR fuels program ( $\text{TRU/HM} \leq 28\%$ ) are targeted.

For a core to burn transuranics, the consumption rate by fission must exceed the production rate (U-238 capture). This criterion is roughly realized when the breeding ratio is less than one. By removing fertile material from conventional IFR core designs, a breeding ratio less than one can be achieved. The starting point for this analysis is a homogeneous 900 MWt core (as developed in Ref. 4) without external blankets; the internal and radial blankets are removed from a conventional radially heterogeneous design. The performance characteristics of such a homogeneous design are compared to a conventional heterogeneous design in Table I. A decrease in breeding ratio from 1.06 to 0.81 is observed; a sodium void worth of around \$5.00 is observed for both cores. The reduction in breeding causes a large increase in burnup reactivity swing from 0.60 % $\Delta k$  to 3.82 % $\Delta k$ .

In this paper, the design of larger (1575 MWt), low void worth, transuranic burning cores is investigated; substantial modifications to the 900 MWt homogeneous core design are required to achieve the design goals. Various design options are evaluated in a series of trade studies; some additional design constraints applied in these studies are:

1. **Enrichment.** The maximum plutonium content being investigated in the current U-Pu-10Zr fuels program is ~25 wt.%; this corresponds to a heavy metal (HM) enrichment of 28 wt.% Pu/HM. The minor actinides are expected to have chemical behavior similar to plutonium in the metal fuel system; thus, an enrichment limit of 28 wt.% TRU/HM is targeted.
2. **Heat Rating.** A prototypic peak linear power limit of 500 W/cm is assumed.
3. **Cycle Length.** A prototypic cycle of length one year is assumed; the capacity factor is allowed to vary from 80% to 85%.
4. **Discharge Burnup.** A prototypic assembly average discharge burnup of 100 MWd/kg is targeted.

To accommodate the higher power rating, the core volume of the homogeneous design must be increased. However, larger cores generally exhibit a higher void worth and breeding ratio. Thus, various options for increasing the core size were evaluated. Volume changes which "spoil" the core shape lead to smaller increases in the void worth and breeding ratio; and volume changes which reduce the core leakage lead to larger increases. Since conventional cores have a H/D ratio less than the "optimum" H/D

(near one), volume changes which reduce the H/D ratio are preferable. Therefore, maintaining (or decreasing) the core height and adding additional assemblies to the outer edge will mitigate the increases in breeding ratio and void worth associated with the power level increase.

To significantly reduce the sodium void worth, substantial modifications of the homogeneous core design are required. The design approach for reducing the void worth is based on interpretation of results given in Ref. 4 where the variation of performance characteristics with void worth was investigated in detail. It was shown that the void worth and breeding ratio can both be reduced by several methods: substitution of moderator for fuel, geometric spoiling (i.e., core height-to-diameter (H/D) ratio reduction), and high sodium fractions (especially for "pancaked" cores). However, of these design options geometric spoiling appears to give the best trade-off between void worth and enrichment. It appears that a near-zero void worth would be difficult to achieve with any of the other methods using prototypic enrichments.

One method for spoiling the core geometry is to decrease the height-to-diameter ratio of the homogeneous core design. H/D ratio reduction can be achieved by reducing the height of the active core region and adding additional driver assemblies to the outer core edge. The effect of H/D reduction was evaluated by progressively adding rings to the homogeneous 900 MWt core design and adjusting the core height to conserve the volume; results are summarized in Table II for H/D ratios varying from 0.54 to 0.17. The void worth decreases smoothly from \$5.34 to \$2.16 and the breeding ratio from 0.808 to 0.603 as the H/D ratio decreases. However, significant increases in enrichment are observed; the maximum enrichment increases from 25.1% TRU/HM to 38.1% TRU/HM as the H/D ratio decreases. Large increases in the burnup reactivity swing are also observed.

The cases shown in Table II were evaluated for infinite recycle where the discharged transuranics are processed back into the core. Significant changes in performance were observed between infinite recycle and startup cores. For low breeding ratio designs, calculations revealed an increase in the relative Pu-240/Pu-239 level with repeated recycle. Since Pu-240 is a fertile material and a significant contributor to the positive spectral component of void worth (because of its threshold fission), the higher Pu-240 content in the recycle case leads to a higher void worth and breeding ratio. As an example, for the 17.4 inch tall core in Table II, the startup core would have a much smaller void worth of \$0.66 and a breeding ratio of 0.50 (the infinite recycle values are \$2.16 and 0.61). The evolution of the transuranic isotopics from the startup core (LWR spent fuel isotopics) distribution to the infinite recycle distribution will require repeated recycle of the discharged transuranics. Since the time required for this isotopic change is a number of years, and since startup cores are of particular interest, the startup isotopics are used throughout the remainder of this paper.

The performance effects of H/D reduction were also evaluated for the target (1575 MWt) core size. H/D reduction was observed to be an effective means for reducing the void worth and breeding ratio; however, the extent of H/D reduction is limited by the targeted enrichment level (28% TRU/HM). The performance characteristics for a 45 cm tall (H/D=0.13) 1575 MWt homogeneous core are summarized in Table III. A void worth of \$1.5 and breeding ratio of 0.56 are achieved at an enrichment level of 29.7% TRU/HM. Thus, some other form of geometric spoiling (which minimizes the enrichment increase) is necessary to achieve a lower void worth.

Another option for spoiling the core geometry is the introduction of a central sink region (creating an annular active core). The performance effects of introducing central regions of varying size and composition were evaluated. The presence of the central region reduces the void worth by two mechanisms:

1. Neutron leakage into the central region when the active core is voided causes an increase in the negative planar leakage component of void worth.
2. An enrichment increase is required leading to a decrease in the driver positive spectral component.

The use of blanket, reflector, sodium, and absorber materials in the central region was evaluated. Since these void worth reduction effects require the central zone to behave as a neutron sink (little reflection back into the core), the presence of absorber in the central zone was found to be most effective in reducing the driver void worth. A significant negative contribution to the void worth can also be achieved by voiding of a central sodium zone. However, it is difficult to propose a passive mechanism which can assure this central (very low power) zone will void with the active core. Without voiding of the central region, the central sodium design behaved similar to a central reflector case; and a central absorber design gave larger reductions in void worth.

Performance evaluations indicate that use of a central absorber zone gives a significant reduction in void worth and breeding ratio; in addition, the presence of a central absorber zone removes the central power peak, and allows a mitigation or elimination of the radial enrichment zoning. Thus, some combination of H/D reduction and a central absorber zone appears to be attractive for void worth reduction at "target" enrichments. The effect of central absorber zone size was investigated by parametrically introducing three, four, and five row absorber zones into the 1575 MWt pancaked homogeneous core; the displaced driver assemblies were added to the outer core edge. Performance results for the annular designs are compared to the homogeneous core performance in Table III. As expected the void worth decreases as the annulus size increases; the void worth is \$0.50, \$0.00, and -\$0.33 for the three, four, and five row cases, respectively. Only a slight decrease in the breeding ratio from 0.56 to 0.50 is observed. Thus, for the four row case a near-zero void worth is achieved with a breeding ratio of 0.52 and an enrichment of 26.7 wt.% TRU/HM; the burnup reactivity swing for this case is 5.97 % $\Delta k$ .

Several other options for reducing the void worth were also investigated. For high leakage configurations, the void worth can be reduced by increases in the fuel pin P/D ratio (higher sodium fraction) for a subset of the fuel assemblies in the core; if the core is sufficiently flat, the increase in local leakage was observed to offset any required volume increase. The void worth of the annular core with a four row central absorber (see Table III) can be reduced by nearly \$0.50 using P/D zoning; if assemblies with a 13% larger lattice pitch are utilized, the enrichment does not increase. However, severe penalties in vessel diameter, heavy metal mass flow, and fuel management complexity are anticipated.

Design options for using thorium (instead of uranium) as a fertile material were also evaluated; significant reductions in void worth and transuranic production (fissile U-233 is created instead of Pu-239) can be achieved using a thorium fuel cycle. However, low void worths were achieved at high fuel enrichment levels; and metal fuel material studies<sup>10,11</sup> indicate that it is doubtful that transuranic enrichment levels above 10% can be achieved in a metal thorium matrix at a reasonable solidus temperature.

Because of the promising performance results exhibited by the flat annular core design with a four row central absorber (see Table III), several refinements of this core were investigated. The use of reflector assemblies in the interior of the central zone was analyzed. Performance characteristics nearly identical to the central absorber case were observed indicating effective absorption in the central zone; thus, the relatively expensive absorber assemblies are needed only in the outer row of the central zone. Based on an evaluation of the control rod worth requirements of this annular core design, additional control locations are allocated to compensate for the large burnup swing. Application of a mid-cycle assembly exchange in the central absorber zone to reduce the burnup reactivity swing was also investigated. By replacing the row 4 absorber assemblies with reflectors at mid-cycle (giving a reactivity insertion and higher void worth), a 1.5 % $\Delta k$  reduction in burnup reactivity swing was observed.

The finally selected low void worth burner design is shown in Figure 1; neutronic performance characteristics are summarized in Table I. The breeding ratio is 0.50 with a void worth of \$0.10. The neutronic performance and reactivity coefficients of this design are evaluated in more detail in Ref. 12; and the passive safety properties are discussed in Ref. 13.

#### IV. TRANSURANIC SELF-SUFFICIENT DESIGN

Since there is a large inventory of LWR spent fuel and a significant current production rate, it is expected that operating advanced LMRs in a transuranic consumption mode will be preferred in the short term. However, it is desirable to allow flexibility in the breeding characteristics; with breeding ratios greater than one, the transuranic inventory can be maintained or increased based on future demand levels. Thus, this section of the paper addresses the design of alternate core models which achieve fissile self-sufficiency (breeding ratio greater than 1.0); in addition, it is desirable to maintain the low sodium void worth. Self-sufficient designs are developed which are interchangeable with the proposed low void worth burner core described above and shown in Fig. 1; the core diameter (number of assemblies) and control rod positions are maintained in the self-sufficient design. Changes in the driver assembly design are kept to a minimum. In many cases, the non-driver assemblies are significantly altered in the self-sufficient design (i.e., reflector assemblies are replaced with blanket assemblies). In addition, design constraints similar to the burner core will be applied (see Section III).

Different material configurations are required for a self-sufficient core with a low void worth; significant amounts of fertile material must be added back to the burner design to achieve fissile self-sufficiency. The design approach for increasing the breeding ratio while maintaining the low void worth is based on interpretation of results given in Ref. 4 where the variation of performance characteristics with void worth was investigated in detail. As discussed in Ref. 4, the same physical phenomena which allow internal breeding lead to positive sodium void worth. Therefore, if low void worth is a design goal, external breeding is preferable.

Fuel cycle calculations were performed with fertile material added externally using radial, axial, and central blanket regions. The radial and central blankets utilize a conventional blanket assembly design; a higher fuel volume fraction is achieved by using thicker pins packed more closely ( $P/D = 1.087$ ) than in the driver. In these blanket assemblies, the fueled region extends 30 cm above and below the active core. Axial blankets are placed within the driver pins; thus, they have a fuel volume fraction identical to the driver assemblies. The axial blankets may be separately placed above and/or below the core with variable thickness. All blanket pins utilize an 85% smear density as compared to 75% in the driver fuel; and a three cycle residence (similar to the driver region) is assumed. The breeding ratio increases from these external breeding zones can be roughly broken down as:

first row Radial Blanket	+0.10
second row Radial Blanket	+0.05
nearest 15 cm Axial Blanket (above and below)	+0.33
next 15 cm Axial Blanket	+0.17
central Blanket (inner 3 rows)	+0.035

Thus, with a single row of radial blanket and 30 cm of axial blanket above and below the core, the breeding ratio can be increased from 0.5 to roughly 1.10.

The performance characteristics for an annular core utilizing a single row of radial blanket and axial blankets above and below the active core are compared to the burner core performance in Table IV. A fissile self-sufficient breeding ratio of 1.09 is achieved. To accommodate the radial blanket, this core design requires displacement of the radial reflector one row outward and the removal of one of the outer shield rows; minor modifications in the driver assembly design are required to accommodate the axial blankets. Thus, this design is readily interchangeable with the burner core design. However, the presence of the upper axial blankets causes a marked increase in the void worth to \$3.0, as compared to \$0.10 in the burner case. This higher overall void worth is largely due to the reduced axial leakage; neutrons do not leak from the core as readily, and the negative upper plenum voiding effect is severely reduced by the presence of the upper axial blanket.

Therefore, it is desirable to remove the upper axial blanket. However, this will significantly decrease the breeding ratio since most of the increase in breeding comes from the axial blankets; thus, additional fertile material must be added elsewhere. To achieve fissile self-sufficiency without an upper axial blanket, a very thick lower axial blanket, a single row of radial blanket, and central blanket assemblies in the inner 3 rows were utilized. In Table IV, the performance results for this core design are also summarized. A breeding ratio of 1.07 is observed with a void worth of \$1.10. Therefore, using a thick (45 cm) lower axial blanket this core achieves fissile self-sufficiency while maintaining an acceptably low void worth. The \$1.00 increase in void worth (compared to the burner core, see Table IV) is caused by a downward shift in the axial power shape; this can also be viewed as a larger effective core height. This power shift decreases the upper axial leakage which reduces the core axial leakage and plenum effects; in addition, the fissile material bred into the lower axial blanket allows a decrease in driver feed enrichment which increases the positive spectral component in the driver. However, the \$1.10 void worth is significantly smaller than the void worth observed for designs with upper axial blankets (\$3.09 as shown in Table IV). Both of the self-sufficient designs require much higher heavy metal mass flows through the fuel cycle facility (over 3 times the burner core rate) to process the large amounts of fertile material. Because of the additional breeding, the burnup reactivity swing is lower (2.5 % $\Delta k$  as compared to 4.6 % $\Delta k$  for the burner core). The enrichment and peak linear power are slightly lower for the self-sufficient designs because of the larger "effective" core volume which includes some power production in the axial and radial blankets. If a slightly higher breeding ratio is desired, one could increase the lower axial blanket thickness, add a second row of radial blanket, increase the pin diameter, or replace the row-4 absorber assemblies with blanket assemblies.

Other options for introducing fertile material were also evaluated. The use of internal blanket assemblies in radially heterogeneous configurations allows fertile blanket assemblies to displace driver assemblies. This allows breeding ratios above 1.0 to be achieved at void worths near \$1.0; however, because of the displaced driver assemblies, significant increases in transuranic enrichment are required. For a configuration with two internal blanket rings, the enrichment requirement is 30.7 wt. % TRU/HM, slightly higher than the "target" enrichment level. The use of mixed-pin bundles, containing both driver and fertile pins, was also evaluated. Because less fertile material is introduced, the mixed-pin assembly is not as effective as an internal blanket assembly for increasing the breeding ratio; a very large number of mixed-pin assemblies would be required to achieve a significant increase in the breeding ratio. Modular configurations, where a favorable void worth is achieved by creating multiple small cores with high neutron leakage fractions, were also evaluated. However, radially and axially modular concepts require large modifications in core geometry; thus, they will not be interchangeable with the burner design shown in Fig. 1.

## V. SUMMARY AND CONCLUSIONS

The core designs developed in this paper differ from conventional IFR designs in two key aspects:

1. sodium void worth. Core designs with a low (near-zero) void worth are developed; the void worth is much larger (\$4 to \$6) in conventional IFR core designs.
2. transuranic management. A fuel cycle which is a net consumer of transuranics is developed. To allow flexibility in breeding characteristics, core designs which are interchangeable with the burner design but achieve fissile self-sufficiency are also developed. Conventional IFR designs are fissile self-sufficient and require no additional transuranics after start-up.

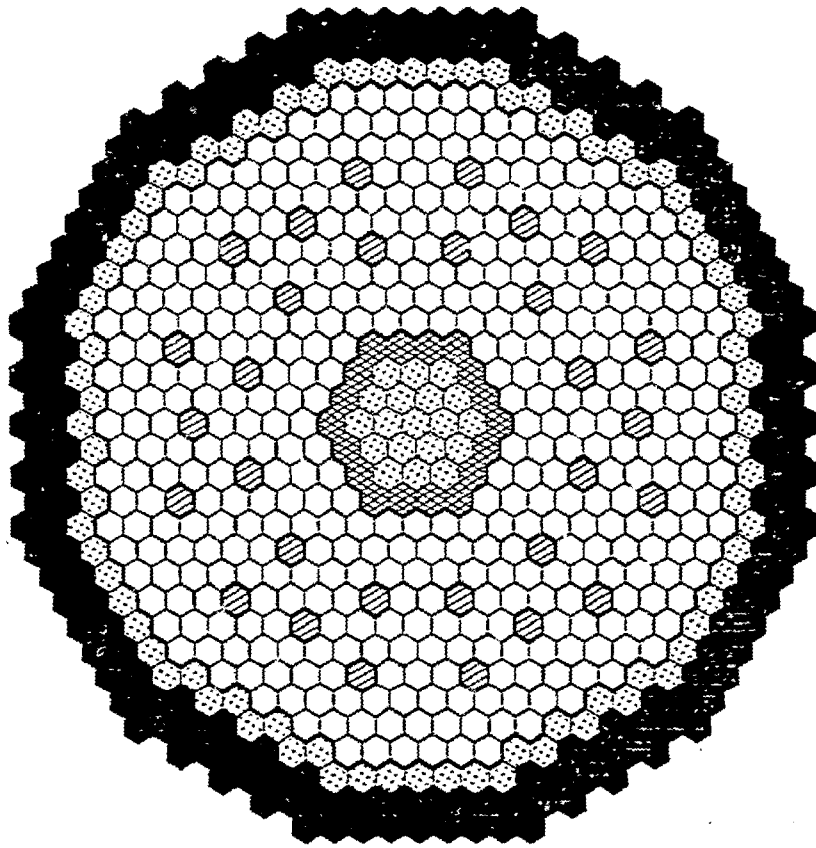
In addition, a power rating of 1575 MWt (600 MWe gross) has been targeted; this is much greater than conventional IFR core designs (i.e., PRISM is 450 MWt). The core designs developed in this study are not viewed as a replacement for the conventional IFR designs, but serve to exhibit the significantly different combination of performance characteristics which are achievable with the iFR metal fuel cycle. The focus of this paper is the neutronics performance of the proposed core designs with the realization

that other design issues (i.e., thermalhydraulic performance, vessel commodities, etc.) remain to be evaluated.

In conclusion, interchangeable transuranic burner and fissile self-sufficient core designs have been developed. These designs utilize a flat, annular core layout; a thick lower axial blanket is used in the self-sufficient design. Both designs utilize prototypic IFR assembly designs (with a short active height) and prototypic IFR metal fuel compositions (less than 28 wt.% TRU/HM). The burner design has a near-zero void worth; and the self-sufficient design has a void worth near \$1.00. It is important to note that these low void worth designs are not unique. The proposed designs evolve from the set of constraints assumed; if additional or conflicting design constraints are used (i.e., limited core diameter), significant changes in the design may be required. The general direction of these changes can be inferred by the results in Ref. 4.

#### REFERENCES

1. R. C. BERGLUND, F. E. TIPPETS, L. N. SALERNO, "PRISM, A Safe, Economic, and Testable Liquid Metal Fast Breeder Reactor Plant," Proc. Intl. Topical Meeting on Safety of Next Generation Power Reactors, Seattle, Washington, p. 599, May 1988.
2. J. S. MCDONALD, "SAFR: An Advanced Modular Liquid Metal Reactor with Inherent Safety Features," Proc. Intl. Topical Meeting on Safety of Next Generation Power Reactors, Seattle, Washington, p. 606, May 1988.
3. R. N. HILL, D. C. WADE, E. K. FUJITA, and H. KHALIL, "Physics Studies of Higher Actinide Consumption in an LMR," Proc. of Int. Conf. on Physics of Reactors, April, 1990 Marseille, France, Vol. 1, p. I-83.
4. R. N. HILL and H. KHALIL, "Evaluation of LMR Design Options for Reduction of Sodium Void Worth," Proc. of Int. Conf. on Physics of Reactors, April, 1990 Marseille, France, Vol. 1, p. II-19.
5. H. HENRYSON II, B. J. TOPPEL, and C. G. STENBERG, "MC<sup>2</sup>-2: A Code to Calculate Fast Neutron Spectra and Multigroup Cross Sections," ANL-8144, Argonne National Laboratory (June 1976).
6. W. M. STACEY Jr. et al., "A New Space-Dependent Fast-Neutron Multigroup Cross-Section Capability," Trans. Am. Nucl. Sci., 15, 292 (1972).
7. B. J. TOPPEL, "A User's Guide to the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, Argonne National Laboratory (March 1983).
8. R. D. LAWRENCE, "The DIF3D Nodal Neutronics Option for Two- and Three-Dimensional Diffusion Theory Calculations in Hexagonal Geometry," ANL-83-1, Argonne National Laboratory (1983).
9. K. L. DERSTINE, "DIF3D: A Code to Solve One-, Two-, and Three-Dimensional Finite-Difference Diffusion Theory Problems," ANL-82-64, Argonne National Laboratory (April 1984).
10. B. BLUMENTHAL, J. E. SANECKI, D. E. BUSCH, and D. R. O'BOYLE, "Thorium-Uranium-Plutonium Alloys as Potential Fast Power-Reactor Fuels, Part II: Properties and Irradiation Behavior of Thorium-Uranium-Plutonium Alloys," ANL-7259, Argonne National Laboratory (October 1969).
11. B. BLUMENTHAL, J. E. SANECKI, and D. E. BUSCH, "Thorium-Uranium-Plutonium Alloys as Potential Fast Power-Reactor Fuels, Part I: Thorium-Uranium-Plutonium Phase Diagram," ANL-7258, Argonne National Laboratory (September 1968).
12. Y. I. CHANG et al., "Core Concepts for Zero-Sodium-Void-Worth Core in Metal Fuelled Fast Reactor," Proc. Intl. Conf. on Fast Reactor and Its Fuel Cycle, Kyoto, October 1991.
13. Y. I. CHANG et al., "Passive Safety Features of Low Sodium Void Worth Metal Fuelled Cores in a Bottom Supported Reactor Vessel," Proc. Intl. Conf. on Fast Reactor and Its Fuel Cycle, Kyoto, October 1991.



DRIVER ASSEMBLY (420)



STEEL REFLECTOR (103)



CONTROL ASSEMBLY (30)



SHIELD ASSEMBLY (186)



B4C EXCHANGE ASSEMBLY (18)

Figure 1. Low Void Worth Actinide Burner Core Layout

Table I. Comparison of Performance Characteristics for Conventional and Low Void Worth Burner and Breeder Designs.

	Conventional Breeder	Conventional Burner	Low Void Burner	Low Void Breeder
Core Layout	Heterogeneous	Homogeneous	Annular	Annular
Power, MWt	900	900	1575	1575
Height, cm	96.5	96.5	45.0	45.0
Breeding Ratio	1.06	0.81	0.53	1.07
EOC Void Worth, $10^{-3}\Delta k/(kk')$				
Total <sup>a</sup>	17.5	18.7	0.54	3.79
Driver:				
Spectral	19.0	32.0	22.2	21.0
Plan. Lkg.	-3.8	-5.6	-3.3	-2.9
Ax. Lkg.	-4.8	-6.9	-10.0	-8.0
Total	11.2	20.9	9.9	11.0
IB	8.2	-	-	-
Plenum	-2.1	-2.3	-9.4	-7.2
Burnup Swing, % $\Delta k$	0.60	3.82	4.17	2.53
Ave. Discharge Burnup, MWd/kg	104.	87.0	82.6	72.8
Peak Liner Power, kW/ft	14.4	15.0	15.1	13.8
Maximum TRU Enrichment <sup>b</sup> , wt. %	24.9	25.1 <sup>c</sup>	25.8	24.8

<sup>a</sup>Total includes active driver, internal blanket, and their plenum regions

<sup>b</sup>Quoted value is weight percent of transuranics in heavy metal; weight percent of transuranics in total fuel matrix is 90% of this value (fuel is 10 wt. % zirconium).

<sup>c</sup>Core uses 1.35 enrichment split

Table II. Comparison of Performance Characteristics<sup>a</sup> for Variation of Core Shape - 900 MWt Size

Height, in.	33.0	28.2	21.8	17.4
Diameter, in.	70.4	80.6	94.8	102.4
H/D ratio	0.54	0.35	0.23	0.17
Breeding ratio	0.808	0.761	0.675	0.603
EOC void worth, $10^{-3}\Delta k/(kk')$				
Total <sup>b</sup>	18.7	15.5	11.5	7.55
Core				
Spectral	32.0	30.6	27.6	24.9
Plan. Lkg.	-5.6	-4.4	-3.4	-3.0
Ax. Lkg.	-6.9	-8.3	-8.8	-9.0
Total	20.9	19.1	16.5	13.8
Plenum	-2.3	-3.6	-5.0	-6.2
Burnup swing, % $\Delta k$	2.88	3.18	3.62	3.90
Ave. discharge burnup, MWd/kg.	87.0	84.4	83.0	81.6
Peak linear power, kW/ft.	15.0	14.5	14.0	14.3
Maximum TRU enrichment <sup>c</sup> , wt. %	25.1	27.9	33.1	38.1

<sup>a</sup> Performance characteristics are based on an infinite recycle calculation, where the transuranics are repeatedly reprocessed back into the core.

<sup>b</sup> Total includes active driver and plenum region.

<sup>c</sup> These cores use 1.35 enrichment split in outer two rows.

Table III. Comparison of Performance Characteristics for Variation of Central Annulus Size<sup>a</sup>

Rows of Annulus	0	3	4	5
Breeding Ratio	0.56	0.53	0.52	0.50
EOC Void Worth, $10^{-3}\Delta k/(kk')$				
Total <sup>b</sup>	5.32	1.72	-0.01	-1.08
Driver				
Spectral	23.4	22.3	21.4	20.8
Plan. Lkg.	-2.8	-4.3	-4.9	-5.3
Ax. Lkg.	-9.2	-9.3	-9.4	-9.4
Total	12.4	9.7	8.2	7.2
Plenum	-7.1	-8.0	-8.2	-8.3
Burnup Swing, % $\Delta k$	5.35	6.00	5.97	5.89
Ave. Discharge Burnup, MWd/kg	90.8	89.6	89.7	82.4
Peak Linear Power, kW/ft	14.9	15.6	15.5	15.1
TRU Enrichment, wt. %	29.7 <sup>c</sup>	26.0	26.7	27.1

<sup>a</sup> Based on a 17.7 inch tall 1575 MWt core design

<sup>b</sup> Total includes active driver and plenum region

<sup>c</sup> This core uses a 1.35 enrichment split in the outer two rows

Table IV. Comparison of Performance Characteristics for Burner and External Breeder Designs.

Lower AB thickness, cm	0	30	45
Upper AB thickness, cm	0	30	0
Breeding Ratio	0.50	1.09	1.067
EOC Void Worth, $10^{-3}\Delta k/(kk')$			
Total <sup>a</sup>	0.35	10.8	3.79
Core			
Spectral	20.7	22.3	21.0
Planar Lkg.	-3.4	-3.3	-2.9
Axial Lkg.	-9.8	-7.1	-8.0
Total	8.5	12.8	11.0
Upper AB	-	-1.7	-
Plenum	-8.2	-0.3	-7.2
RB	-	-0.2	-0.2
Burnup Swing, % $\Delta k$	4.64	2.53	2.53
Ave. Discharge Burnup, MWd/kg	89.6	79.9	72.8
Pk. Linear Power, kW/ft	15.1	13.6	13.8
TRU Enrichment, wt. %	27.8	25.1	24.8
HM. Mass Flow, kg/y			
Total	5330	16200	16728
Driver	5330	5330	5781
AB	-	8000	6552
RB	-	2850	3377
IS <sup>b</sup>	-	-	1018

<sup>a</sup> Total includes active driver as well as above-driver regions (plenum).

<sup>b</sup> IB includes central blanket assemblies