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AN EVALUATION OF LMR DESIGN OPTIONS FOR REDUCTION OF SODIUM VOID WORTH

by

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SUMMARY

I. Introduction

In this study, we analyze the relationship between the sodium void worth (ρ_{NA}) and other important performance characteristics for various design options which reduce ρ_{NA}. Our objective was to identify a preferred design option for reducing ρ_{NA} based on an overall consideration of performance tradeoffs.

The focus of this study is on core designs of recent interest in the U. S. LMR program, i.e. designs in the 450 to 1200 MWt size range that make use of metal alloy fuel. A key objective of the LMR development program in the U.S. [1,2] has been to design cores that can passively avoid damage when the control rods fail to scram in response to postulated accident initiators (e.g. inadvertent reactivity insertion or loss of coolant flow). Analyses and experimental tests [3-7] of such unprotected events have demonstrated that the physical properties of metallic fuel alloys and the neutronic feedback characteristics of metal-fueled cores can be exploited to obtain favorable relations among the power, power/flow, and inlet temperature coefficients of reactivity and, consequently, large margins to sodium boiling and fuel damage under accident conditions. Since the reactivity effects of sodium density variation during postulated accidents are effectively compensated by other feedback effects [3], reduction of the sodium void worth has not been a primary design objective for recent LMR concepts; relatively large values ($4 to $6) are predicted for current core designs [8,9].

Although large margins between the peak coolant temperature and the sodium boiling temperature have been demonstrated for various unprotected transients, there necessarily remains a non-zero probability of at least a limited amount of sodium boiling in a LMR. Several mechanisms have been postulated that can lead to limited voiding, including flow blockages and fuel pin failures leading to release of fission product gases that may "blanket" the pins. The possibility of large-scale voiding as a result of extremely unlikely or unforseen events, e.g. multiple ruptures of inlet coolant pipes, cannot be entirely dismissed either. Such voiding would introduce substantial reactivity ($4 to $6) in current LMR designs and may present an obstacle to their licensing 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.

The goal of reducing the positive sodium void worth of large, Pu-fueled reactors has motivated numerous studies of the sodium void effect; a review of many of these studies, as well as a detailed discussion of the underlying physics is provided by Hummel and Okrent [10]. References 11-13 contain discussions of various aspects of computing the sodium void worth, including uncertainties and comparisons with measurements on critical facilities.

A large number of studies (e.g. Refs. 14-21) have also been performed of the sodium void worth characteristics of different reactor concepts (radially and axially heterogeneous cores, modular cores, "pancaked" cores), as well as of the variation of the sodium void worth with design parameters and its sensitivity to various reactor characteristics [15,17-21]. However, because these studies have not been performed using common sets of data, methods, and assumptions, an evaluation of the relative merits of the different concepts cannot be made with confidence. Moreover these studies have typically either neglected to satisfy important physics and design constraints (e.g. the need to maintain criticality over an operating cycle), failed to base the analyses on a well established set of constraints (e.g. fixed peak linear power and discharge burnup), or applied a set of constraints that may be outdated or overly restrictive (e.g. minimum doubling time). Finally, previous studies have not comprehensively evaluated and reported the various core physics performance tradeoffs associated with design changes made to reduce the sodium void worth; these studies have generally focused on a limited number of performance measures.

In this paper, an actual core design concept is developed for each design change; the methodology and scope of the analyses is described in Section II. Various design options for reducing the sodium void worth are explored in a systematic and self-consistent manner; the options considered encompass geometric changes, compositional changes, and combinations of compositional and geometric changes (e.g. blanket arrangement). In Section III, the performance characteristics of the design options which reduce ρ_{NA} are intercompared.

II. Methods and Analyses

We determined the performance characteristics of the different core designs from equilibrium-cycle diffusion/depletion calculations performed using the REBUS-3 code [22]; the fuel enrichment required for criticality was determined using the REBUS-3 enrichment search techniques. Calculations of ρ_{NA} were done using twenty-one group cross sections processed individually for flooded and flowing-sodium-voided cells. The sodium void worth was calculated for EOEC configurations using exact perturbation theory (using the flooded-core real flux and voided-core adjoint flux) in order to obtain the components of ρ_{NA} by reaction type. Typically, in the voided configuration, the flowing sodium was removed from core and blanket assemblies and from their upper regions (i.e. plenum and, if present, the upper axial blanket).

First, various changes in the core composition with the core geometry fixed were analyzed. The performance effects of replacing a fraction of fuel by steel, sodium, void, BeO, or B_4C were calculated; the results are summarized in Fig. 1. The BeO and B_4C are representative of moderating and absorbing materials. Substitution of other materials not explicitly analyzed is expected to produce a weighted combination of the moderator and absorber substitution effects. Changes in the assembly design which increase the sodium fraction were investigated in greater detail; the sodium fraction was varied from 35% to 60% by increasing the pitch-to-diameter (P/D) ratio and replacing structural material with sodium. In addition, axial streaming corrections were applied using the Benoist method [23].

Next, the dependence of ρ_{NA} and other core performance parameters on core size and shape were addressed for fixed driver and blanket volume fractions. The effects of H/D variation and core size were evaluated by analyzing the characteristics of 450 and 900 MWt cores with similar power densities and varying shape; the results are summarized in Fig. 2. The effect of lattice design changes at different core heights was addressed; leakage effects are more pronounced for shorter cores. The effect of using axial blanket (to increase breeding) or absorber regions was also calculated as a function of H/D. Although most of the design changes conserve the power density and discharge burnup, their variation was also addressed.

Finally, the dependence of the core performance parameters on the internal blanket configuration was addressed. Axial and radial heterogeneous cores with varying blanket content and arrangement were analyzed. The configurations analyzed included annular cores with a single central blanket region (of varying size) and modular cores separated by blanket subassemblies. The results for various blanket configurations are summarized in Fig. 3.

III. Comparison of Design Options for Void Worth Reduction

The design methods which were found to permit significant decreases in ρ_{NA} are (a) replacement of a fraction of the fuel content by moderator (specifically BeO), (b) substantially increasing the sodium volume fraction in the core, (c) reducing core volume, (d) "spoiling" core geometry by reducing the height-to-diameter ratio (H/D), (e) introducing absorbing material above the core, and (f) use of thick blanket regions to separate driver regions in the core. In general, reducing the void worth lead to a deterioration in the other performance characteristics (e.g. a smaller breeding ratio, and larger burnup swing, fissile requirement, and core radius).

In this section we evaluate the relative merits of the different methods for reducing the void worth. The design options affect a specified core performance parameter in different ways for a **fixed reduction in** ρ_{NA}. Thus, plots of a specified performance parameter as a function of void worth for the various design changes illustrate the tradeoff between that parameter and void worth for each design option. In Section III.A, we analyze the performance tradeoffs for various design options applied to a 900 MWt core size. In Section III.B, the effect of core size is addressed by comparing results for 450 and 900 MWt cores.

III.A Comparison of Design Options for 900 MWt Size

Figures 4 through 8 show the performance tradeoffs for several design methods which reduce the void worth; these figures illustrate the burnup reactivity swing, breeding ratio, fissile loading requirement, core volume, and core radius as a function of the sodium void worth. The tradeoff between ρ_{NA} and each of these performance characteristics is discussed below; based on the single performance objective being considered, the best method for reducing the void worth is identified.

III.A.1 Burnup Reactivity Swing

Figure 4 reveals that the various design options for reducing ρ_{NA} generally lead to an undesirable increase in the burnup reactivity. Fundamentally, design changes that reduce void worth have an adverse effect on neutron economy and, therefore, on the internal breeding efficiency. For example, the introduction of moderating material (effective in reducing the spectral component) is harmful to the neutron economy because it displaces heavy metal and softens the energy spectrum. Similarly, a large reduction in H/D degrades the neutron balance by increasing leakage.

Based on the results shown in Fig. 4, there appears to be a lower bound on the burnup swing achievable for a given void worth; this bound decreases as the void worth increases. This "minimum burnup swing line" (whose position is estimated in Fig. 4) quantifies the best achievable tradeoff between burnup reactivity and void worth; the slope of this line is approximately $(0.1\%\Delta k/(kk'))_{NA}$ / $(0.16\%\ \Delta k)_{BU}$ or an increase in burnup swing by \$1.60 for a \$1.0 decrease in void worth. Many core designs (e.g. a conventional homogeneous core) fall above the minimum burnup swing line. For such cores, it is clearly possible to reduce void worth without increasing burnup reactivity. On the other hand, the tightly coupled heterogeneous cores typical of current designs in the U.S. [8,9] appear to fall on the minimum void worth line, indicating that a reduction in void worth cannot be accomplished without an increase in burnup swing.

For an initial design point falling on (or near) the minimum void worth line, the best options for reducing void worth are those which follow the minimum burnup swing line (implying minimum burnup swing penalty for the specified reduction in void worth). Examination of Fig. 4 reveals that three design options satisfy this goal: H/D reduction, moderator substitution, and increasing the thickness of blanket regions separating core zones in heterogeneous designs. Design options producing points above the minimum burnup swing line include increasing the core sodium fraction and the use of annular cores. It can be observed, however, that for high burnup swings (> 3.0% Δk), the annular and high-sodium-fraction cores move closer to the minimum void worth line and could be competitive methods for reducing void worth and minimizing the burnup swing penalty.

III.A.2 Breeding Ratio

The tradeoff between void worth and breeding ratio for the various designs is shown in Fig. 5; the trends suggest that the best tradeoff between void worth and breeding ratio is provided by cores with substantial external breeding and relatively poor internal breeding (because of the fundamental inconsistency between efficient neutron economy and a low void worth). Thus, loosely coupled cores and annular cores with large central blanket regions allow the void worth reduction to be achieved without a substantial penalty in breeding ratio. Note that if H/D reduction is employed to reduce void worth, the breeding ratio decreases almost linearly with the void worth; this decrease is a result of the increases in leakage and enrichment as H/D is reduced to lower the void worth. Also note that design options that reduce the heavy metal concentration (e.g. moderator or sodium substitution for fuel) lead to the most severe breeding ratio penalties.

III.A.3 Fissile Requirement

The various options for void worth reduction consistently result in increased fissile loading requirement. Figure 6 illustrates the void worth as a function of annual fissile requirement for various designs. There appears to be a minimum fissile loading line analogous to that previously described for burnup swing. This line coincides with the void worth vs. fissile requirement tradeoff as the size of the central blanket region increases in going from a homogeneous to an annular core. A tightly coupled heterogeneous core is seen to be penalized relative to a homogeneous core in both void worth and fissile requirement. However, reducing H/D for such a core produces a comparable decrease in void worth for a given increase in fissile requirement as is obtained by increasing the blanket size in the annular core (the tradeoff line is displaced upward from the minimum void worth line but has roughly the same slope). Figure 6 also shows that the fissile penalty for a fixed void worth reduction is greater if void worth reduction is achieved by moderator substitution, sodium fraction increase, or use of loosely coupled heterogeneous cores.

III.A.4 Core Volume and Radius

The variations in void worth with core volume and radius are shown in Figs. 7 and 8, respectively. These figures display substantial penalties resulting from void worth reduction by means of H/D reduction or the use of loosely coupled or annular configurations. The annular and loosely coupled concepts lead to large increases in both volume and radius, while the reduction of H/D preserves volume but leads to a large increase in core radius. On the other hand, material substitutions (e.g. sodium or moderator for fuel) performed for a fixed core geometry enable void worth reduction with no penalty in core volume or radius.

III.B Performance Trends as a Function of Core Size

Another option for void worth reduction is the use of (a larger number of) smaller cores; i.e. greater "modularity" for a specified total thermal output. The performance tradeoffs for 450 and 900 MWt cores with different H/D values are compared in Figs. 9, 10, and 11; these figures illustrate the tradeoffs for the various cores between void worth and burnup reactivity, fissile requirement (per MWt), and breeding ratio, respectively.

Figure 9 shows that the slope of the tradeoff between void worth and burnup swing (as H/D is varied) is very similar for the two core sizes, although the "minimum burnup swing line" appears to be slightly lower for the 450 MWt size. However, the lowest burnup swing achievable with the 450 MWt size (for H/D ≈ 1) is not as small as with the 900 MWt size.

Figure 10 shows that the 450 MWt core size results in a slightly less favorable tradeoff between sodium void worth and fissile requirement per MWt than the 900 MWt size as H/D is varied.

The void worth vs. breeding ratio trends with H/D variation (see Fig. 11) appear rather similar for the two core sizes. However, a higher breeding ratio (at H/D ≈ 1) is seen to be achievable with the 900 MWt size.

Figures 9 through 11 also illustrate how the introduction of axial blanket material or absorbing material into the above- and below-core regions affects the tradeoffs between void worth and performance characteristics for the 450 MWt core. From Fig. 9, it can be seen that the use of axial blankets affects the tradeoff between void worth and burnup reactivity in a manner similar to an increase in H/D. Conversely, the use of an absorbing material has an effect similar to a decrease in H/D. The magnitudes of the changes in void worth and burnup swing (as a result of the axial region composition change) are greater when the axial composition change is made for cores with small H/D, fundamentally because axial leakage increases with decreasing H/D. The principal benefit of axial blanket use is the improved tradeoff between void worth and breeding ratio, as shown in Fig. 11. However, axial blanket use would make other tradeoffs less favorable (for example the tradeoff between void worth and core radius). Conversely, the use of absorbing material above and below the core permits a decrease in core radius for a specified void worth but also results in less favorable tradeoffs between void worth and other performance parameters such as fissile requirement and breeding ratio.

IV. SUMMARY AND CONCLUSIONS

Systematic analyses of alternative methods for reducing the sodium void worth for plutonium-fueled liquid metal reactors (LMRs) have been performed. The focus has been on core designs of recent interest in the U.S. LMR program, i.e. designs in the 450 to 1200 MWt size range that make use of metal alloy fuel. The design alternatives encompass changes in composition and geometry. A self-consistent and comprehensive evaluation has been made of the void worth reduction achievable by various methods and of the associated core physics performance tradeoffs. We have quantified the performance penalties (e.g. the reduced breeding efficiency and the increases in burnup reactivity loss and fissile mass requirement) caused by design changes that significantly reduce the void worth and assess the relative merits of each design option.

Our results indicate that the penalties in burnup reactivity loss and fissile requirement can be minimized by use of a "tightly-coupled" radially heterogeneous configuration of minimum volume consistent with fuel rating limits and by adjusting the core height-to-diameter ratio to a value sufficiently small to yield an acceptable void worth. The reactor breeding ratio penalty, however, is minimized by the use of loosely coupled heterogeneous cores or annular cores with a large central blanket zone. Penalties in core radius and volume can be minimized by core composition changes, specifically replacement of a fraction of the fuel (or steel) by sodium or a moderating material.

In conclusion, the results presented in this report clarify the design options which exhibit superior performance tradeoffs for individual performance parameters. However, no design option appears to be superior for all performance characteristics. Thus, choice of a "best" method for reducing void worth depends on the importance attached to various core characteristics in a particular design effort; such a choice must also be based on broader considerations related to technical feasiblity, economic viability, and safety.

REFERENCES

1. D. C. Wade, "Overview of Advanced LMR Design in the U.S.," Proc. Intl. Reactor Physics Conference, Jackson Hole, Wyoming, Vol. I, p. I-159, September 1986.

2. C. E. Till, W. H. Arnold, and J. D. Griffith, "The U.S. Liquid Metal Reactor Development Program," Proc. Intl. Topical Meeting on Safety of Next Generation Power Reactors, Seattle, Washington, p. 592, May 1988.

3. D. C. Wade and Y. I. Chang, "The Integral Fast Reactor (IFR) Concept: Physics of Operation and Safety," Proc. Intl. Topical Meeting on Advances in Reactor Physics, Mathematics, and Computation, Paris, Vol. 1, p. 311, April 1987.

4. J. E. Cahalan, R. H. Sevy, and S. F. Su, "Accomodation of Unprotected Accidents by Inherent Safety Design Features in Metallic and Oxide-Fueled LMFBRs," Proc. Intl. Topical Meeting on Fast Reactor Safety, Knoxville, Tennessee, Vol. 1, p. 29, April 1985.

5. H. P. Planchon et al., "Implications of the EBR-II Inherent Safety Demonstration Test," Nuclear Engineering and Design, 101, 1 (1987).

6. H. P. Planchon et al., "The Experimental Breeder Reactor II Inherent Shutdown and Heat Removal Tests - Results and Analysis," Proc. Intl. Topical Meeting on Fast Reactor Safety, Knoxville, Tennessee, Vol. 1, p. 281, April 1985.

7. J. I. Sackett et al., "Inherent Safety and Operability Testing in EBR-II," Proc. Intl. Topical Meeting on Safety of Next Generation Power Reactors, Seattle, Washington, p. 385, May 1988.

8. R. C. Berglund, F. E. Tippets, and 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.

9. 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.

10. H. H. Hummel and D. Okrent, Reactivity Coefficients in Large Fast Power Reactors, American Nuclear Society, LaGrange Park, Illinois, pp. 82-132 (1970).

11. M. Salvatores, "Fast Reactor Calculations," in CRC Handbook of Nuclear Reactor Calculations (Y. Ronen, Editor), CRC Press, Boca Raton, Florida, Vol. III, pp. 334-346 (1986).

12. A. T. D. Butland, W. N. Simmons, and J. M. Stevenson, Calculating Sodium-Voiding Reactivity in Plutonium Fuelled Reactivity in Plutonium-Fuelled Fast Reactors," Proc. Intl. Symposium on Fast Reactor Physics, Aix-en-Provence, France, Vol. I, p. 281, September 1979.

13. C. L. Beck et al., "Sodium Void Reactivity in LMFBR's, A Physics Assessment," Proc. ANS Topical Meeting on Advances in Reactor Physics and Core Thermal Hydraulics, Kiamesha Lake, New York, Vol. 1, p. 78, September 1982.

14. S. F. Su, "Physics Performance of Heterogeneous LMFBRs with Internal Axial Blankets," Trans. Am. Nucl. Soc., 29, 578 (1978).

15. S. F. Su, "The Effect on Performance of Core Height Reduction in 1200-MW(e) LMRBRs," Trans. Am. Nucl. Soc., 27, 578 (1977).

16. W. P. Barthold et al., "Potential and Limitations of the Heterogeneous Reactor Concept," Trans. Am. Nucl. Soc., 26, 552 (1977).

17. S. F. Su and W. P. Barthold, "Sodium Void and Doppler Reactivities in Oxide and Carbide LMFBRs," Trans. Am. Nucl. Soc., 26, 458 (1977).

18. "Liquid Metal Fast Breeder Reactor Design Study," CEND-200, Combustion Engineering, Inc. Report Prepared for the U.S. Atomic Energy Commission, Vol. II, January 1964.

19. W. P. Barthold et al., "Core Design and Optimization of High-Performance, Low-Sodium-Void, 1000-MW(e) Heterogeneous Oxide LMFBR Cores," Proc. Intl. Symposium on Fast Reactor Physics, Aix-en-Provence, France, Vol. II, p. 135, September 1979.

20. B. R. Seghal et al., "Studies on Heterogeneous Core Designs for 1000-MW(e) LMFBRs," Proc. Intl. Symposium on Fast Reactor Physics, Aix-en-Provence, France, Vol. II, p. 191, September 1979.

21. K. Koyama et al., "Effect of Fission Product Accumulation on Sodium-Void Worth," Proc. Intl. Symposium on Fast Reactor Physics, Aix-en-Provence, France, Vol. I, p. 583, September 1979.

22. B. J. Toppel, "A User's Guide to the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, Argonne National Laboratory, March 1983.

23. P. Benoist, "Theorie du Coefficient de Diffusion des Neutrons dans us Reseau Comportant des Cavites," CEA-R-2278, Saclay, France, 1964.

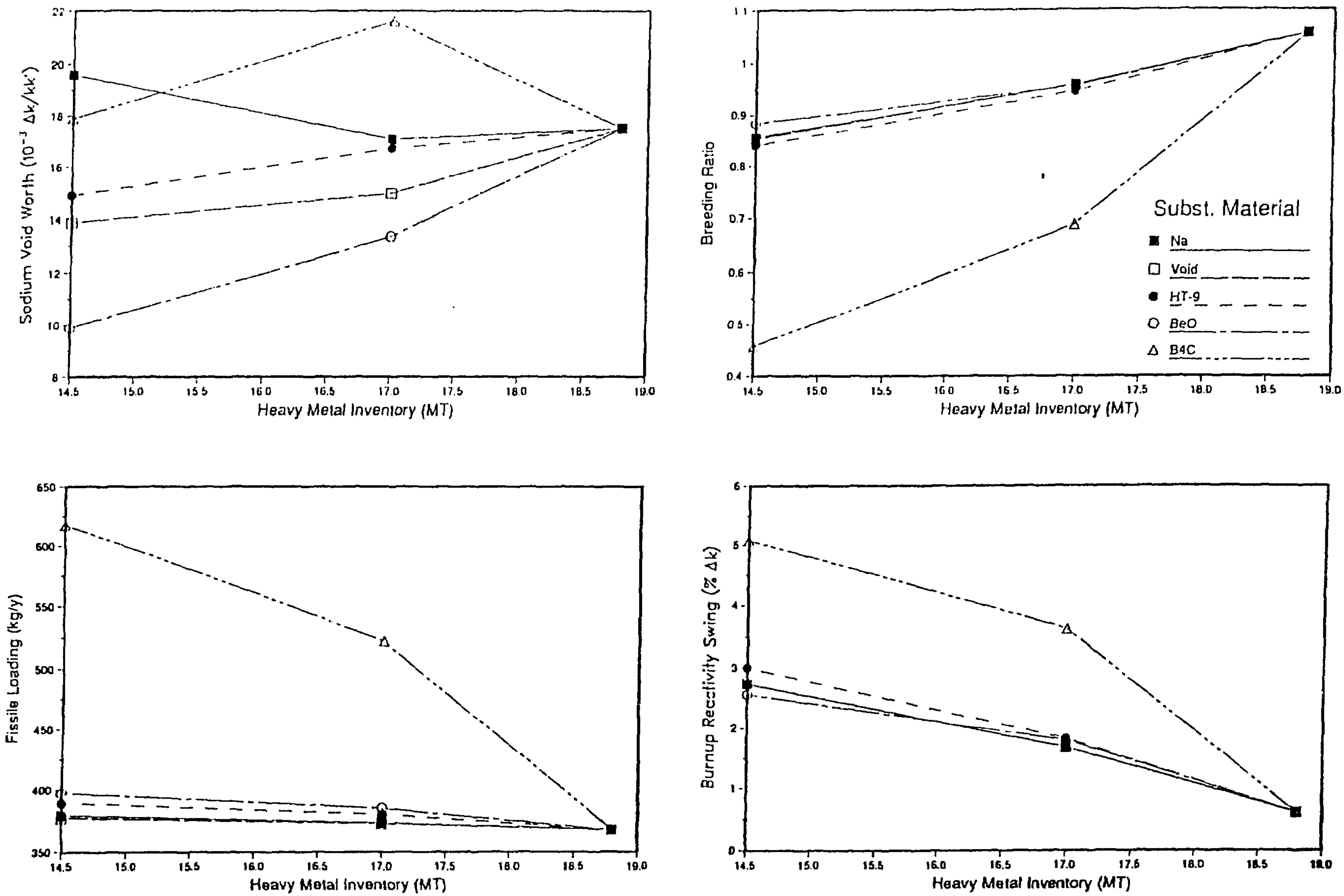


FIG. 1. VARIATION OF PERFORMANCE CHARACTERISTICS WITH HEAVY METAL INVENTORY FOR SUBSTITUTION OF FIVE DIFFERENT MATERIALS FOR FUEL

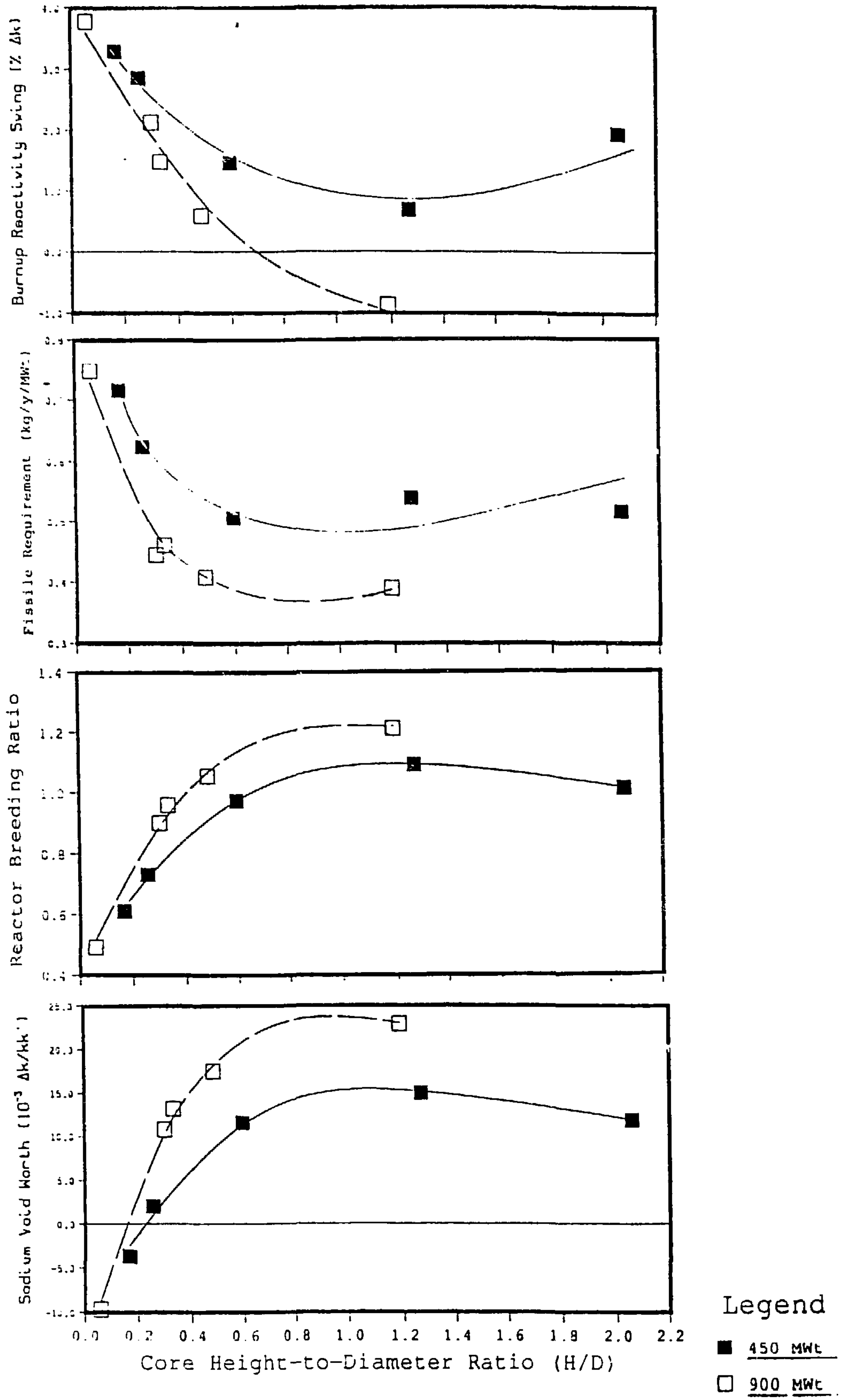


FIG. 2. VARIATION OF PERFORMANCE CHARACTERISTICS WITH CORE SHAPE FOR 450 AND 900 MWt CORE SIZES

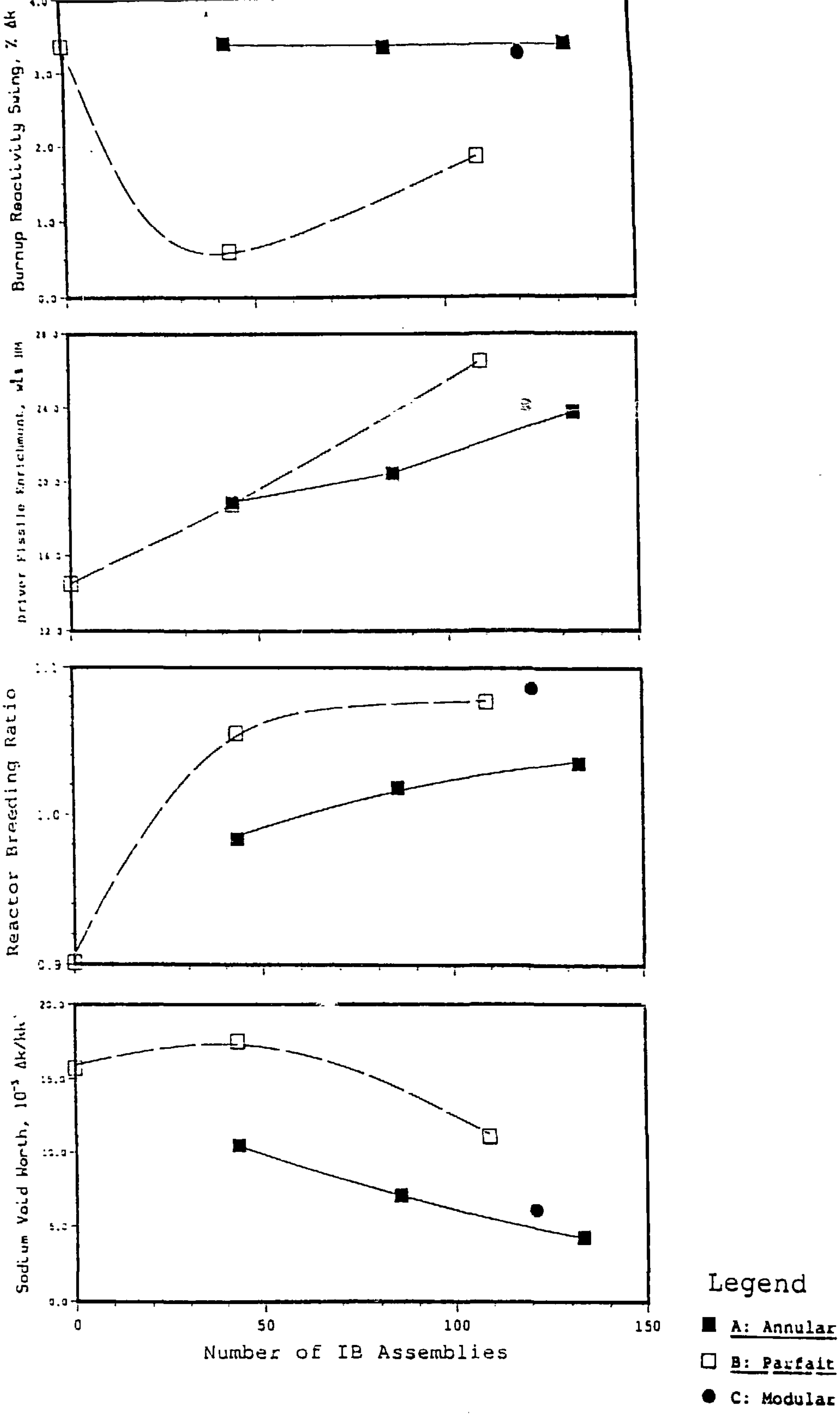
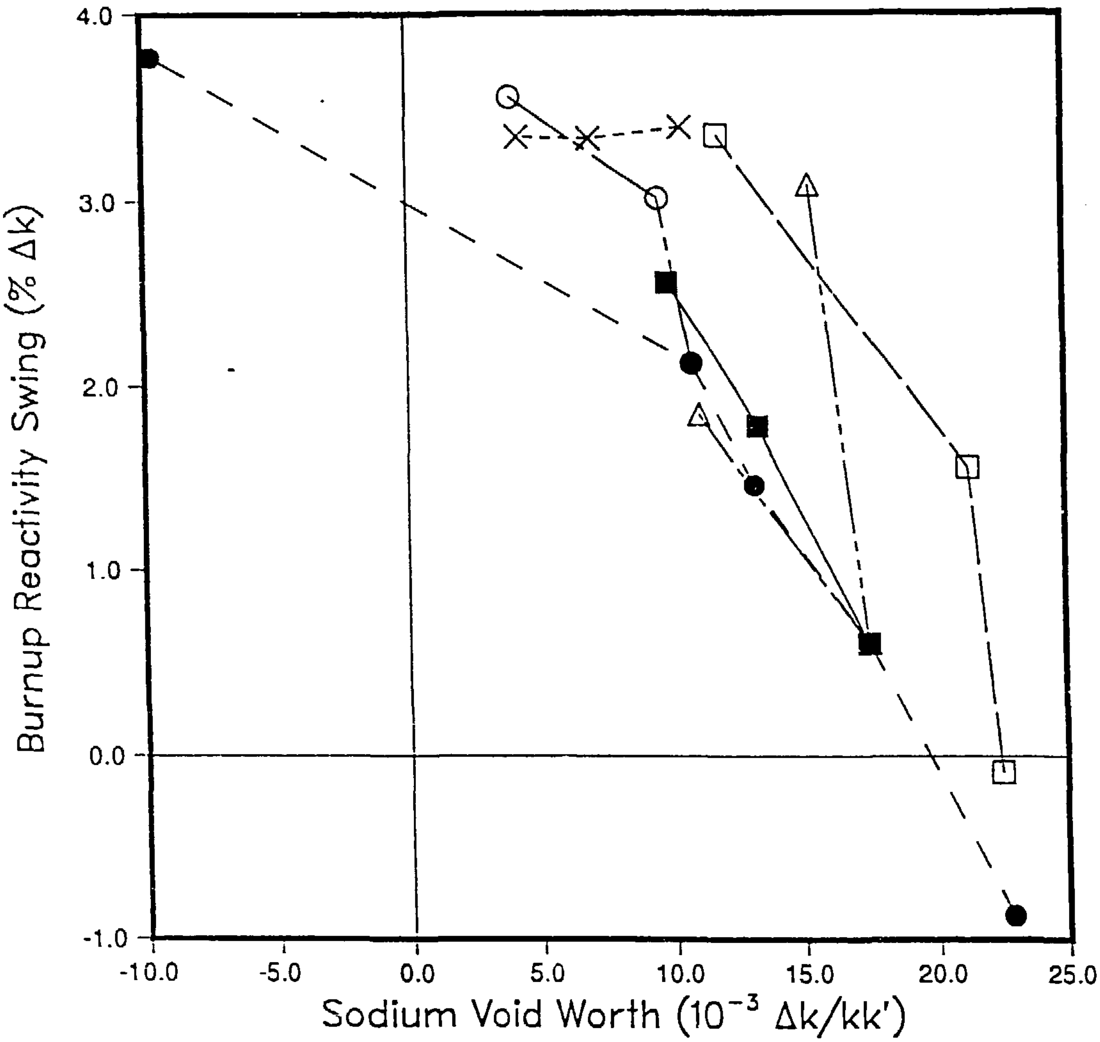


FIG. 3. VARIATION OF PERFORMANCE CHARACTERISTICS WITH THE NUMBER AND ARRANGEMENT OF INTERNAL BLANKET ASSEMBLIES



■ Substitution of Moderator (BeO) for Fuel

□ Increasing Core Sodium Fraction (Subst. of Na for fuel and steel)

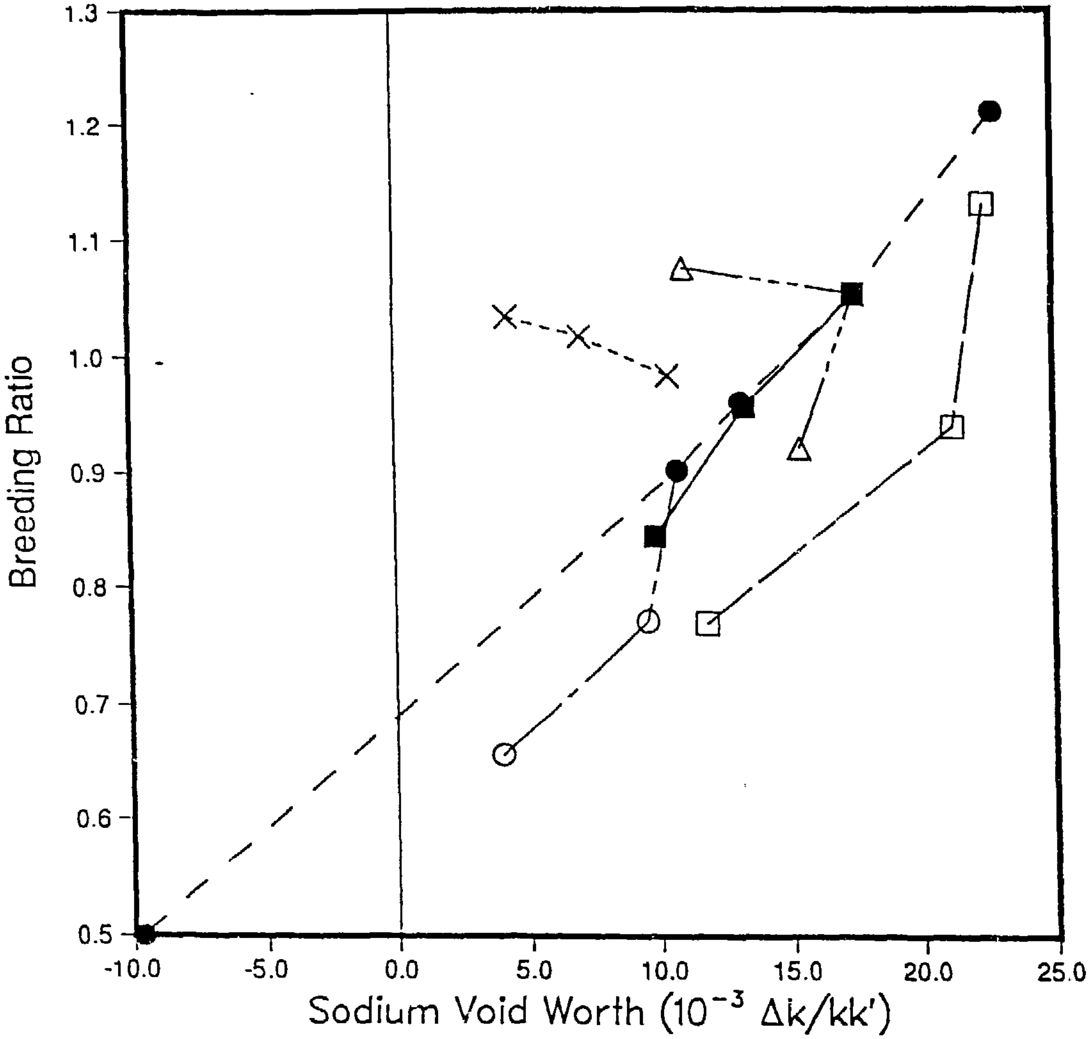
● Reduction of Core H/D Ratio

○ Increasing P/D Ratio for Short Cores

△ Increasing Blanket Thickness Separating Core Zones (includes homog.)

× Increasing Size of Central Blanket for Annular Cores

FIG. 4. TRADE-OFF OF VOID WORTH AND BURNUP SWING FOR 900 MWt CORES



■ Substitution of Moderator (BeO) for Fuel

□ Increasing Core Sodium Fraction (Subst. of Na for fuel and steel)

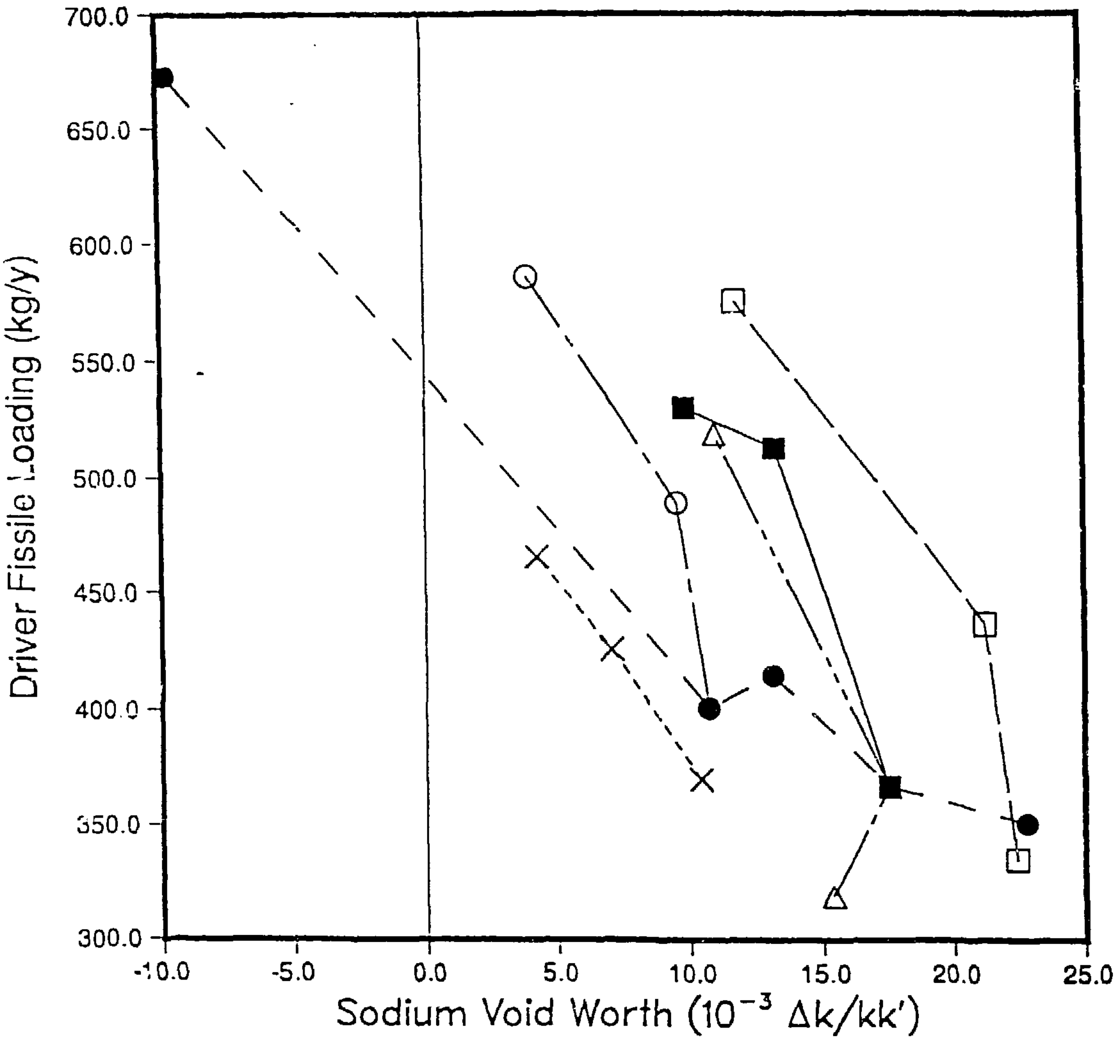
● Reduction of Core H/D Ratio

○ Increasing P/D Ratio for Short Cores

△ Increasing Blanket Thickness Separating Core Zones (incudes homog.)

× Increasing Size of Central Blanket for Annular Cores

FIG. 5. TRADE-OFF OF VOID WORTH AND BREEDING RATIO FOR 900 MWt CORES



■ Substitution of Moderator (BeO) for Fuel

□ Increasing Core Sodium Fraction (Subst. of Na for fuel and steel)

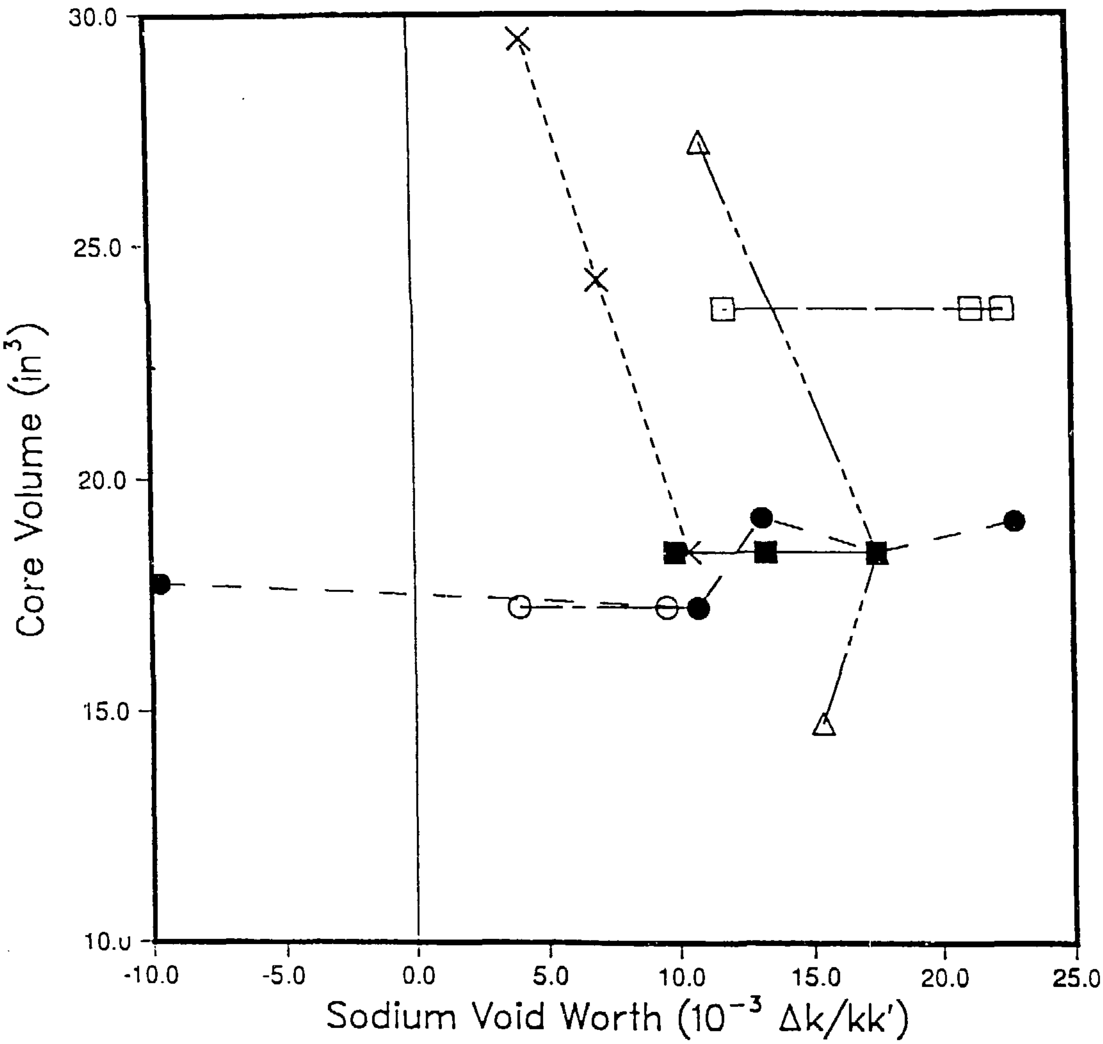
● Reduction of Core H/D Ratio

○ Increasing P/D Ratio for Short Cores

△ Increasing Blanket Thickness Separating Core Zones (includes homog.)

× Increasing Size of Central Blanket for Annular Cores

FIG. 6. TRADE-OFF OF VOID WORTH AND FISSILE LOADING FOR 900 MWt CORES



■ Substitution of Moderator (BeO) for Fuel

□ Increasing Core Sodium Fraction (Subst. of Na for fuel and steel)

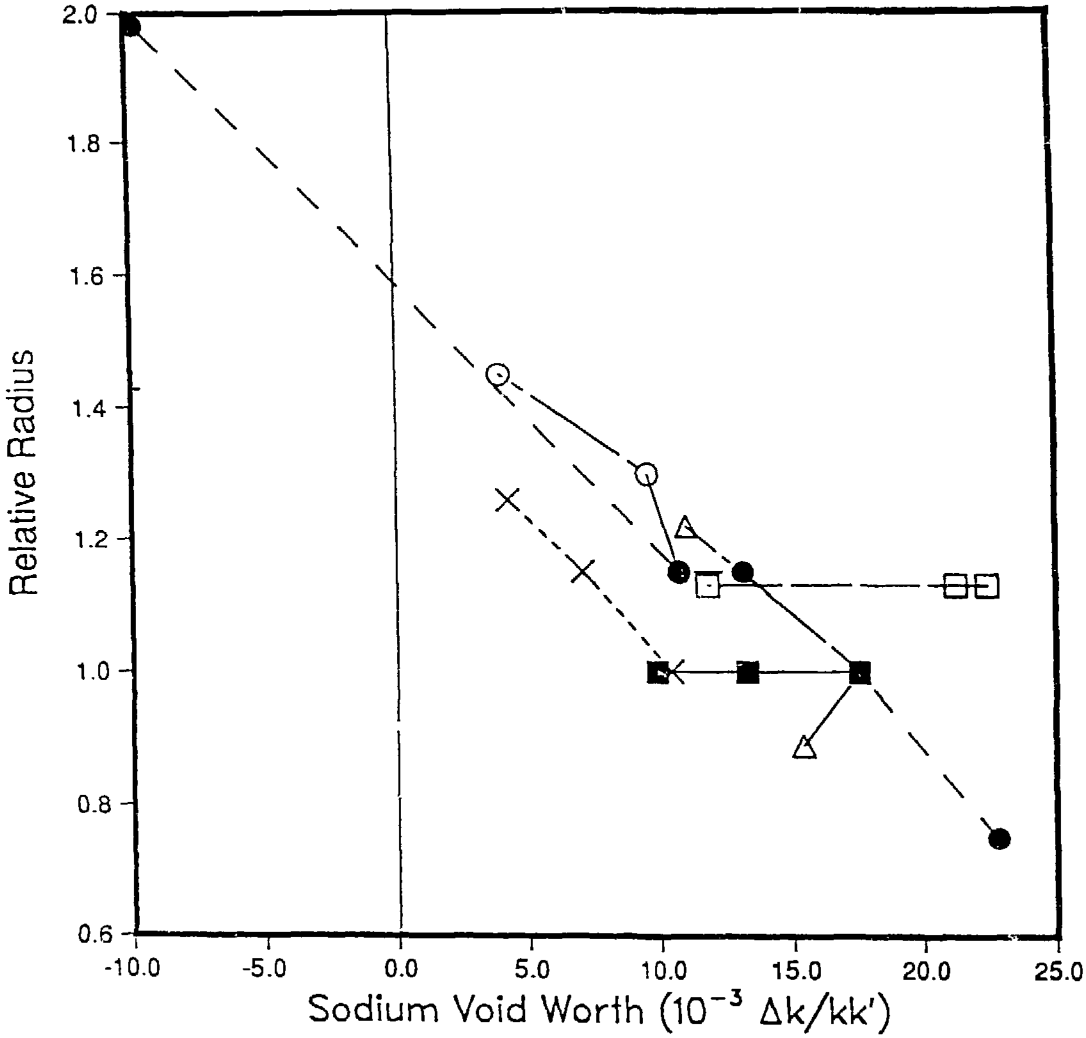
● Reduction of Core H/D Ratio

○ Increasing P/D Ratio for Short Cores

△ Increasing Blanket Thickness Separating Core Zones (includes homog.)

× Increasing Size of Central Blanket for Annular Cores

FIG. 7. TRADE-OFF OF VOID WORTH AND CORE VOLUME FOR 900 MWt CORES



■ Substitution of Moderator (BeO) for Fuel

□ Increasing Core Sodium Fraction (Subst. of Na for fuel and steel)

● Reduction of Core H/D Ratio

○ Increasing P/D Ratio for Short Cores

△ Increasing Blanket Thickness Separating Core Zones (includes homog.)

× Increasing Size of Central Blanket for Annular Cores

FIG. 8. TRADE-OFF OF VOID WORTH AND CORE RADIUS FOR 900 MWt CORES

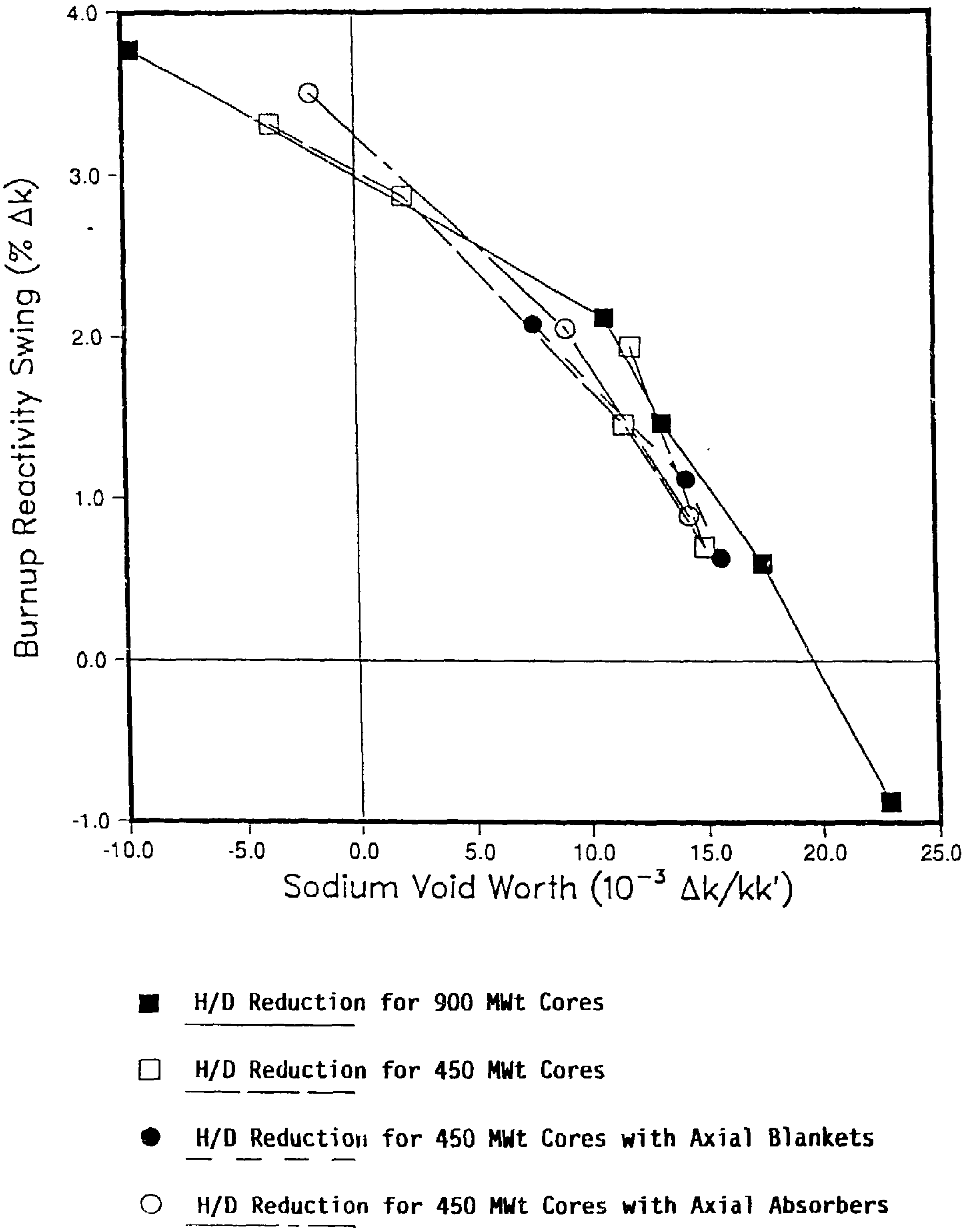
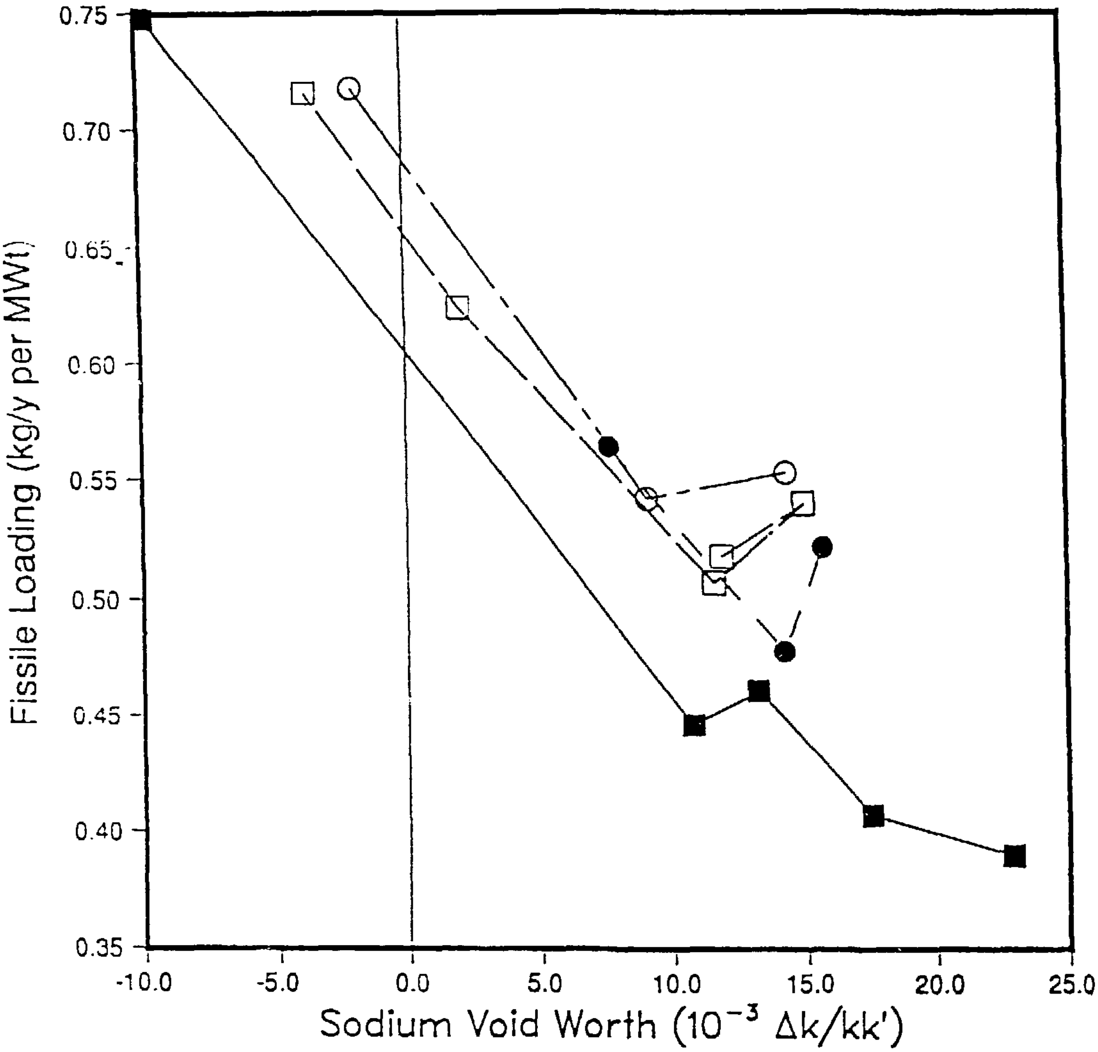


FIG. 9. COMPARISON OF VOID WORTH TO BURNUP SWING TRADE-OFFS FOR 900 AND 450 MWt CORE SIZES



■ H/D Reduction for 900 MWt Cores

□ H/D Reduction for 450 MWt Cores

● H/D Reduction for 450 MWt Cores with Axial Blankets

○ H/D Reduction for 450 MWt Cores with Axial Absorbers

FIG. 10. COMPARISON OF VOID WORTH TO FISSILE LOADING TRADE-OFFS FOR 900 AND 450 MWt CORE SIZES

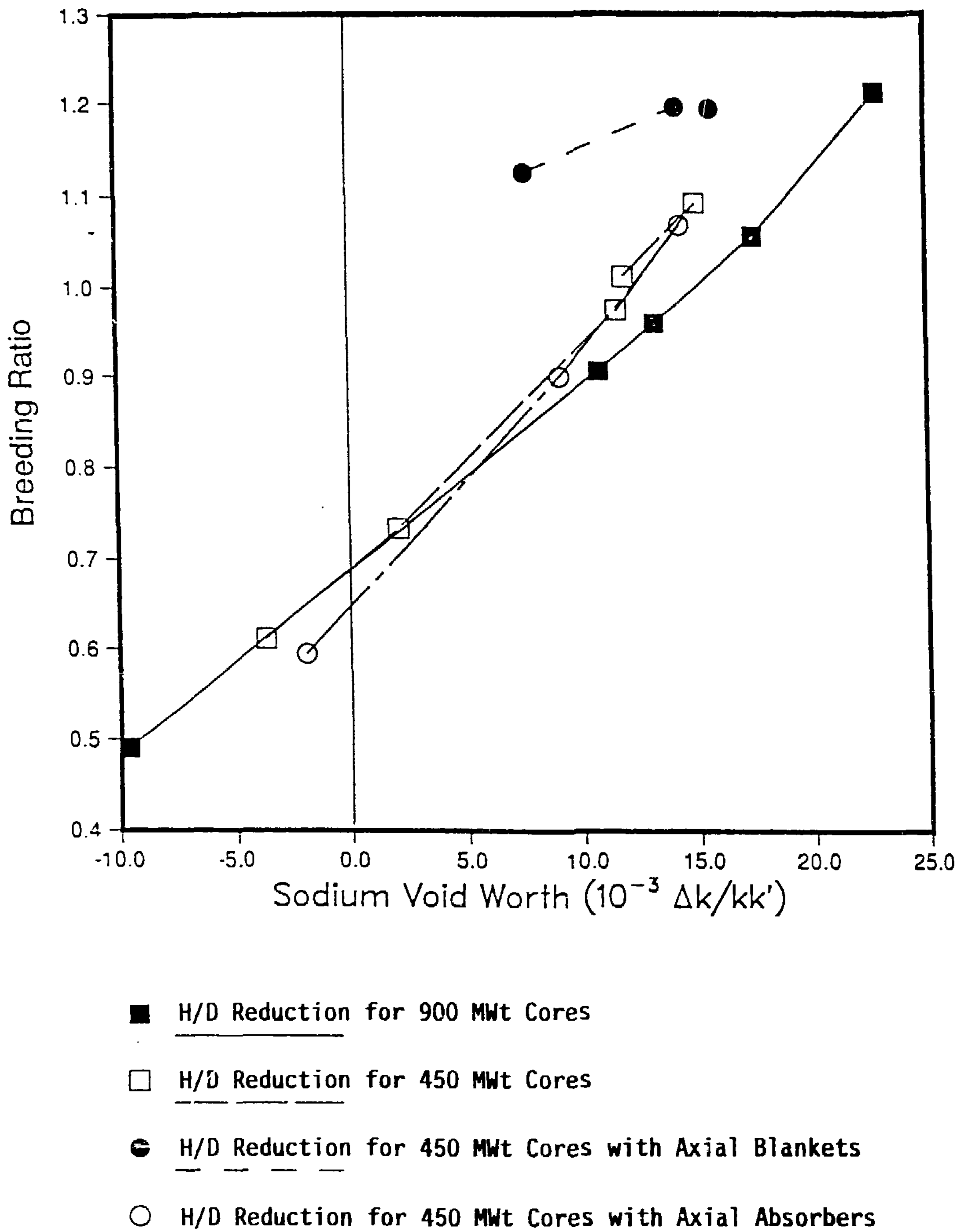


FIG. 11. COMPARISON OF VOID WORTH TO BREEDING RATIO TRADE-OFFS FOR 900 AND 450 MWt CORE SIZES