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D. J. Bender and J. D. Lee

MASTER

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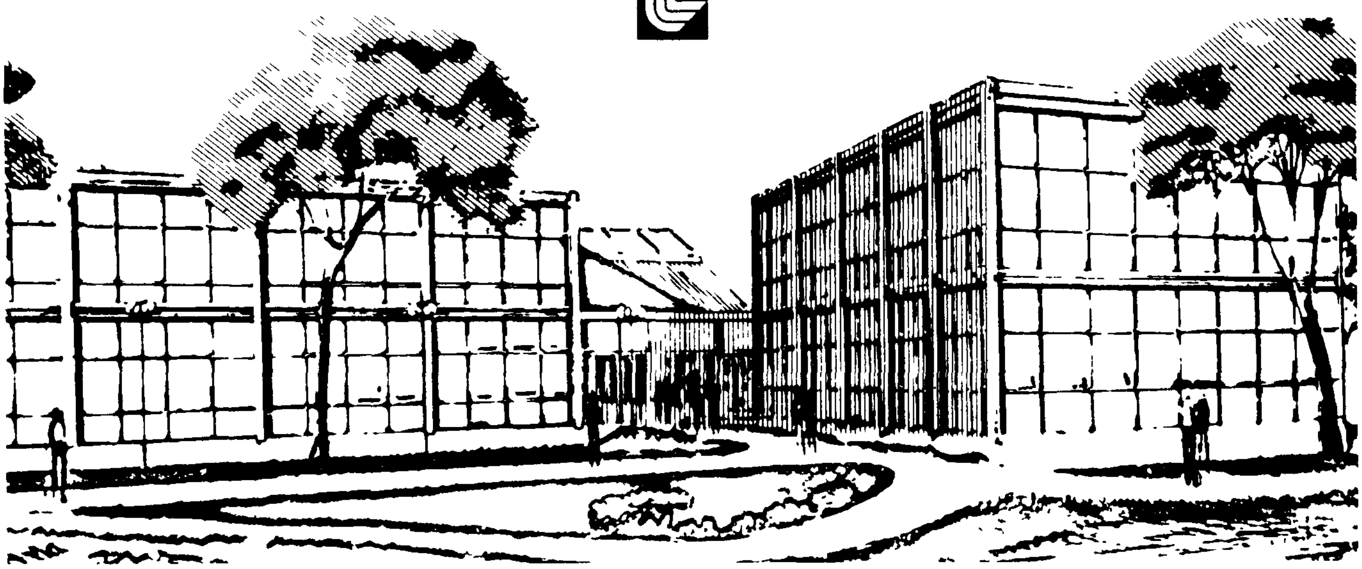

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THE POTENTIAL FOR FISSILE BREEDING WITH THE FUSION-FISSION HYBRID REACTOR

D. J. Bender

J. D. Lee

Lawrence Livermore Laboratory

The primary objectives of the first LLL fusion-fission hybrid reactor point design[1] were to determine a manner in which all of the necessary system components could be integrated into the reactor, to assess the technological problems, and to obtain a rough cost estimate. The resulting design was not optimized in either an engineering or economic sense, but rather was a reference point design from which further study could proceed.

Based on the point design cost estimates, it appeared that a generic feature of the hybrid reactor was that the requirement of incorporating fusion and fission components in the reactor would make the hybrid capital cost ($/kWe) more expensive than a fission reactor. However, the impressive fissile breeding performance of the hybrid, as compared to a fast breeder reactor, indicated that the most promising avenue for commercialization of this reactor concept was as a fissile breeder, with electricity production as a

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by-product. Therefore, the LLL hybrid study this year has concentrated on optimizing the hybrid for fissile production, employing the technique of parametric system analysis of the plant ecomonics. Additional reactor aspects receiving attention this year include the following.

- The uranium blanket has been modified from the original design to improve neutronic performance. Also, preliminary neutronic design of a thorium blanket has been complete.
- The blanket mechanical design has been reconfigured into a spherical shell, providing a uniform first wall loading and a simple blanket removal-replaced operation.
- In conjunction with General Atomic Co., a more detailed treatment of the fission components and heat transfer loop has been completed. This work has emphasized the use of state-of-the-art gas-cooled reactor technology. Although the present presentation does not explicitly delineate the General Atomic contribution[2], we acknowledge the significant impact the General Atomic effort has had on improving the mirror hybird concept.
- A simultaneous DT mirror power reactor study at LLL[3] has required consideration of many problem areas in common with the hybrid, such as fusion component design, cost analysis and plant layout. A significant portion of the design and analysis developed for the power reactor has been incorporated in the hybrid study.

Preliminary results of the present study were presented at the 1975 Winter ANS meeting[4], at which time we predicted hybrid Pu costs of 35 $/gm (reduced by about a factor of 4 from the point design value). Since that presentation, we have continued to refine our reactor system model, primarily in the areas of plasma physics, capital cost and component modeling. The result has been to increase our predicted hybrid Pu value to 55 $/gm, a still economically attractive product. At this time, we are reporting final results of this year's system optimization studies of a uranium blanket hybrid, and preliminary scoping studies of a thorium blanket hybrid.

The general features of the mirror reactor design are shown in Fig. 2. They include a spherical blanket enclosed within a Yin-Yang magnet, neutral beam injectors and direct convertors. In Fig. 2 a version of our proposed blanket maintenance operation is illustrated, where the top half of the coil is raised with a flotation scheme and segments of the blanket are removed with a straight vertical lift. Details of the blanket-coil geometry are shown in Fig. 3. The inside face of the blanket segments, or modules, shown in Fig. 3 are subdivided into individual pressure vessels as shown in Fig. 4. These "submodules" contain fissile breeding material located directly behind the first wall, a fusile breeding material behind the fertile breeder, and then coolant inlet and outlet plena. The fertile materials are contained in standard fission reactor fuel pins, and are helium cooled.

In the design of the reactor components we have attempted to employ the simplest technology possible, thus making the hybrid a near-term concept in the overall time table for fusion commercialization. Specific components are listed in Fig. 5.

Two blankets are examined and compared in this study. One contains uranium (nat) + 7 weight percent molybdenum (U-MOLY), the second contains thorium metal. Both are based on the same mechanical design described in Ref. 1 and are modeled as concentric spherical shells. The shells contain homogeneous mixtures of materials. The inner most shell is 100 v/o (percent by volume) SS (stainless steel), 0.5 cm thick. The next shell is the fission zone and consists of 8.6 v/o SS, and 54 v/o fuel, the remaining 37.4 v/o is He coolant and void. The third zone is a tritium breeding zone with the same material volume fractions as the fission zone; the fuel in the third zone consisted of 45 v/o graphite plus 10 v/o lithium aluminate ($^{6}LiAlO_2$).

With the zone material compositions specified the zone thicknesses were varied to maximize fissile breeding while also getting a tritium breeding ratio of $\sim$ 1.1. Total blanket thickness was held constant at 1 metre. Method of analysis is described in Refs. 7 and 8.

For the U-MOLY blanket a 25 cm fission zone was found to give fissile and tritium breeding ratios of 1.80 ^{239}Pu atoms and 1.14 ^{3}H atoms per 14 MeV neutron.

For the thorium blanket it was necessary to add tritium breeding material to the fission zone in order to achieve the necessary tritium breeding ratio. With the 54 v/o of fuel consisting of 45.9 v/o thorium, 5.4 v/o lithium oxide ($^{6}Li_2O$) plus 2.7 v/o void and a fission zone thickness at 30 cm, the fissile and tritium breeding ratios are 0.732 ^{233}U and 1.09 ^{3}H atoms per 14 MeV neutron.

The final step in the nuclear analysis of the two blankets was to estimate exposure effects. This was done in a first order manner by iterating in time with rather large steps and using average reaction rates for the whole fission zone. Results of the exposure analysis are displayed in Figs. 6 and 7.

The components of the system model developed for the parametric analysis are listed in Fig. 8. The mirror reactor model is essentially the analysis developed by Carlson[3], and includes mirror plasma physics, magnet design, blanket geometry and power flows. The capital costs are a key element in the analysis, and here we have attempted to be as thorough and consistent as possible. However, the costing is a procedure entailing a high degree of uncertainty due to the infancy of fusion technology.

A unique feature of hybrid economics, as compared to strictly power producing fission and fusion reactors, is that the principle product of the hybrid, fissile fuel, does not generate revenues on a continuous basis. Revenue from fissile fuel is only realized when blanket segments are removed from the reactor and reprocessed. To model these effects, we have developed a fuel management package that evaluates the time dependent flow of fertile material into the reactor and fissile fuel out of the facility. In addition, this analysis specifies the timing and magnitude of fuel and blanket fabrication costs, and spent fuel shipping and reprocessing costs. The economics of this time dependent "fuel cycle" is evaluated using cash-flow accounting techniques[9].

A second unusual feature of the economic analysis is that the hybrid produces two products, fissile fuel and electricity. To fix the price of these two products, it is necessary to specify a constraint. In our present analysis, we have chosen to fix the value of hybrid electricity at the same value as the electricity produced by the fission reactors which burn the hybrid fissile fuel. By considering the hybrid plus its associated "burner" reactors as a single entity producing just electricity, we are able to calculate the electricity value. Having established the electricity value, the fissile material value from the hybrid can then be evaluated.

The optimization studies to date have employed variation of the parameters listed in Fig. 9. It has been our experience that these quantities have the most important influence on the hybrid economics. Two dependent quantities which have been found to strongly influence the plant economics are shown in Figs. 10 and 11. The geometric relationship between the plasma and blanket are shown in Fig. 10. Holes in the blanket must be provided for plasma leakage and neutral injection. We have found that if the power density in the blanket exceeds 100-200 watts/cm^3, the required plenum dimension to handle the helium flow becomes excessively large, pushing the blanket inward and severely decreasing the blanket coverage. Also, large neutral beam current requirements demand large injection ports, thus reducing the blanket coverage. The equation used to model the plant duty factor is shown in Fig. 11. Here, top is the operating time for the reactor, t_{sm} is the time for scheduled maintenance, t_{um} is the time for unscheduled maintenance and t_{BC} is the time required for the blanket change operation. The duty factor evaluates the trade-off between high first wall flux, and therefore high product generation rates, and the need to shut the plant down and perform blanket change operations when the maximum blanket exposure has been reached.

The fission reactors chosen as burners of the hybrid fissile fuel are listed in Fig. 12, along with their requirements for hybrid fissile fuel. As a burner of Pu, we have used a light water reactor (LWR) on a Pu recycle fuel cycle and supplemented with hybrid Pu. As a ^{233}U burner we have used a high-gain HTGR, using the thorium -^{233}U fuel cycle. Another possibility as a ^{233}U burner, but not yet examined, is the CANDU reactor.

The optimized reactor parameters for the uranium and thorium blankets are listed in Fig. 13. There are several significant differences between the two reactors.

- The uranium blanket, because of its high energy multiplication, results in a plant with a large electrical output. The thorium blanket reactor does not produce net electricity, just fissile fuel.
- Both blankets have about the same thermal rating, this being the result of a much larger fusion power

output from the thorium blanket reactor as compared to the uranium blanket reactor.

- The high fusion power of the thorium blanket reactor is obtained by using a more intense magnetic field than for the uranium blanket reactor. The uranium blanket reactor may therefore rely on existing NbTi superconductor magnet technology, whereas the thorium blanket reactor will require the more technologically advanced Nb_3Sn superconductor.

The blanket parameters for the optimized reactors are listed in Fig. 14. Both produce between 2 and 3 metric tons of fissile fuel per year. However, the thorium blanket requires a rather high exposure, and the possibility of the blanket structure being able to attain $\sim$ 9 MW-YR/m^2 exposure is quite uncertain. The average energy multiplication of the uranium blanket is about a factor of 4 higher than for the thorium blanket; these blanket multiplications include the effect of the fractional blanket coverage.

The hybrid economic parameters are listed in Fig. 15. The higher capital cost of the thorium blanket hybrid is associated with the fusion components required to generate the higher fusion power than the uranium blanket hybrid. The ^{233}U value is more than a factor of two greater than the Pu value. However, the lower fissile requirements of the HTGR as compared to the LWR results in approximately the same electricity value from the two fission power plants (see Fig. 16) . The break-down of the fissile material costs indicate that they are dominated by capital costs. The fuel cycle costs account for fabrication, reprocessing and spent fuel shipping. Current (high) estimates for these services have been used[5], but they are not a dominant cost. For the uranium blanket reactor, approximately 60% of the plant revenues are generated by fissile production in contrast to the total revenue generation by fissile material for the thorium hybrid.

The fission reactor economics are listed in Fig. 16. The important result here is that the hybrid fissile fuel costs of 4.0 and 5.3 mills/kw-hr is a small fraction of the total electricity value. The conclusion is that the mirror hybrid reactor, based on our current capital cost model, is capable of converting the large fertile resources of the US into fissile fuel at a cost that does not strongly influence the net cost of electricity.

In Figs. 17-21, we illustrate some of the details of the optimization process, primarily for the uranium blanket. Fig. 17 shows the plasma physics variation. A rather broad optimum exists for various combinations of mirror ratio and injection energy (W_{INJ}).

The variation of reactor size is shown in Fig. 18. A minimum economical size is about 10 m, mirror-to-mirror. Below this size, the blanket coverage decreases rapidly, strongly degrading the plant economics. A 7.5 metre machine appears to be the minimum "demo" size.

The optimization on magnetic field is shown in Fig. 19. For the uranium blanket, a near optimum can be attained at 8 Tesla, which yields the maximum blanket power density of $\sim$ 100 W/cc. For the thorium blanket, 12T - 14T fields are required to minimize the fissile value.

The variation of fissile value with fertile burnup is shown in Fig. 20. At low burnup, high fabrication-reprocessing costs and low duty factor are incurred. As the maximum burnup increases, larger temporal variations are incurred in the thermal output due to increasing blanket multiplication with burnup. This thus requires an increasing fraction of the plant thermal capacity to remain idle during periods of non-peak thermal output. Also, the higher burnup implies longer delays in the realization of the revenues from fissile breeding. For the uranium blanket, the optimum occurs at a 1% burnup, which is about the maximum tolerable burnup for this U-MOLY fuel. For thorium, the 0.5% burnup is well below the maximum obtainable with this fuel.

There is some degree of uncertainty in the actual plasma Q that will be attained in mirror reactors. It is possible that microinstabilities will limit Q to a value somewhat below the classical value, and a second possibility is that Q enhancement techniques under consideration[6] will elevate Q above our presently predicted values. The variation of fissile value and electricity costs with Q is shown in Fig. 21. Here it can be seen that electricity costs are not strongly perturbed even if classical confinement is not attained. A factor of two enhancement of Q improves the Hybrid economics, but generally, the electricity costs are rather insensitive to higher Q.

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OBJECTIVES

- ECONOMIC OPTIMIZATION OF THE MIRROR FUSION-FISSION REACTOR
  - SCALING LAWS BASED ON PREVIOUS POINT DESIGNS
  - FUEL MANAGEMENT STUDIES
- CHARACTERISTICS OF URANIUM AND THORIUM BLANKET HYBRIDS

FIG. 1

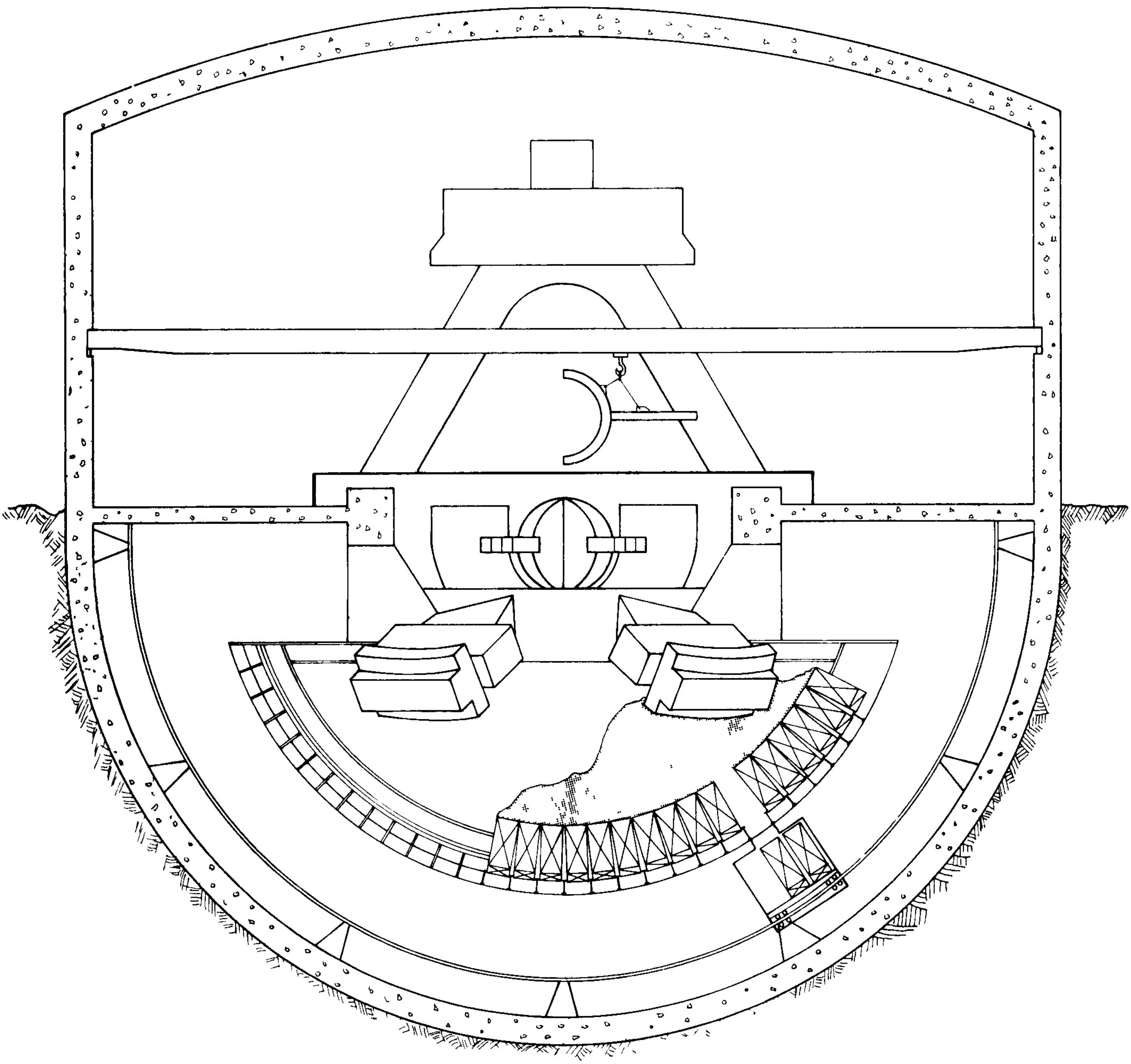


FIG.2

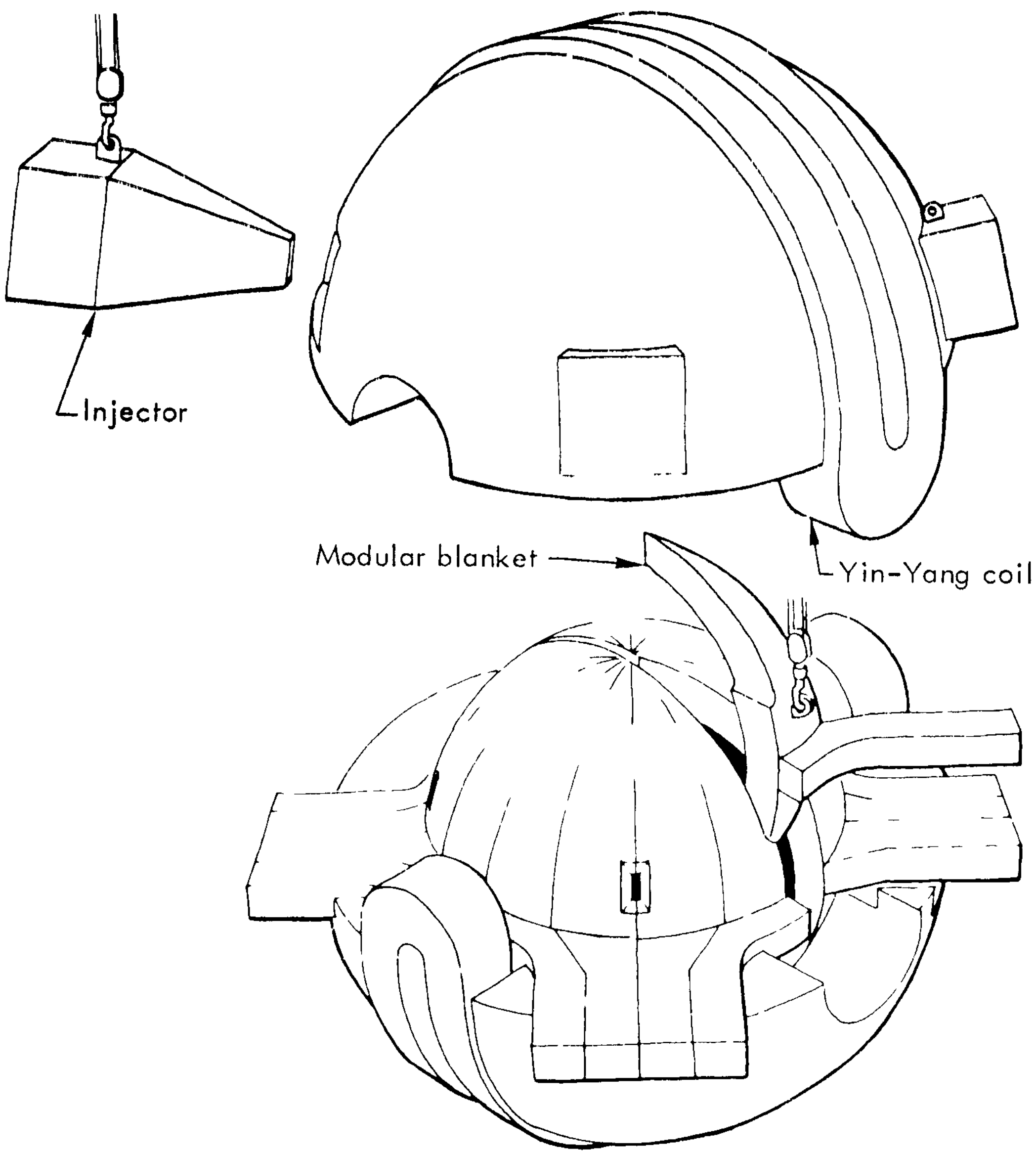


FIG. 3

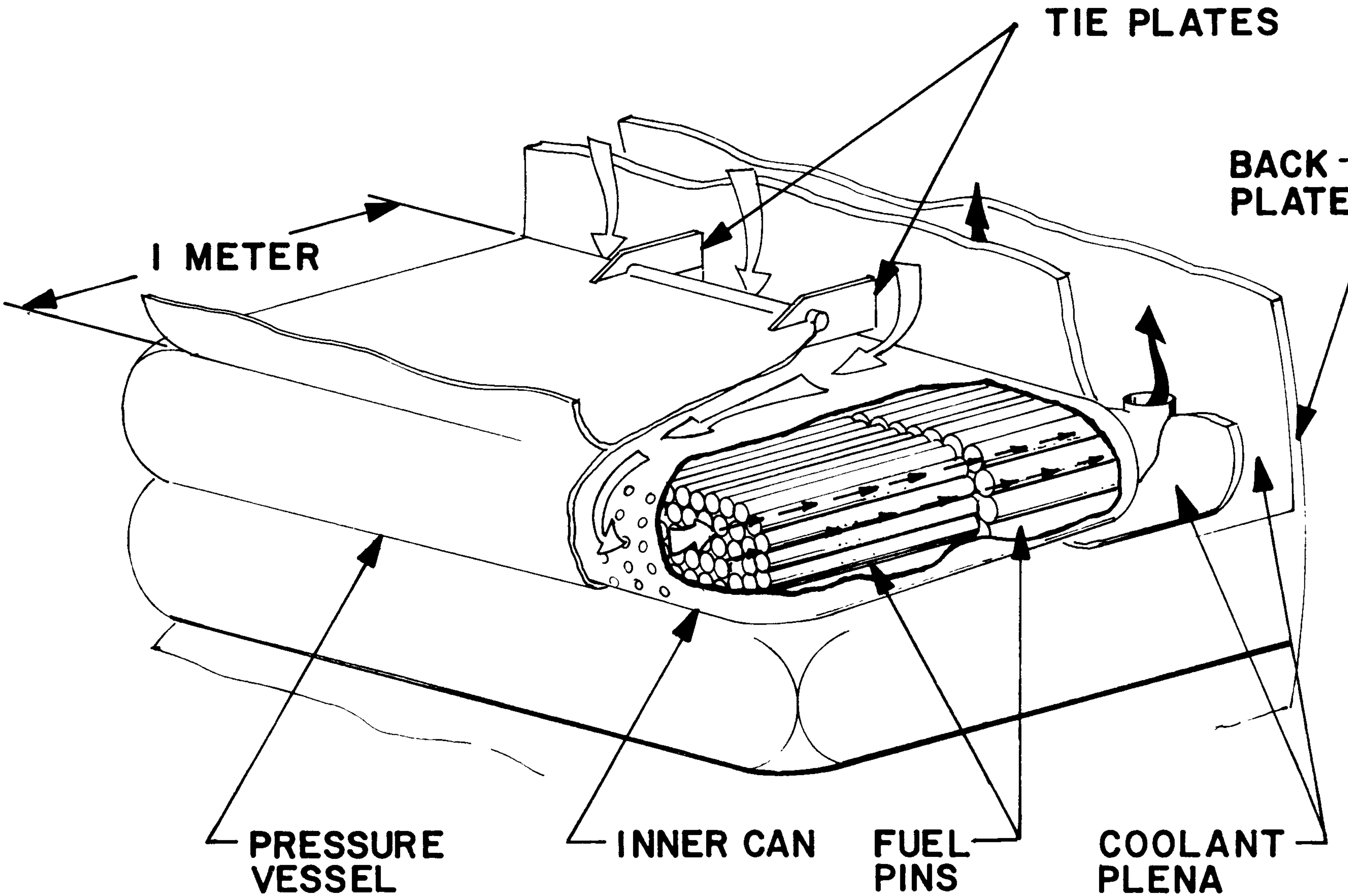

TIE PLATES
BACK PLATE
I METER
PRESSURE VESSEL
INNER CAN
FUEL PINS
COOLANT PLENA

FIG. 4

HYBRID PLANT COMPONENTS

- POSITIVE ION INJECTORS
- SINGLE STAGE DIRECT CONVERTER
- HELIUM COOLED BLANKET
  INCOLOY 718 STRUCTURE
- YIN-YANG MAGNET (8T & 12T)
- STEAM THERMAL CONVERSION SYSTEM

FIG. 5

U-MOLY BLANKET PERFORMANCE VS EXPOSURE

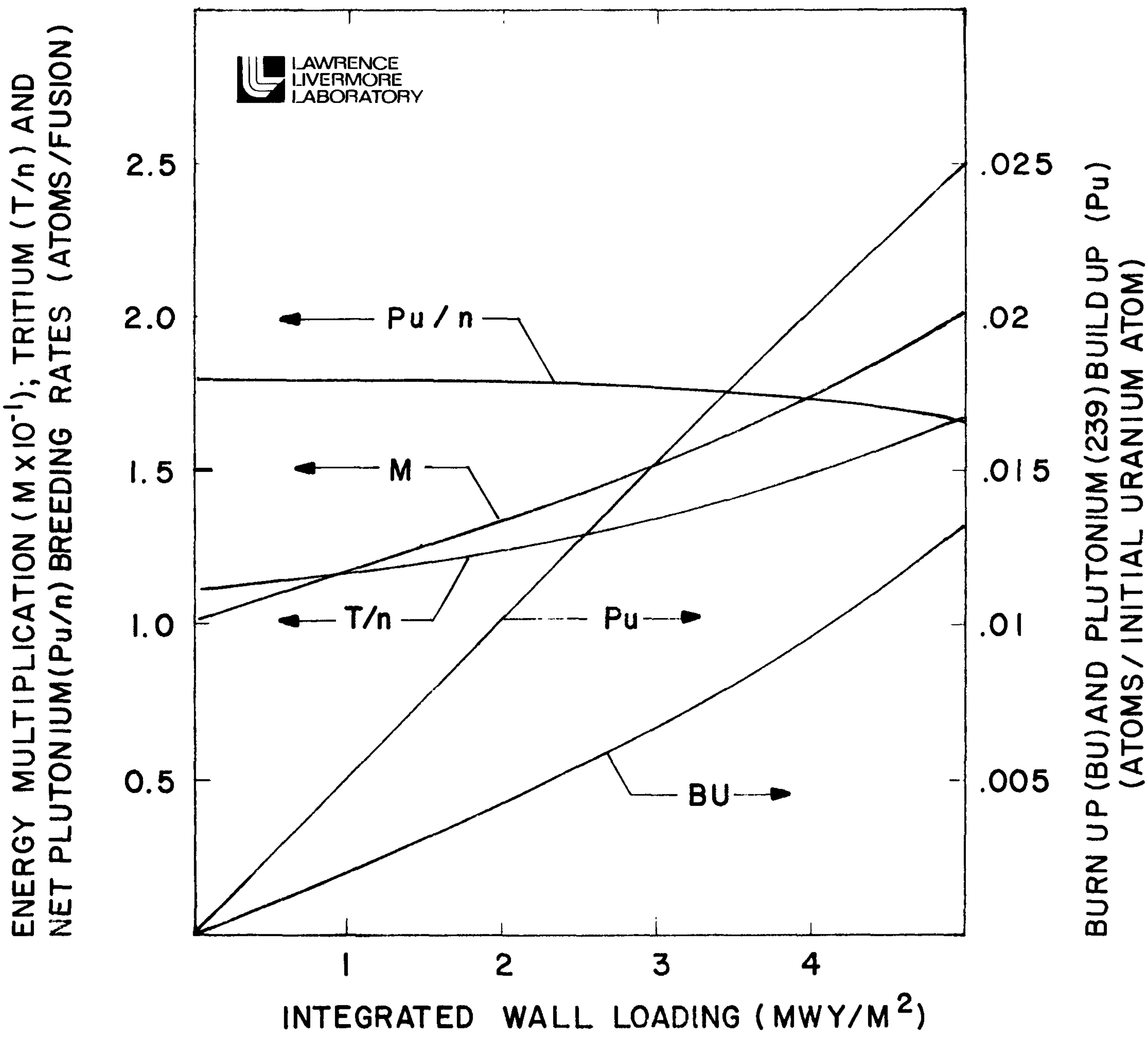


FIG. 6

LAWRENCE LIVERMORE LABORATORY

THORIUM BLANKET PERFORMANCE VS. EXPOSURE

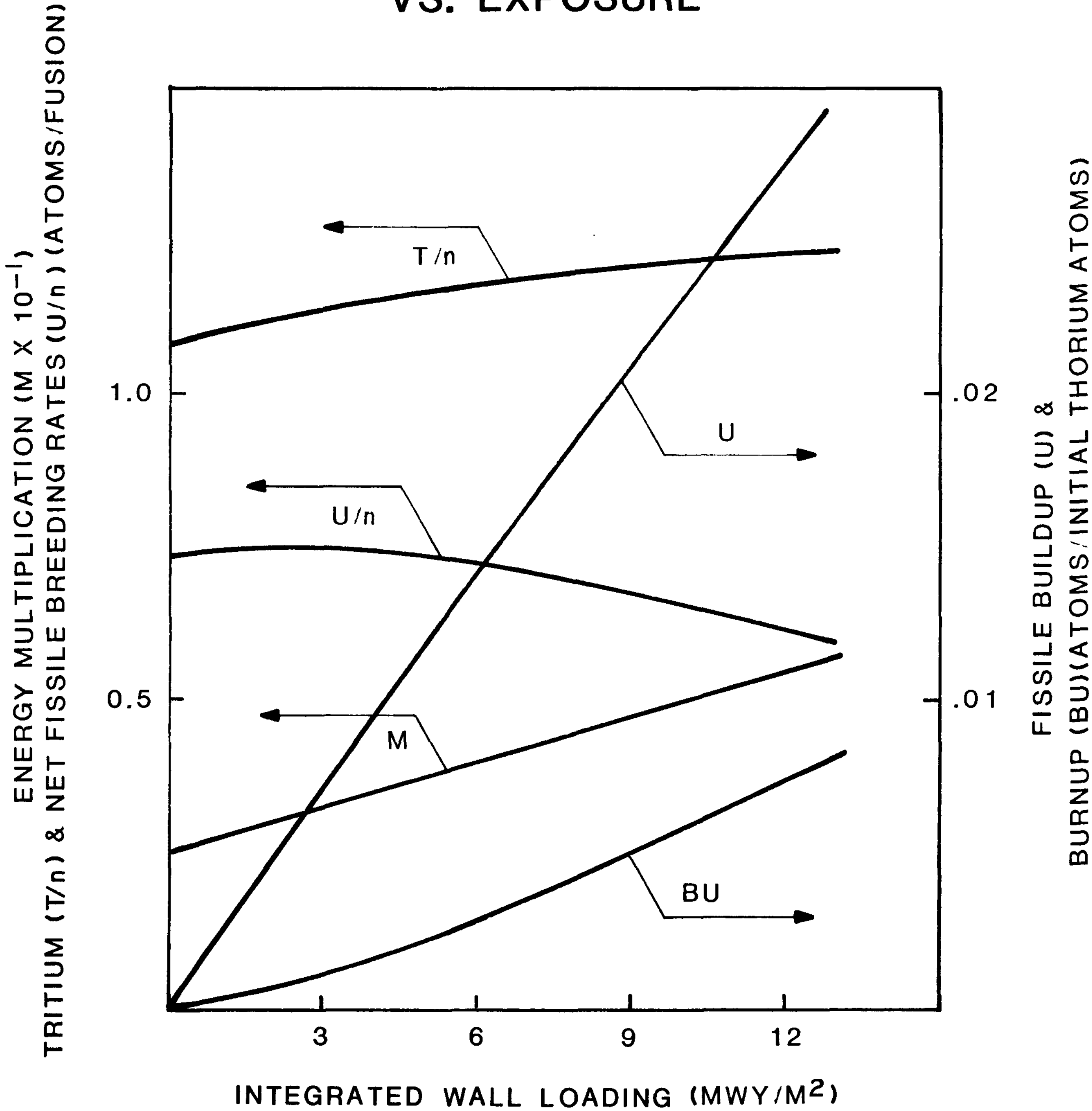


FIG. 7

MODEL COMPONENTS

- REACTOR DESCRIPTION
  - PLASMA PHYSICS
  - MAGNET DESIGN
  - BLANKET GEOMETERY
  - POWER FLOW
- CAPITAL COST
- FUEL MANAGEMENT
  - TIME DEPENDENT MASS & ENERGY FLOWS
  - DUTY FACTOR
- CASH-FLOW FUEL CYCLE ACCOUNTING
  - TIME DEPENDENT VALUE OF PRODUCTS
- "NUCLEAR PARK" ECONOMICS
  - HYBRID + FISSION REACTORS

FIG. 8

OPTIMIZATION PARAMETERS

- PLASMA PHYSICS
  - INJECTION ENERGY
  - MIRROR RATIO
  - INJECTION ANGLE
- MAGNET DESIGN
  - CONDUCTOR FIELD
  - MIRROR-TO-MIRROR LENGTH
- FUEL MANAGEMENT
  - FERTILE BURNUP
  - BLANKET SEGMENTATION

FIG. 9

BLANKET COVERAGE

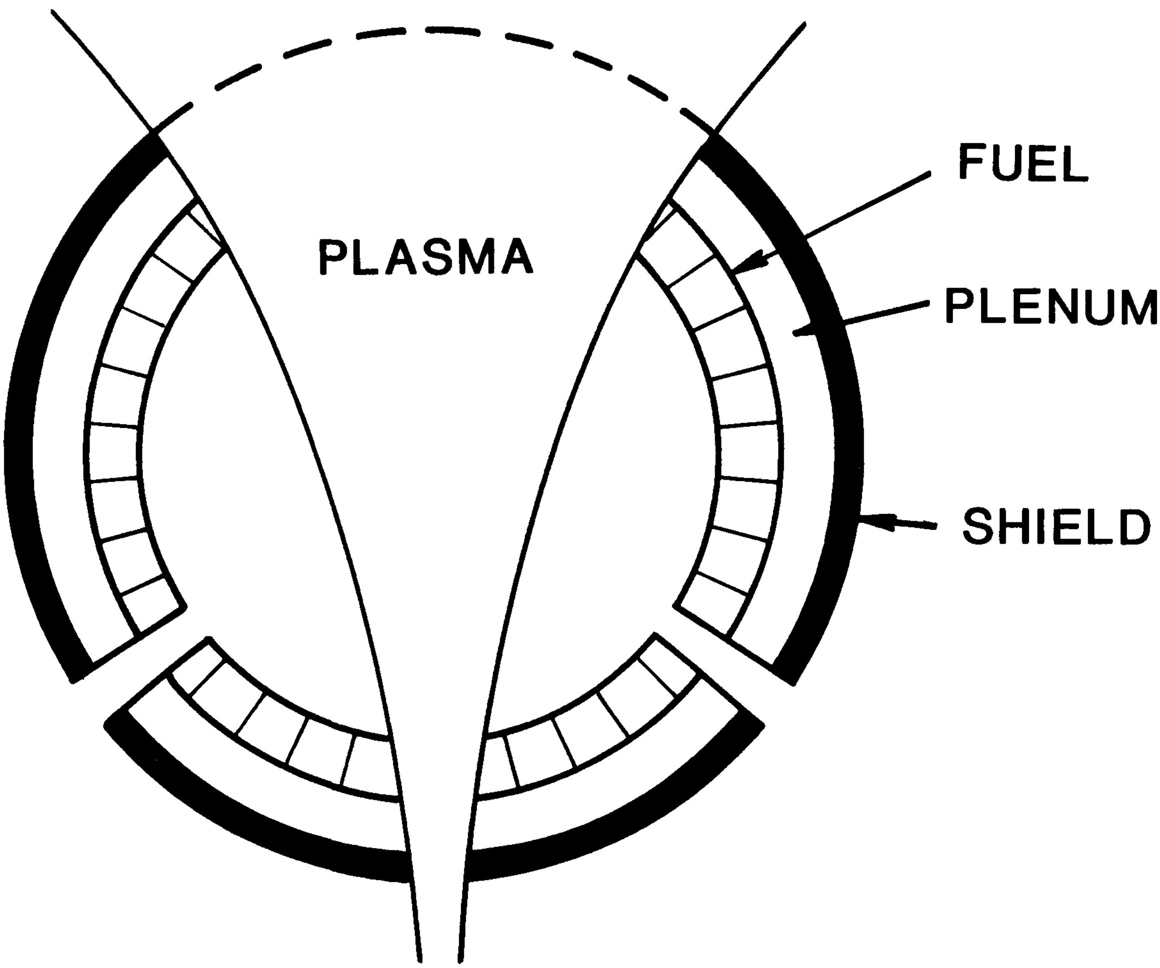


FIG. 10

DUTY FACTOR

$$\delta = \frac{t_{op}}{t_{op} + t_{sm} + t_{um} + t_{bc}}$$

$$\delta = \frac{1}{1.2 + t_{bc} / t_{op}}$$

$$t_{op} = \frac{\text{EXPOSURE (MW-YR/M}^2\text{)}}{\text{FLUX (MW/M}^2\text{)}}$$

FIG. 11

THERMAL CONVERTER REACTORS

- Pu BURNUP
  - LWR WITH Pu RECYCLE
  - CR ≃ 0.5
  - 0.35 KG FISSILE / MWE / YR

- ^{233}U BURNUP
  - HIGH GAIN HTGR / CANDU
  - CR ≃ 0.85
  - 0.185 KG FISSILE / MWE / YR

FIG. 12

HYBRID REACTOR PARAMETERS

	Mo	TH
MIRROR RATIO	2.50	2.75
INJECTION ENERGY (KEV)	100	100
CONDUCTOR FIELD (T)	8	12
Q	0.68	0.75
FUSION POWER (MW)	474	1500
FIRST WALL FLUX (MW/M^2)	1.3	4.2
BLANKET THERMAL POWER (MW)	4220	3340
ELECTRICAL OUTPUT (MW)	1044	-40
DUTY FACTOR	0.75	0.73
MIRROR-TO-MIRROR LENGTH (M)	15	15

FIG. 13

HYBRID BLANKET PARAMETERS

	U/Mo	TH
FISSILE OUTPUT (KG/YR)	2360	2590
AVG. ENERGY MULTIPLICATION	11.1	2.8
BLANKET COVERAGE	0.86	0.77
FERTILE BURNUP (%)	1.0	0.5
BLANKET EXPOSURE ($MW-YR/M^2$)	4.1	9.2
FUEL POWER DENSITY (W/CC)	150	110

FIG. 14

HYBRID ECONOMICS

	U/Mo	TH
CAPITAL COST (10^9 $)	2.3	3.3
($/KWE)	2170	-
FISSILE MAT'L VALUE ($/GM)	55	127
CAPITAL	80	103
FUEL CYCLE	13	21
O & M	1	1
ELECTRICITY REVENUES	-39	2
ELECTRICITY VALUE (MILLS/KW-HR)	24.7	-

FIG. 15

FISSION REACTOR ECONOMICS

	U/Mo	TH
CAPITAL COST ($/kWE)	750	750
ELECTRICITY VALUE (MILLS/KW-HR)	24.7	25.3
CAPITAL COST	16.1	16.1
FUEL CYCLE W/o FISSILE MATL	3.9	3.2
FISSILE FUEL	4.0	5.3
O &M	0.7	0.7

FIG. 16

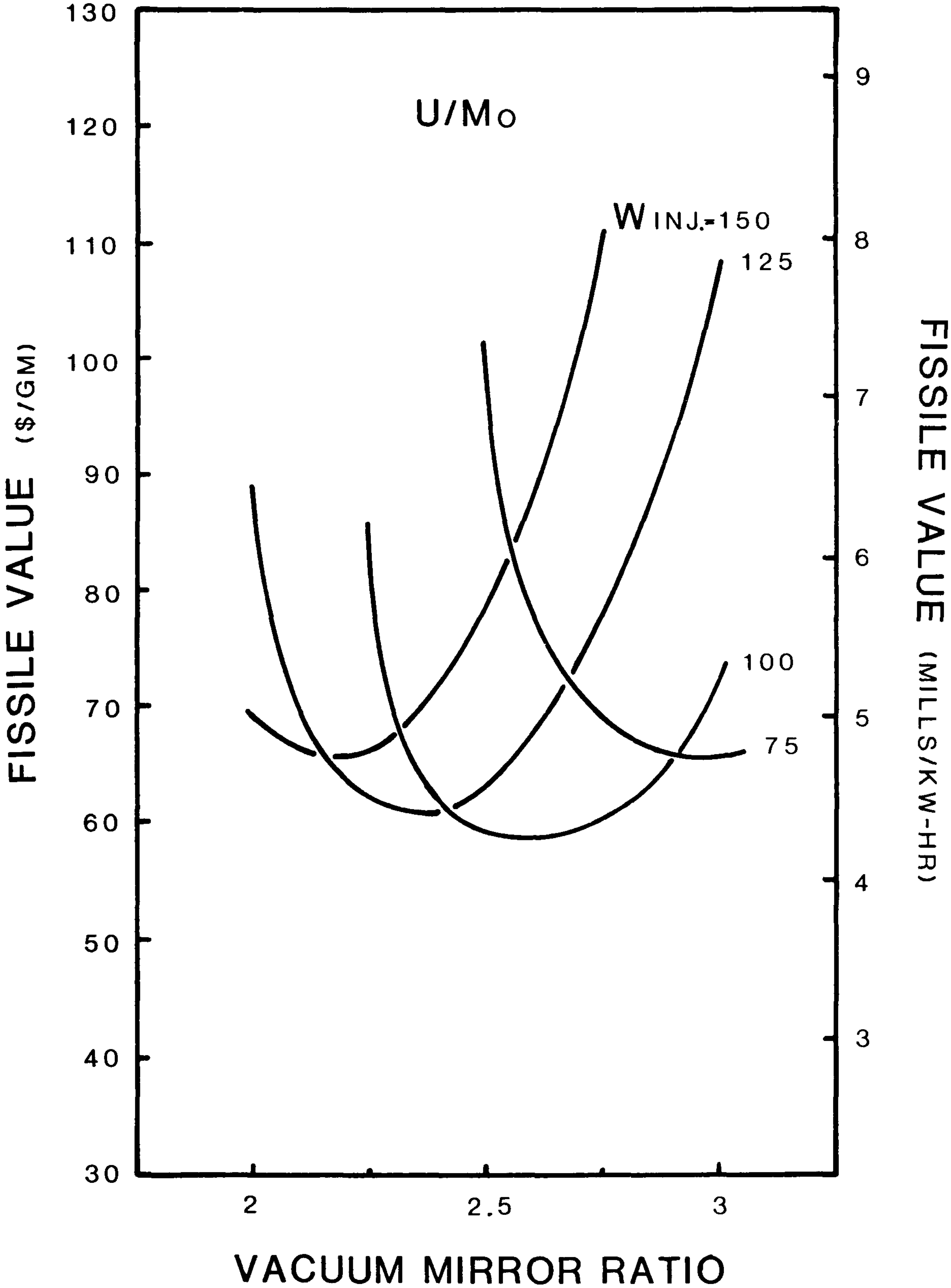
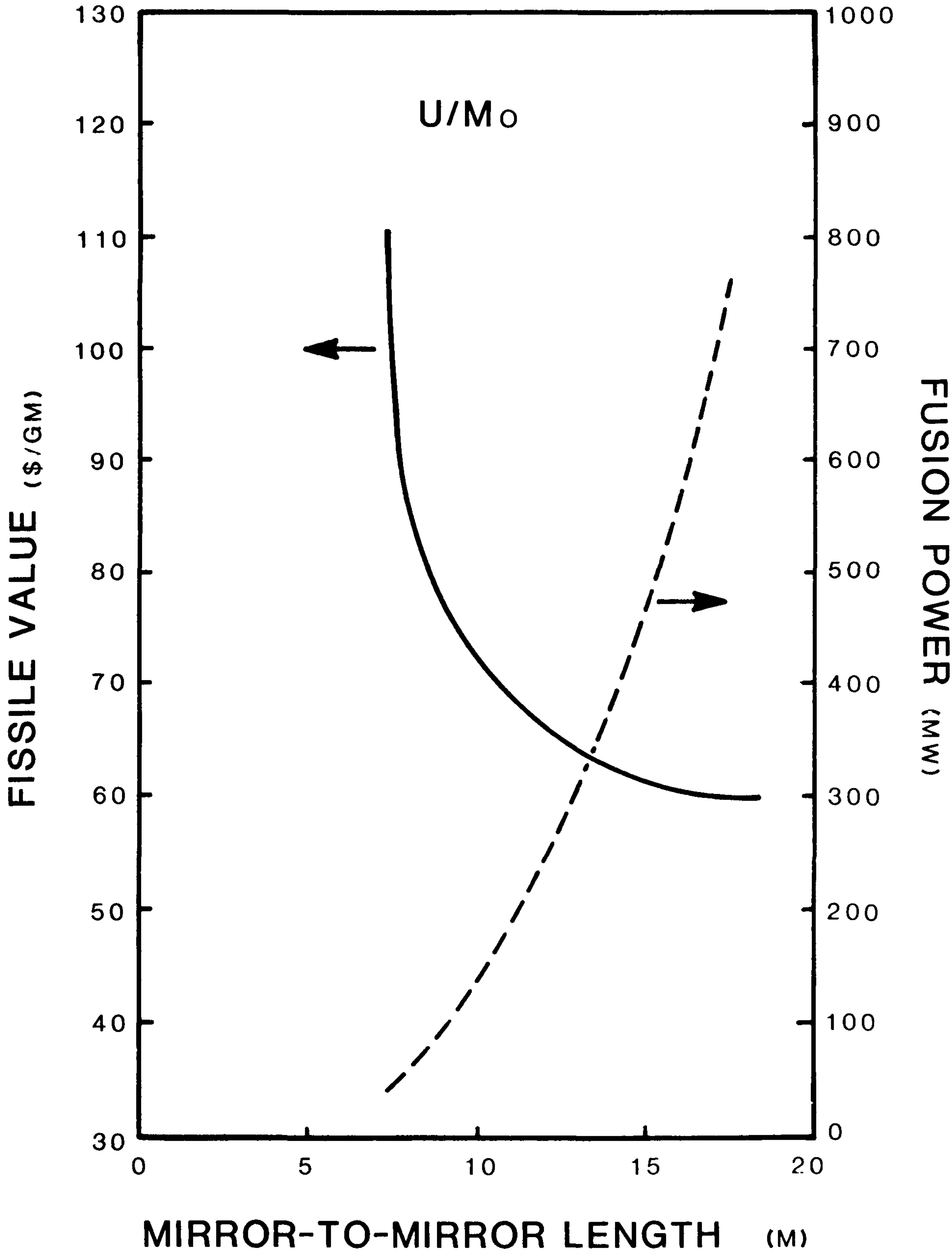

U/Mo
W INJ.=150
125
100
75
FISSILE VALUE ($/GM)
FISSILE VALUE (MILLS/KW-HR)
VACUUM MIRROR RATIO
130
120
110
100
90
80
70
60
50
40
30
9
8
7
6
5
4
3
2
2.5
3

FIG. 17



U/Mo
FISSILE VALUE ($/GM)
FUSION POWER (MW)
MIRROR-TO-MIRROR LENGTH (M)
130
120
110
100
90
80
70
60
50
40
30
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20

FIG. 18

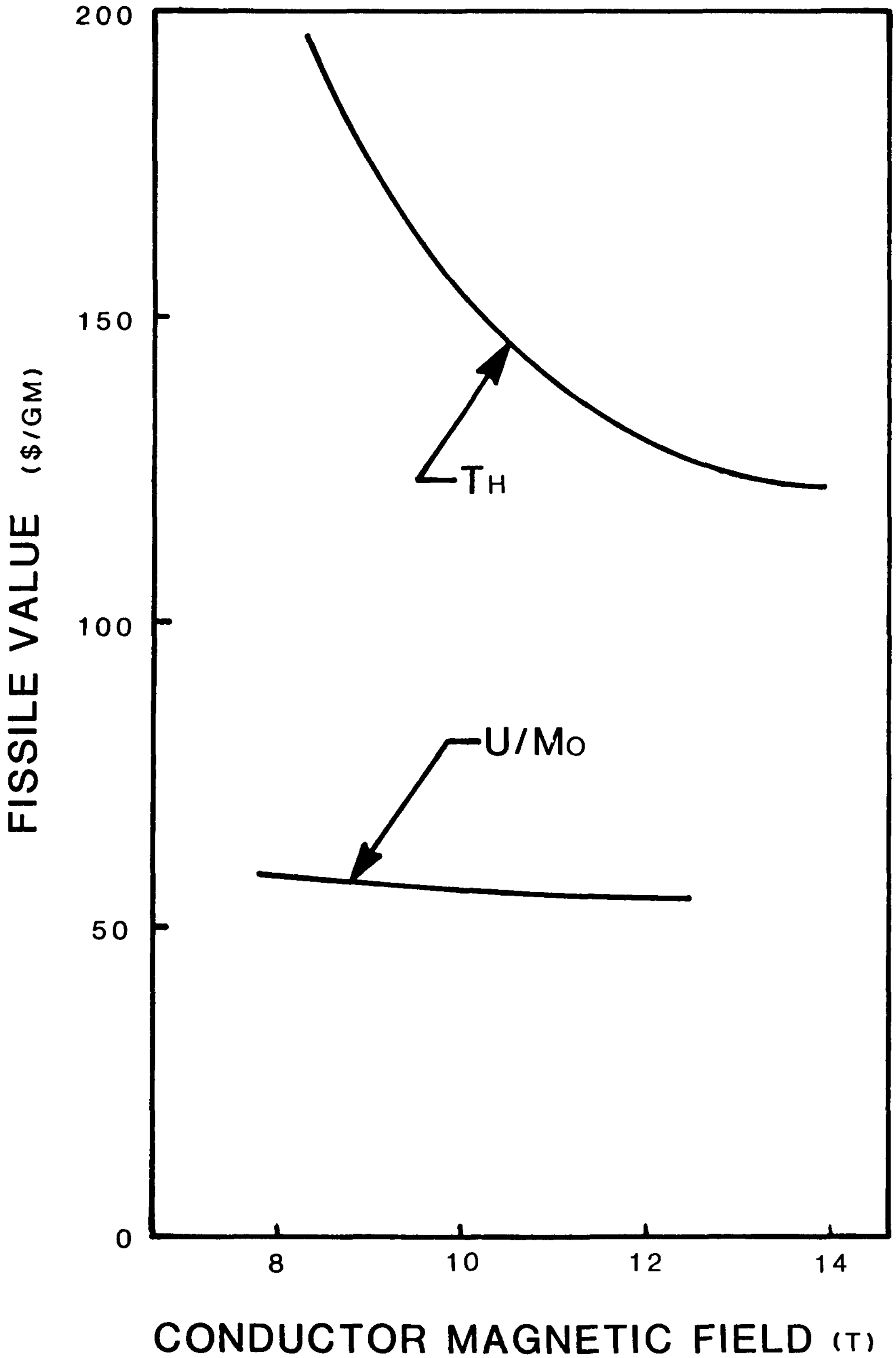
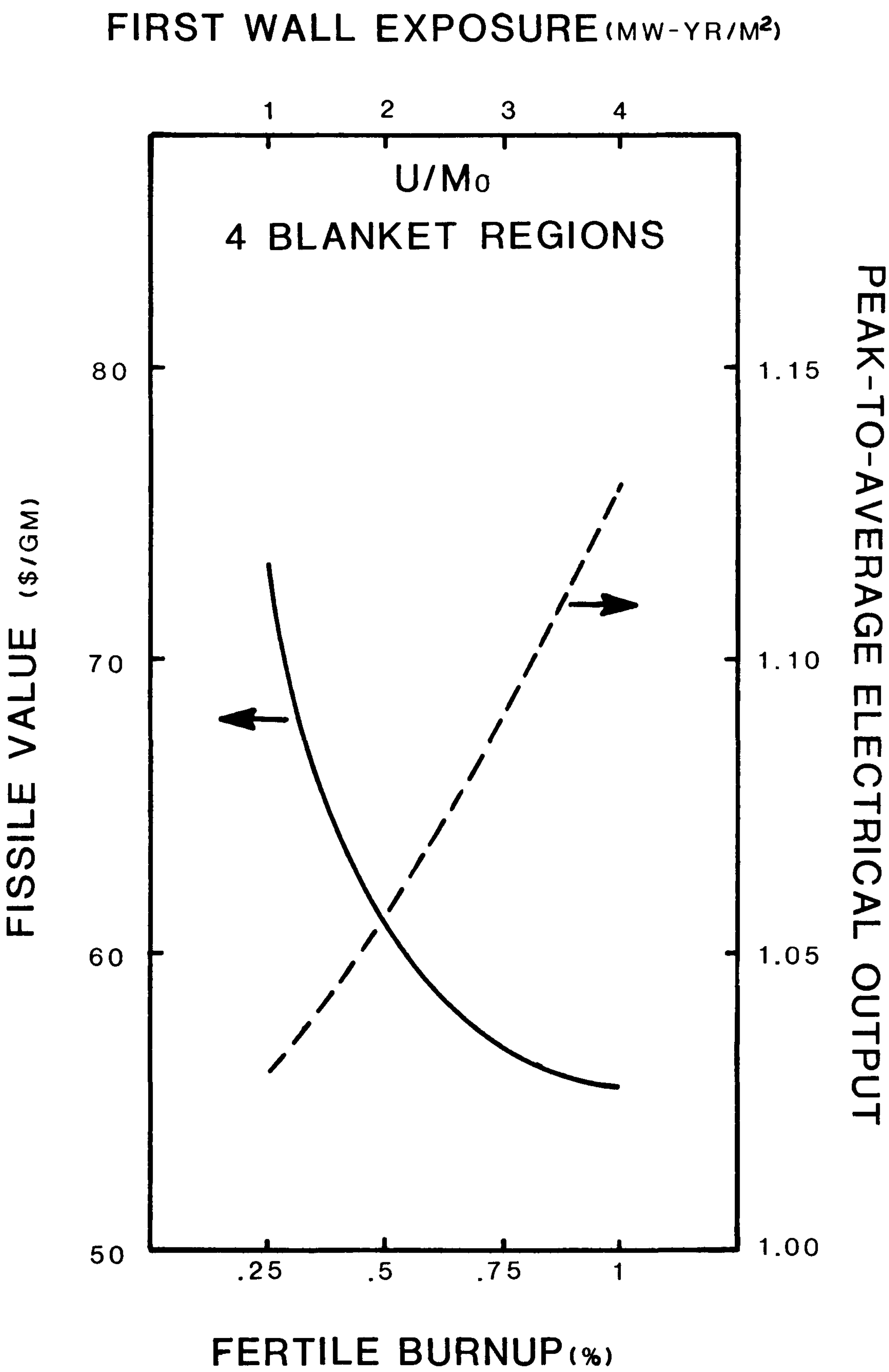
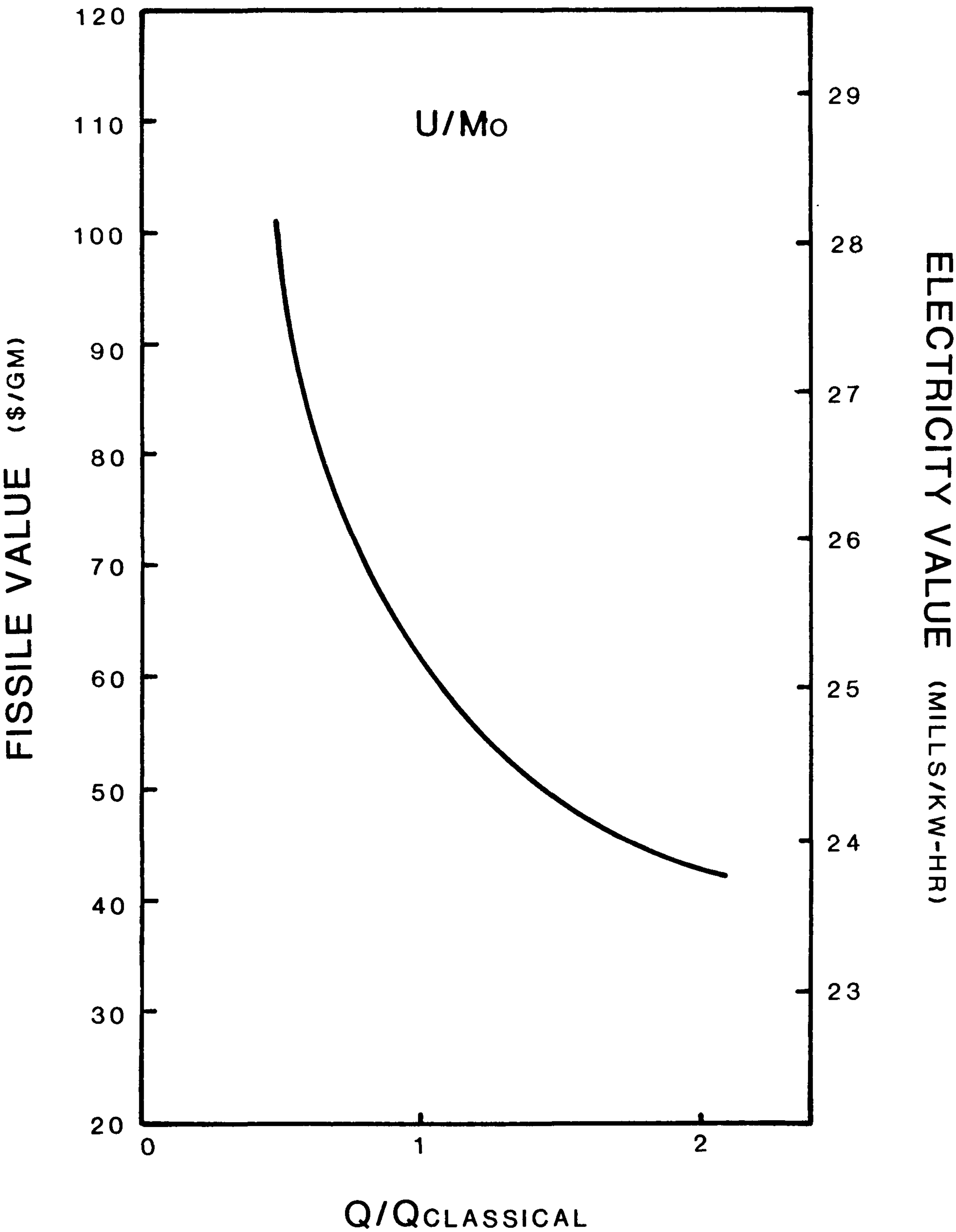

200
150
100
50
0
FISSILE VALUE ($/GM)
TH
U/MO
8
10
12
14
CONDUCTOR MAGNETIC FIELD (T)

FIG. 19



FIRST WALL EXPOSURE (MW-YR/M²)
1
2
3
4
U/Mo
4 BLANKET REGIONS
FISSILE VALUE ($/GM)
80
70
60
50
PEAK-TO-AVERAGE ELECTRICAL OUTPUT
1.15
1.10
1.05
1.00
.25
.5
.75
1
FERTILE BURNUP(%)

FIG. 20



120
110
100
90
80
70
60
50
40
30
20
29
28
27
26
25
24
23
U/Mo
FISSILE VALUE ($/GM)
ELECTRICITY VALUE (MILLS/KW-HR)
0
1
2
Q/QCLASSICAL

FIG. 21

Distribution:

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T.I.D.	L-9	15 "
T.I.C., Oak Ridge, TN		2 "

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