PERFORMANCE AND ECONOMIC PENALTIES OF SOME LEU CONVERSION OPTIONS FOR THE AUSTRALIAN REACTOR HIFAR

D.B. McCulloch

and

G.S. Robinson

Australian Nuclear Science and Technology Organisation*
Lucas Heights Research Laboratory, Private Mail Bag 1, MENAI, NSW, 2234
AUSTRALIA

ABSTRACT

Performance calculations for the conversion of HIFAR to low enriched uranium (LEU) fuel have been extended to a wide range of ^{235}U loadings per fuel element. Using a simple approximate algorithm for the likely costs of LEU compared with highly enriched uranium (HEU) fuel elements, the increases in annual fuelling costs for LEU compared with HEU fuel are examined for a range of conversion options involving different performance penalties. No significant operational/safety problems were found for any of the options canvassed.

INTRODUCTION

HIFAR (High Flux Australian Reactor) is a 10 MW, Dido-class heavy water moderated and cooled research reactor, operated by the Australian Nuclear Science and Technology Organisation at the Lucas Heights Research Laboratories, near Sydney, New South Wales. The fuel is highly enriched uranium/aluminium alloy.

In recent years, a number of studies relating to the proposed conversion of HIFAR to low enriched (19.75 wt % ^{235}U) fuel have been published.[1,2,3,4] They were concerned primarily with neutronics and thermohydraulics, for both normal operation and the assessment of safety; they also addressed the likely detriment to reactor performance for the main areas of reactor application.

A basic assumption of those studies was that the current highly enriched uranium (HEU) fuel cycle, fuel element burn-up, etc would be matched as closely as practicable with low enriched uranium (LEU) fuel by selecting an LEU ^{235}U loading which would give the same end-of-cycle core reactivity as the HEU fuel. Within this framework, the studies suggested that the main cause for concern was the effect on reactor applications of the concomitant reduction in (predominantly thermal) neutron fluxes. Judgements could then be made regarding the extent, if any, to which the performance losses should be compensated by an increase in reactor operating power with its attendant increase in fuel element consumption rate and fuel cycle cost.

Accumulating experience in the fabrication of LEU dispersion fuels, particularly U_3Si_2-Al, strongly suggests that fabrication costs for LEU fuel elements will be substantially greater than for the HEU ones they replace, and will show a significant dependence on the uranium loading. In these circumstances, the simple conversion strategy previously studied may not be appropriate, since it may incur unnecessarily severe economic penalties, particularly in a reactor like HIFAR, where the normal HEU (150 g ^{235}U) fuel elements require only a very modest uranium density (~ 0.54 gcm^{-3}) in the fuel 'meat'.

---

*The Australian Nuclear Science and Technology Organisation (ANSTO) replaced the Australian Atomic Energy Commission (AAEC) on 27 April 1987

The present study surveys the economic implications of a range of fuel loading options to meet specified reactor performance criteria in HIFAR's conversion to LEU fuel. It primarily addresses the effect of ^{235}U loading per LEU element on fuel consumption rates and neutron flux levels in comparison with those for standard HEU (80% ^{235}U) 150 g ^{235}U elements. The LEU fuel considered is U_3Si_2-Al fuel of 19.75% enrichment, with identical geometry to the HEU fuel. Relative reactor fuelling costs are deduced from simple assumptions based on preliminary fuel element cost information.

HIFAR

HIFAR has 25 fuel elements on a 152.4 mm square pitch in a 4,6,5,6,4 array with the central row displaced one half-pitch. The heavy water for the moderator and reflector is contained in a cylindrical aluminium tank, 2 m diameter and 12.7 mm thick. The dished, 16 mm thick bottom of the tank provides space for an equivalent uniformly 0.4 m thick bottom D_20 reflector. The top D_2O reflector extends 0.78 m above the active core. Further radial and bottom reflectors of 0.6 m thick graphite are located outside the tank, and a large number of horizontal beam tubes and vertical facilities extend into the heavy water reflector. The reactor is controlled by six 'signal arm' absorber blades, and operates at 10 MW over a 28-day cycle of which about 24 days are at power. The general arrangement of the reactor is shown in Figures 1 and 2.

The standard fuel element (Figure 3) contains 150 g ^{235}U at 80% ^{235}U enrichment, and consists of four concentric fuel tubes, each of 0.66 mm thick U-Al alloy meat clad in 0.43 mm thick aluminium. The active length is 603 mm. Each fuel tube is made up of three curved plates welded together and the consequent aluminium seams between plates reduce the notional volume available for fuel meat by 9.1%. The inner radii of the fuel tubes are 30.39, 35.29, 40.19 and 45.09 mm. Inner and outer aluminium tubes, of inside radii 25.36 and 49.90 mm and thicknesses 1.63 and 1.59 mm respectively, complete the element and provide five coolant channels of width (inner to outer) 3.40, 3.38, 3.38, 3.38 and 3.29 mm.

REACTOR MODELS AND MAJOR ASSUMPTIONS

Reactor modelling for the present study followed the same general approach as previous AAEC studies of conversion to LEU.[3] In brief, few-group macroscopic cross sections for a cell consisting of a section through a fuel element were obtained from a cell burn-up calculation. Global calculations with these cross sections were performed first in RZ geometry to obtain axial bucklings and then in an XY model which included detail of in-core and reflector rigs and facilities. A uniform burn-up was assumed throughout the core. The adequacy of this approach was established previously.[2]

As in previous studies, fuel cycle data for HEU fuel were taken as the average of HIFAR operating programs 266 to 286. Where necessary, data were obtained from the HIFUEL program[5] which is used for HIFAR fuel management. The average data extracted were

- 46 fuel elements per year with an average discharge burn-up of 64.7 MWd per element;
- 22.8 effective full power days of operation at 10 MW per 28-day cycle;
- reactivity balance at end-of-cycle of 2.3% for in-core rigs, 2.2% for reflector rigs and 1.6% excess held in the coarse control arms (CCAs); and
- core loading at end-of-cycle of 2.48 kg of ^{235}U with an average burn-up per element of 40.5 MWd.

The reactivity unit used throughout was per cent reactivity in a core containing 3.2 kg of ^{235}U. Calculated values of reactivity, ρ, were obtained from k_{eff} using

$$\rho = 100(1 - 1/k_{eff})(M/3.2)^{0.7},$$

where M is an equivalent ^{235}U core mass (kg) after allowing for ^{239}Pu.

The main neutronics calculations established, for a given LEU fuel element, the core average burn-up which gives the same excess reactivity at end-of-cycle (1.6%) as HEU fuel of a given burn-up. Two situations were considered:

(i) the standard in-core rig burden of 2.3% for which the HEU burn-up is 40.5 MWd and

(ii) an increased in-core rig burden of 5.3% for which the corresponding average burn-up was calculated to be 32.0 MWd for HEU fuel.

The criterion of matching excess reactivity in a 3.2 kg core was chosen because it allows for the smaller xenon override requirement in a core with a larger fissile mass.

The fuel consumption rate was obtained from the core-average burn-up at end-of-cycle, I, using the approximate relationship

$$I = cP\,(1/n + 1/N)$$

where P is the reactor power,

n is the average number of elements changed per 28 day cycle,

N is the number of fuel elements (25) in the core, and

c is a constant determined from the average fuel cycle data given above.

Such a relationship gives good results when normalised to actual fuel cycle data.

FUEL COST DATA

To compare fuel costs for LEU and HEU fuel, a number of simplifying assumptions and approximations, considered to be adequate in terms of the available preliminary cost data and their accuracy, were made. They were

- Cost per gram of ^{235}U is the same for 80 or 20% enrichment
- Breakdown of HEU fuel element cost is 50% for uranium and 50% for fabrication
- meat processes account for 30% of HEU element fabrication cost, i.e. 15% of total cost.
- Cost of meat processes is proportional to the mass of uranium handled.
- In the relevant limited range of uranium density the rejection rate for LEU fuel plates is constant.

On this basis, the costs of LEU elements relative to the HEU 150 g element are 1.46, 1.61 and 1.83 for ^{235}U loadings of 150, 170 and 200 g respectively. Although the relative costs of LEU fuel and HEU fuel may change when firmer data are available, the variation of LEU element costs with ^{235}U loading is unlikely to change much since about 80% of their cost is proportional to the ^{235}U loading.

COMPARISON OF THREE LEU FUEL LOADINGS

Comparative fuel-cycle data for standard HEU fuel and LEU fuel with ^{235}U loadings of 150, 170 and 200 g per element are given in Table 1. For each element type, data are presented for both standard and high rig burdens. The table is further subdivided to give fuel consumption rates and relative fuel cost at 10 MW and at that power which is required to ensure no flux reduction for any application of the reactor facilities.

For the cases considered, the maximum uranium densities required are very modest compared with the 4.8 g cm^{-3} being qualified in the RERTR programs. Core fissile mass data are included in the table because of their influence on the reactivity scale. The average discharge burn-up values are for 10 MW operation; there would be a slight reduction at the higher powers. In terms of fission density, the discharge burn-ups are also modest compared with those already demonstrated in the RERTR program.

Whether operation at 10 MW or at the increased power corresponding to no reduction in neutron fluxes is considered, the Table 1 data show clearly that considerable savings in fuel costs can be achieved by the use of high ^{235}U fuel element loadings; the savings become more pronounced when the rig burden is assumed to increase from its current, rather low value.

Table 2 gives some details of neutron fluxes (including those at some beam facilities) and isotope activities for 10 MW operation with the current rig burden. The latter were derived using the effective isotope cross sections of Harrington and McCulloch[4]. As expected, the fluxes at the beam facilities and the (n, γ) Mo activity in particular, show much less variation than the core thermal flux. Results for higher power levels may be taken as directly proportional to power.

Figure 4 shows neutron fluxes, along the X-axis (i.e. through the C3, C4, C5 fuel positions) at the core midplane, for HEU fuel. Figures 5 to 7 give the flux ratios for 150 g, 170 g and 200 g LEU fuel relative to HEU fuel and Figure 8 shows the penalty in selected fluxes and activation levels if 10 MW operation is retained. The relative increase in fuelling cost for LEU is varied by changing the ^{235}U loading of the fuel elements. In all these figures, the fast flux is > 0.8 MeV, the epithermal flux is from 9.1 keV to 1.1 eV, and the thermal flux is the Westcott flux.

Table 2 also gives absorption coefficients, and the good agreement of the variation in core average values with the $1/(\text{fissile mass})^{0.7}$ ratios validates the reactivity worths used throughout the study. The power fractions in each ring of a fuel element were also calculated for the four fuel types and proved to be practically independent of fuel type. The greatest change was an increase in the fraction in the outer ring from 0.315 for standard HEU fuel to 0.319 for 200 g LEU fuel.

ADDITIONAL CALCULATIONS FOR 200 g LEU ELEMENTS

Because the 200 g LEU element gave the lowest fuel costs for those elements considered and its use represents the biggest change from the current fuel cycle, additional calculations were performed for this case.

Flux peaking in a new fuel element was calculated for standard HEU and 200 g LEU fuels. The results basically refer to a new element in the C3 position, which is the worst case. The results of seven cases are given in Table 3. All cases except case 2 were performed in RZ geometry, and comparison of cases 1 and 2 shows that RZ model results may be used directly. Cases 3 and 4 model the start-up for standard fuel with standard rig burden. Case 4 attempts to increase the peak power by surrounding C3 with fuel elements of very high burn-up, but retaining the same average burn-up as case 3. Case 5 represents the worst possibility in changing fuel types. Cases 6 and 7 are the equivalent of cases 3 and 4 for 200 g LEU fuel. It is clear that peaking with 200 g LEU fuel differs little from that with standard HEU fuel, and the extreme case (5) could be easily avoided in the HEU/LEU change-over.

An operational limit on fuel element power is determined from consideration of the margin to excursive flow instability. This has been investigated for operation at 13 MW, which is approximately the power required with 200 g ^{235}U elements to ensure that no application of the reactor is disadvantaged compared with operation with HEU fuel at 10 MW.

For operation at 13 MW with two coolant pumps, the normal inlet coolant temperature was calculated to be 48°C.[6] An analysis of HIFAR flow instability power by Romberg[5] gave a value of 2400 kW for this inlet temperature. By applying the same uncertainty factors on coolant flow rate and fuel loading used for HIFAR safety assessments with HEU fuel, this value is reduced to 1680 kW. The margins between this reduced value and the calculated powers of 860 and 975 kW for the worst cases under operation with LEU fuel and with mixed cores are 1.95 and 1.72 respectively. These margins, which have not been reduced to allow for uncertainty in the peak power, still remain adequately large.

The loss of reactivity over an operating cycle was calculated for HEU fuel at 10 MW and 200 g LEU fuel at 10 and 13 MW. The results given in Table 4 were obtained for cores of uniform burn-up. The validity of the 'uniform burn-up' assumption for this purpose was demonstrated by comparison with HIFAR 'core-follow' calculations[2] and experimental observations. It can therefore be deduced with confidence from the results of Table 4, that 200 g ^{235}U LEU fuel elements would not give rise to significant reactivity control problems.

DISCUSSION

Earlier conversion calculations for HIFAR[2,7] showed that an LEU element with about 160 g ^{235}U matched the reactivity of the standard HEU element with 150 g ^{235}U; that is, the same number of fuel elements would be required. Assuming that the operating power of 10 MW was retained, the main effects on reactor performance were reduction in thermal flux of about 15% in the core and 5-10% (depending on distance from the core) in the reflector. Changes in reactivity coefficients were minor. Although these results were for U_3O_8-Al LEU fuel elements, neutronics calculations are very little affected by a change from U_3O_8 to the now preferred U_3Si_2. The results were generally in line with those for other DIDO-class reactors, though the higher power levels and rig burdens of the latter complicated detailed comparisons.

A later study[4] of the same fuels examined in more detail the effects on irradiation facilities. Briefly, the results indicated reductions of about 5% in (n, γ) Mo activity, 14% in fission-product Mo activity, 10% in Ir activity at typical irradiation positions and 6 to 10% in thermal neutron fluxes at the beam facilities, again assuming that the 10 MW operating power level was retained. These results promoted some consideration of whether a power increase on LEU conversion might be desirable to restore, fully or in part, the performance of the HEU fuelled reactor in at least some applications. The costs of such options, however, could hardly be even crudely estimated at that time because no satisfactory cost data for LEU production fuel elements were available.

The present work extends the range of conversion options previously considered. In terms of reactor performance changes, the results are entirely consistent with those of the earlier studies, as was expected. The significant difference is that some reasonably reliable indicative cost data for U_3Si_2-Al LEU fuel elements relative to those for U-Al alloy HEU elements are now available. Although these may change in detail in the light of manufacturing experience, it is considered unlikely that the main conclusions of the present investigation would be seriously affected.

For HIFAR, the ^{235}U loading of the HEU fuel is low, and LEU fuel loadings considerably higher than the maximum of 200 g ^{235}U considered in this study (U density in meat 2.9 g m^{-3}) could in principle be used before the U density limit of ~ 4.8 g cm^{-3} validated for U_3Si_2 fuel was approached. The fuel cost algorithm used would, however, require reconsideration before any upward extension of the study was made. Any conclusions drawn should therefore not be extrapolated beyond the range of ^{235}U loadings (150 - 200 g) actually considered.

Within that range, the reactor fuelling costs decrease monotonically with increasing fuel element ^{235}U loading. If the current 10 MW authorised power limit for HIFAR is retained, the results show that 200 g LEU elements should enable the incremental annual cost of fuel compared with HEU to be held to about eight percent. The associated flux and activation penalties, ranging from about 6 to 23% are unlikely to be wholly acceptable, and a compromise loading of 160-170 g ^{235}U with attendant flux/activation penalties in the 5-17% range may be preferred. The LEU cost penalty compared with HEU would then be some 40-60%. The principal findings are summarised in Table 5.

If, however, it is considered necessary to maintain some or all fluxes and activations at the levels now applying with HEU fuel, LEU incremental fuelling costs, again within the limits of the range considered, are lowest for the highest ^{235}U loadings. If no current application of the reactor is to be disadvantaged by conversion to LEU, the study shows that 200 g ^{235}U LEU elements would necessitate a reactor power of about 13 MW. The annual fuelling cost is then estimated to be about 40% higher than for the present HEU fuel at 10 MW (Table 5).

CONCLUSIONS

The fuel (^{235}U) loading per element in HIFAR can be significantly increased without difficulties in fabrication or in reactor operations. The incremental costs of LEU fuelling compared with HEU would be reduced by such increased element loadings.

If the current 10 MW authorised power limit is retained, practical considerations of performance penalties would probably limit the increase in ^{235}U loading for LEU fuel elements to about 10% more than the HEU elements now used. It is estimated that the LEU fuelling costs would then be some 40-60% higher than for the present HEU fuel. The concomitant flux and activation penalties would be in the general range from 5-17%.

If the authorised reactor power can be increased, following conversion to LEU fuelling, to restore flux and activation levels for some or all current applications to their present levels, the economic case for higher fuel element ^{235}U loadings is strong. For the range considered, the maximum loading of 200 g ^{235}U per element would require an operating power of approximately 13 MW to ensure that no current application of the reactor was disadvantaged by the conversion to LEU. The annual fuelling cost increment compared with HEU (at 10 MW) is estimated to be about 40%, which is about the same as that which would apply for the practicable (170 g ^{235}U) option if the 10 MW power limit were retained.

Since 200 g ^{235}U for a HIFAR U_3Si_2-Al LEU fuel element is equivalent to a uranium density of 2.9 g cm^{-3} compared with the maximum validated density of 4.8 g cm^{-3} for this type of fuel, an even higher fuel loading (and corresponding increase in reactor power) may have economic advantages. The fuel cost algorithm used in the present study may, however, be inappropriate for use in that extended loading range.

REFERENCES

(1) D.B. McCulloch, "Fuel Enrichment Reduction For Heavy Water Moderated Research Reactors". Proceedings of the International Meeting on RERTR 24-27 October 1983, Tokai, Japan. JAERI-M84-073 (1983).

(2) B.V. Harrington and G.S. Robinson, "A Neutronics Study of Reduced Enrichment Fuel for the HIFAR Research Reactor" AAEC/E604 (1985).

(3) T.M. Romberg, IAEA Tecdoc 324, Appendix C/Paper C2 (1985).

(4) B.V. Harrington and D.B. McCulloch, "Consequences For Some HIFAR Irradiation Facilities Of Conversion To The Use of Low Enriched Uranium Fuel". IAEA Seminar on Applied Research and Service Activities for Research Reactor Operation, Copenhagen Denmark, 9-13 September 1985. IAEA-SR-119/25 (1985).

(5) G.S. Robinson, "HIFAR Fuel Burn-up Calculations" - Dido Reactor Operators' Meeting, Lucas Heights Research Laboratories, Sydney, Australia. (1982).

(6) N.A. Parsons, Unpublished AAEC Report (1986).

(7) B.V. Harrington and G.S. Robinson, IAEA Tecdoc 324, Appendix C/Paper C1 (1985).

TABLE 1 COMPARATIVE FUEL-CYCLE DATA

		HEU 80% ^{235}U	LEU 20% ^{235}U		
	^{235}U/element (g)	150	150	170	200
	^{235}U density in meat (10^{21} atoms cm^{-3})	1.10	1.10	1.24	1.46
	Total U/element (g)	187.5	750	850	1000
	U density in meat (g cm^{-3})	0.535	2.17	2.46	2.90
1	Average end-of-cycle burnup (MWd/element)	40.5	32.9	46.0	65.4
2	End-of-cycle core fissile mass (kg)	2.504	2.855	3.003	3.234
3	Average discharge burnup (MWd/element)	64.7	50.9	74.6	110.0
4	Average discharge burnup (10^{21} fissions cm^{-3})	0.50	0.39	0.58	0.85
	For 10 MW operation:				
5	Fuel Elements per year	46	58	40	27
6	Relative fuel cost	1.0	1.86	1.40	1.08
	For operation with no flux reduction:				
7	Reactor power (MW)	10	11.4	12.0	12.9
8	Fuel elements per year	46	68	49	36
9	Relative fuel cost	1.0	2.17	1.71	1.42
1		32.0	23.0	36.0	55.1
2		2.765	3.124	3.275	3.514
3	As above but	49.2	32.8	56.4	91.4
4	for high rig	0.38	0.25	0.44	0.70
5	burden rather	60	91	53	33
6	than standard	1.0	2.20	1.41	0.99
7	rig burden	10	11.3	11.8	12.7
8		60	102	64	43
9		1.0	2.57	1.71	1.29

TABLE 2 COMPARISON OF FLUXES AND ACTIVITIES

^{235}U/element (g)	HEU 150	LEU 20% ^{235}U 150	 170	 200
	Result	Result relative to HEU		
Thermal Flux (10^{14} n cm^{-2} s^{-1}):				
Central element	1.287	0.875	0.832	0.773
Core average	1.051	0.886	0.847	0.792
At 10H	0.609	0.943	0.924	0.896
At 6H	0.952	0.935	0.912	0.880
At 4H1 and 4H2	0.607	0.958	0.944	0.924
At 4H3 and 4H4	0.904	0.930	0.906	0.873
At 4H5 and 4H6	0.615	0.957	0.942	0.921
Mo (n,γ) activity:				
At C2		0.963	0.951	0.935
Core average		0.965	0.955	0.939
Mo fission product activity:				
At C2		0.882	0.842	0.786
Core average		0.892	0.855	0.803
Ir activity:				
At C2		0.907	0.876	0.833
Core average		0.912	0.883	0.842
1/(Fissile mass)		0.877	0.834	0.774
1/(Fissile mass)$^{0.7}$		0.912	0.881	0.836
Absorption coefft ($\delta k/k$ per m^2):				
Central element	2.904	0.894	0.857	0.804
Core average	1.791	0.911	0.875	0.824

TABLE 3 HEU/LEU FLUX PEAKING

No.	Case description	C3 Power (kW) at 10 MW
1	Uniform core of HEU at 40.5 MWd	501
2	Same as case 1 but using XY model	491
3	New HEU element in C3, remainder of core HEU at 33.1 MWd	632
4	New HEU element in C3, 6 surrounding elements HEU at high burnup (50 MWd), rest HEU at 27.5 MWd	643
5	Same as case 4 but new LEU element in C3	750
6	New LEU element in C3, remainder of core LEU at 59 MWd	649
7	New LEU element in C3, 6 surrounding elements LEU at high burnup (95 MWd), rest LEU at 47 MWd	663

TABLE 4 REACTIVITY LOSS OVER AVERAGE FUEL CYCLE

Fuel Type	Power (MW)	Reactivity Loss % (in 3.2 kg core)		
		Long Term	Transient	Total
150 g HEU	10	3.16	2.06	5.22
200 g LEU	10	2.61	2.69	5.29
200 g LEU	12.9	3.36	2.55	5.91

TABLE 5 PRINCIPAL PENALITIES OF SOME LEU CONVERSION OPTIONS

Conversion Option	Reactor Power After Conversion (MW)	Selected Fuel Element Loading (g ^{235}U)	Performance Penalty C/W 150 g HEU Core			Estimated Annual Fuel Cost Relative To 150 g HEU elements at 10 MW
			ϕTh (Core)	ϕTh (reflector)	$(n,\gamma)^{99}$Mo Activity	
Constant Power	10	200	21%	8-13%	6-7%	+8%
		170	15%	6-10%	5-6%	+ 40%
		160	13%	4- 8%	4-5%	+ 60%
No Current Application Disadvantaged	13	200	0	0	0	+ 42%

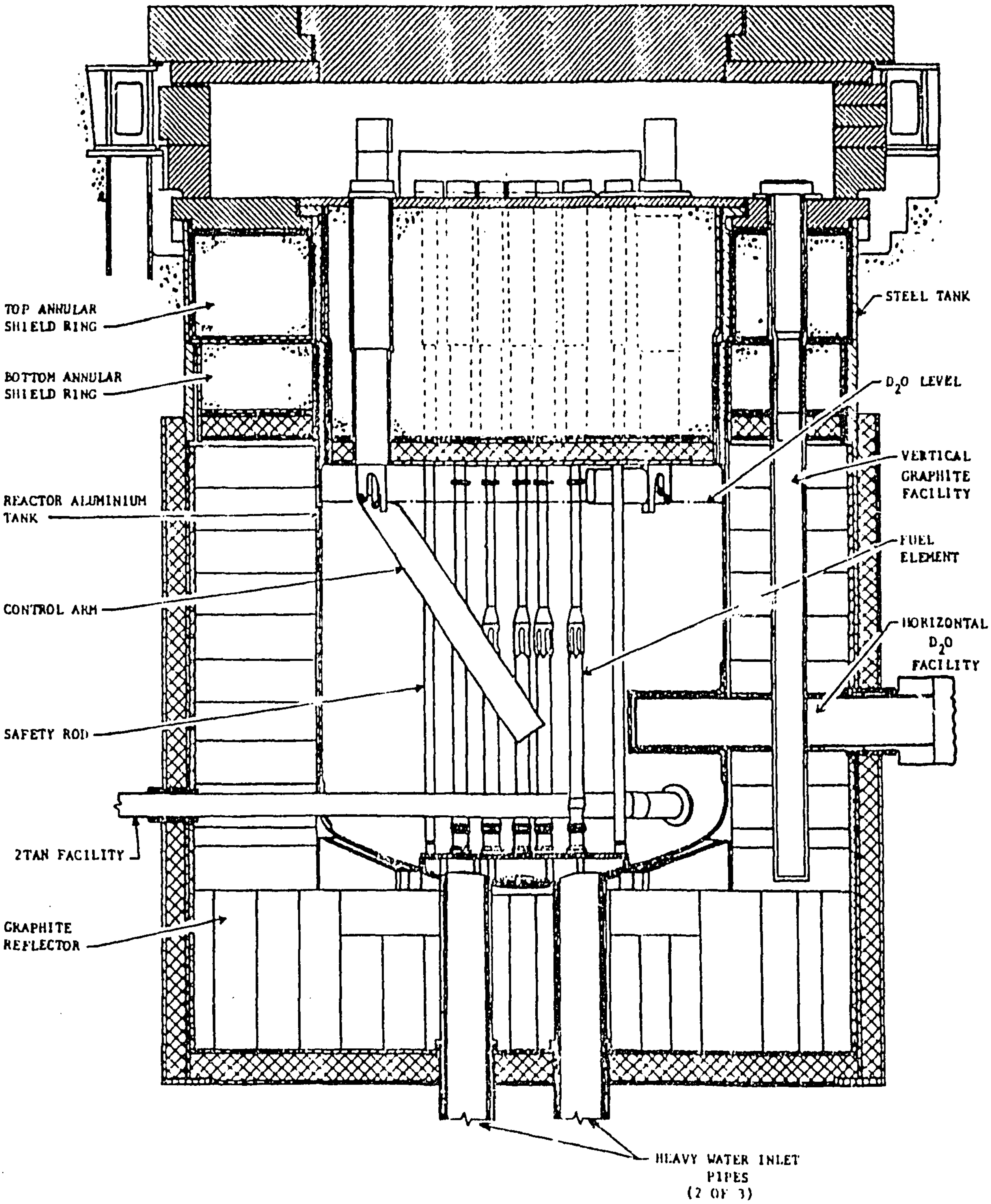

FIGURE 1. REFLECTOR AND ALUMINIUM TANK

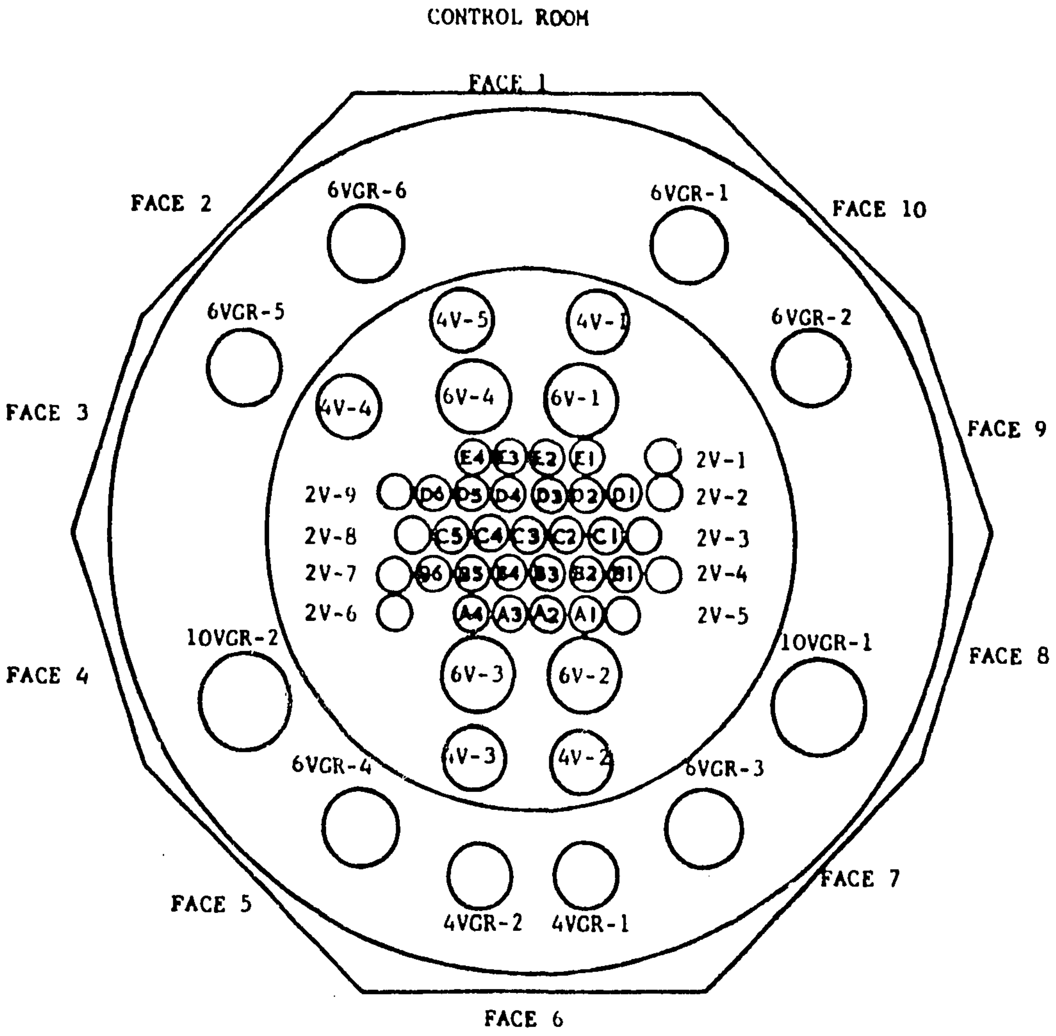

FIGURE 2. VERTICAL FACILITY LOCATIONS

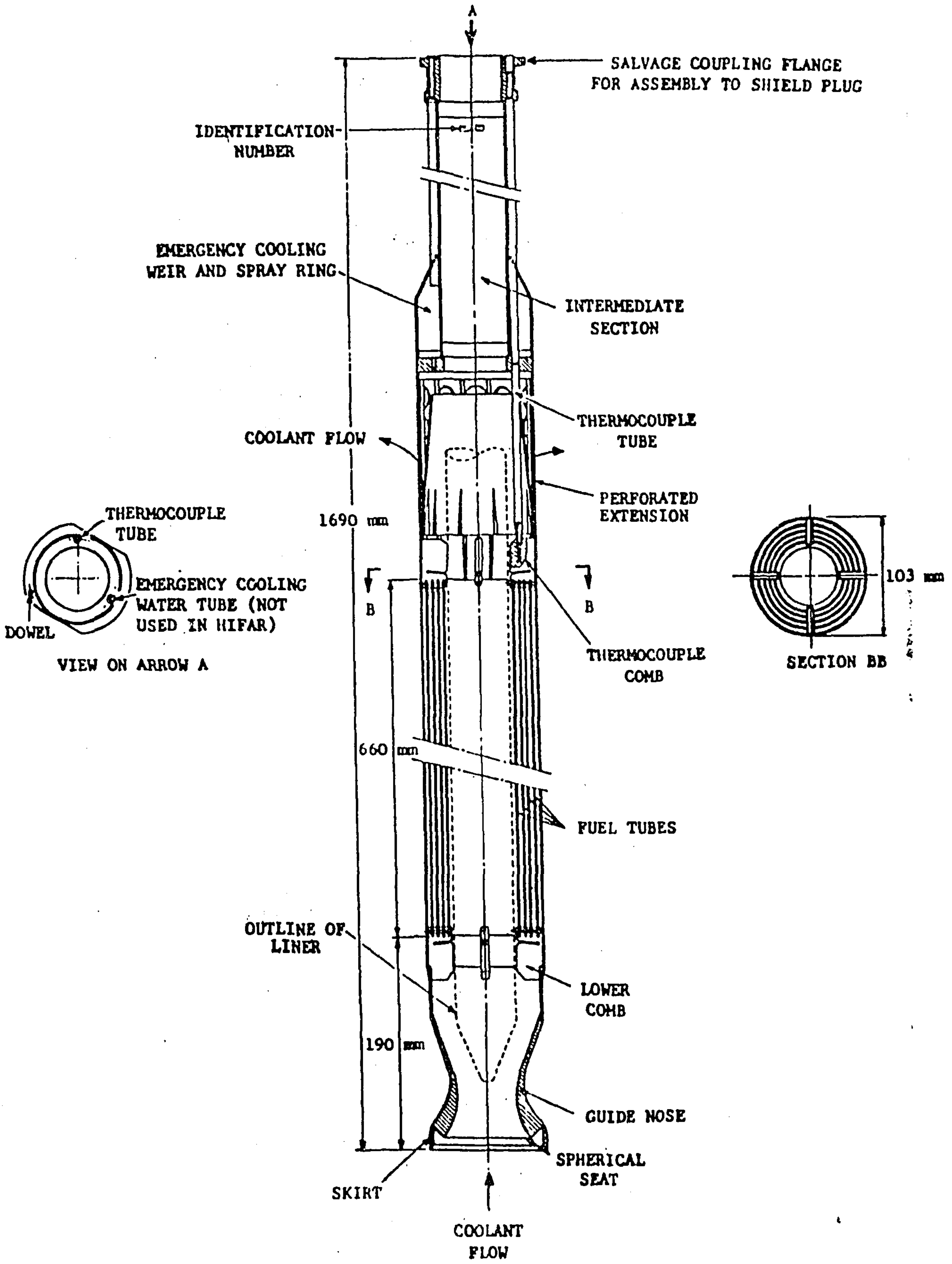

FIGURE 3. FUEL ELEMENT MARK IV/5A

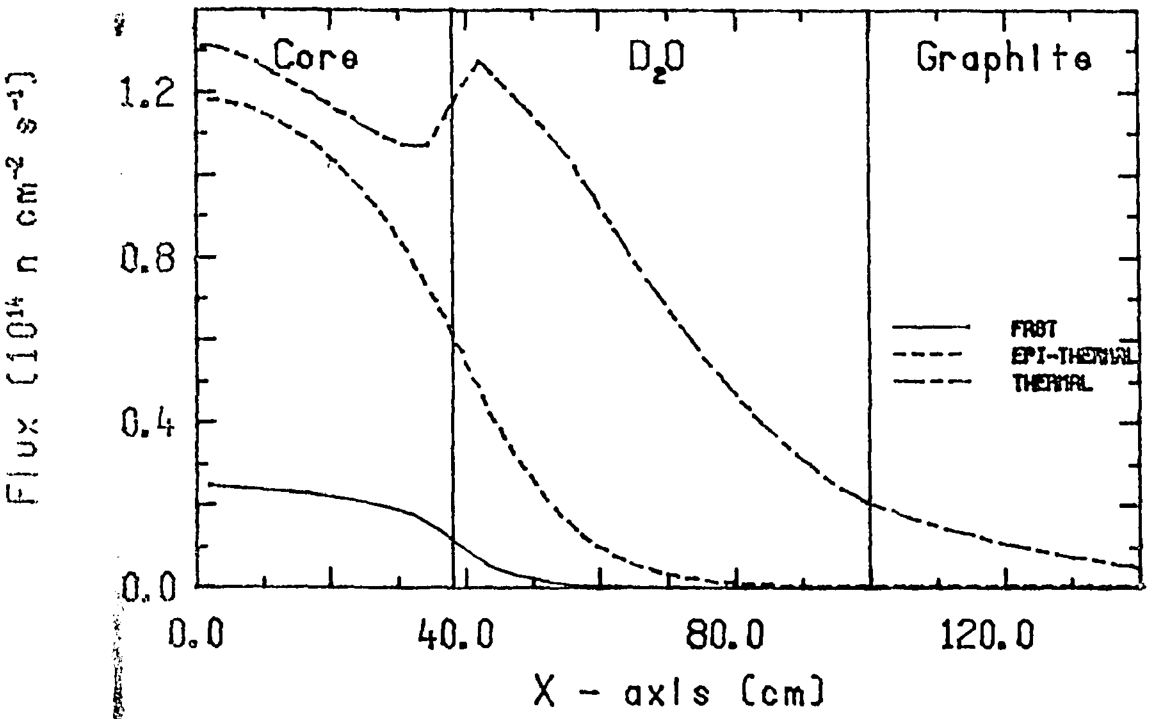

FIGURE 4. FLUXES AT CORE MID-PLANE FOR HEU FUEL

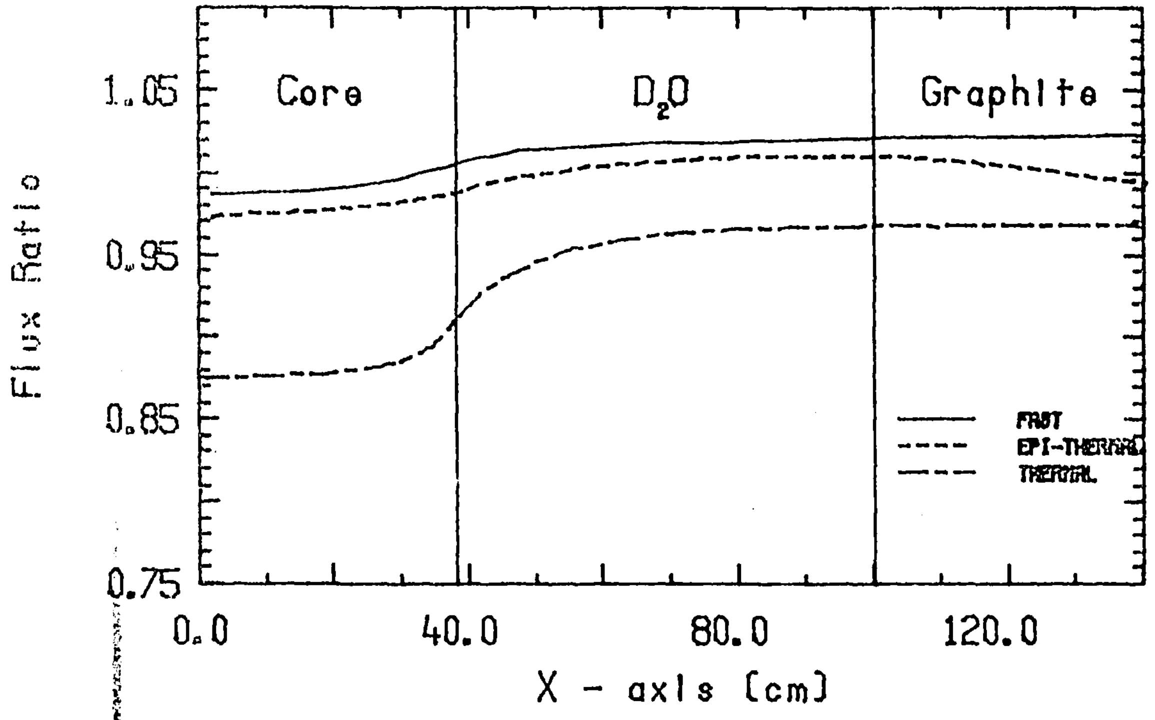

FIGURE 5. FLUX RATIOS AT CORE MID-PLANE 150g LEU / HEU FUEL

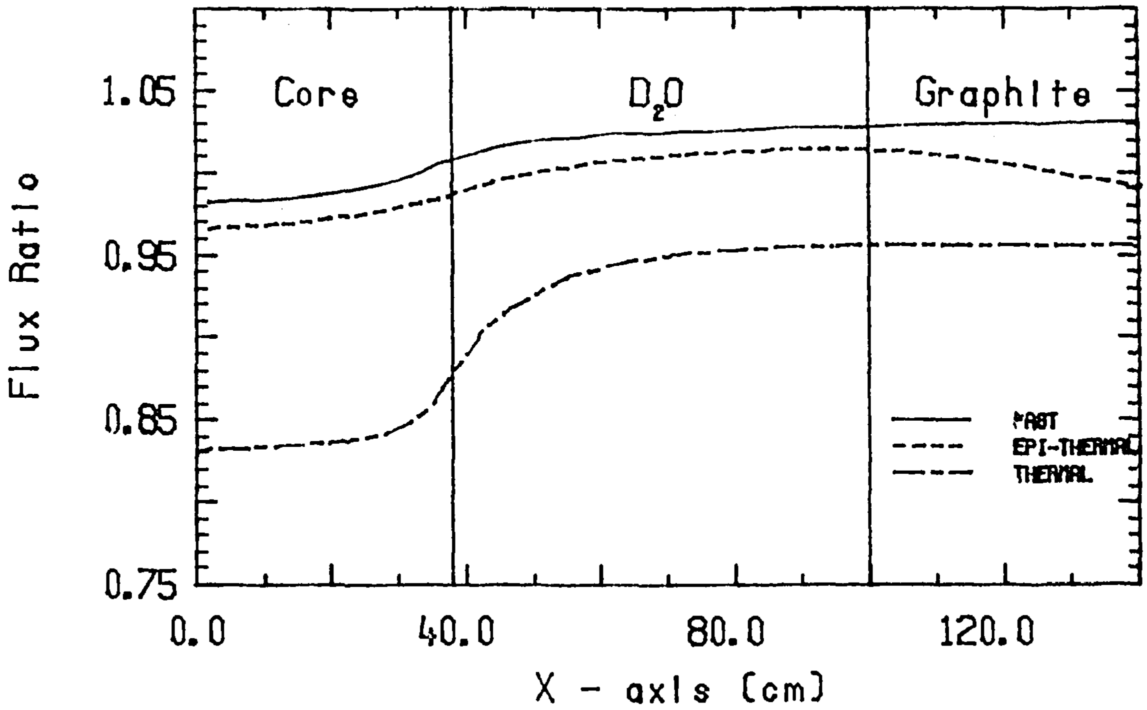

FIGURE 6. FLUX RATIOS AT CORE MID-PLANE
170g LEU / HEU FUEL

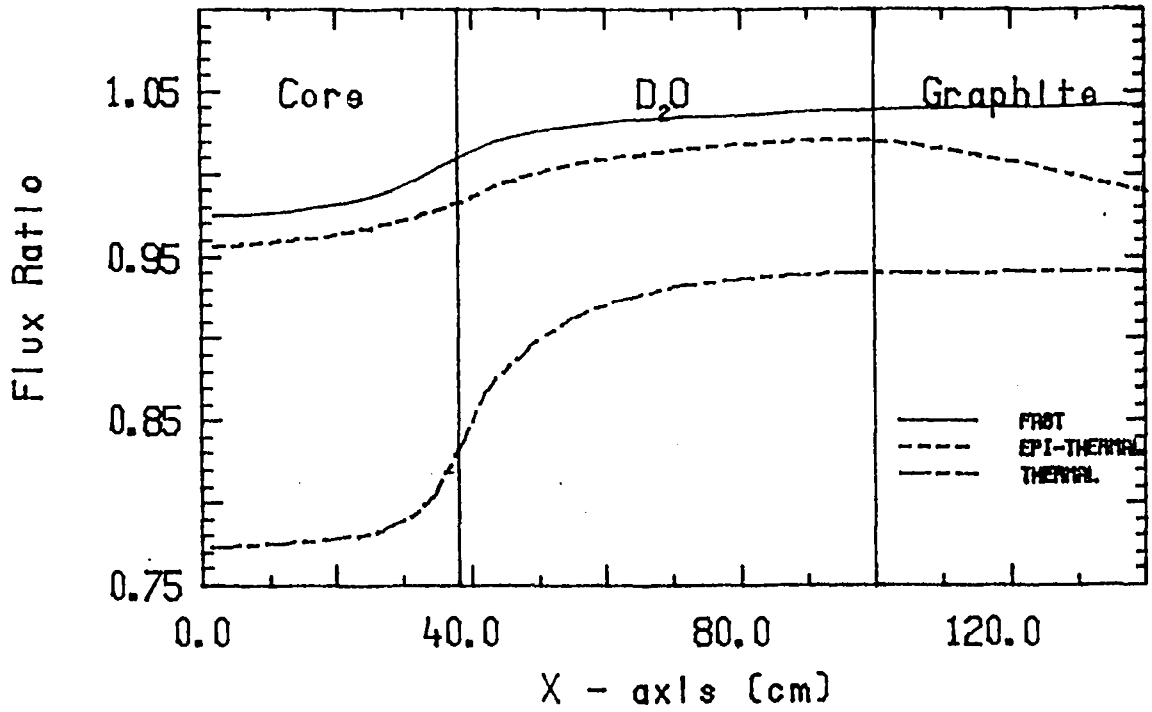

FIGURE 7. FLUX RATIOS AT CORE MID-PLANE
200g LEU / HEU FUEL

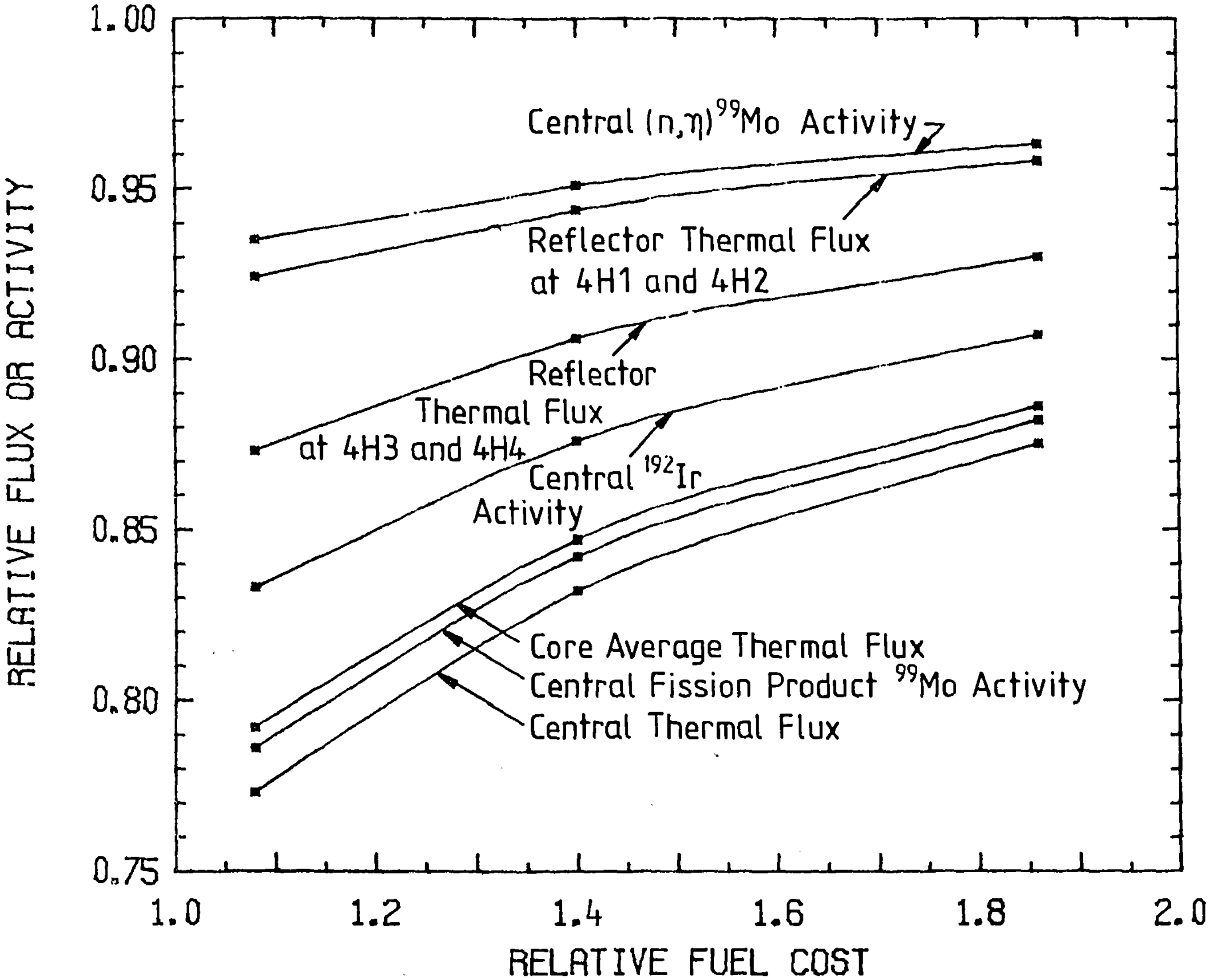

FIGURE 8. FLUX AND ACTIVITY VERSUS FUEL COST