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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS RESEARCH LABORATORIES

REPORT OF THE WORKING PARTY ON CONVERSION OF HIFAR TO LOW ENRICHMENT URANIUM FUEL

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EXECUTIVE SUMMARY

This report states the effect on research reactor operations and applications of international and national political decisions relating to fuel enrichment. Technical work done in Australia and overseas to establish parameters for conversion of research reactors from High Enrichment Uranium (HEU) to Low Enrichment Uranium (LEU) have been considered in developing a strategy for HIFAR. The requirements of the research groups, isotope production group and reactor operating staff have been considered. For HIFAR to continue to provide the required facilities in support of the national need, it is concluded there should be no reduction of neutron flux.

LEU fuel elements, even of the same nominal ^{235}Uranium content, will be more expensive to manufacture than the present HEU fuel. Based on currently projected cost structures for LEU fuel elements, the analysis shows that the most economic way of operating the reactor and meeting the flux requirement is to increase the ^{235}U content of the fuel elements more than is necessary solely to compensate for the negative reactivity of the ^{238}U, and also to increase the reactor power to restore the neutron flux. A reactor power of 13 MW using fuel elements each with 200 g ^{235}U is considered to be a good compromise between the economic and technical factors involved; the projected fuel cost increase is 40% to 45% compared with HEU fuel and operation at 10 MW.

Although the fuel 'meat' composition of LEU fuel is significantly different from that of HEU fuel, information so far available indicates there will be no safety problems from the change to LEU. The small increase in power level recommended is covered in previous safety analyses to 15 MW (HSD 1972). There are some further confirmatory data to be received and they are expected to support the confidence that there are no safety reasons why HIFAR should not operate in the recommended manner.

Strategies and schedules are provided for three possible dates of conversion to LEU depending on the continued availability of HEU. However, it should be noted that in the event of no further HEU being available, there is insufficient

time to establish a supply of LEU fuel to ensure continuity of operations.

RECOMMENDATIONS

Consequent on its deliberations, the Working Party makes the following recommendations.

Level of Neutron Flux in Facilities

1. The neutron flux in the beam facilities used for neutron scattering experiments should not be reduced when HIFAR is converted to LEU fuel.

2. The neutron flux used in the core for irradiation purposes should not be reduced when HIFAR is converted to LEU.

Safety Case and Documentation

3. The conversion of HIFAR to using LEU is a major modification in the terms of the HIFAR Authorisation, and it will be necessary to prepare a full safety case to obtain approval from the Commission for the conversion.

4. It is estimated that the effort required to prepare the Safety Case for conversion to LEU is about three man years. The commitment to this effort should be accepted, with the knowledge there will be delays to pre-existing programs.

5. The advice of the Regulatory Bureau should be sought to confirm that there do not appear to be any contra-indications to the use of LEU fuel in HIFAR with a 200 g ^{235}U loading in each fuel element and the operation of HIFAR at 13 MW.

6. The advice of the Regulatory Bureau should be sought to confirm that there do not appear to be any contra-indications to the use of fuel with 45% ^{235}U enrichment in 150 g elements and operation at 10 MW should this be necessary as an interim step to obviate a shutdown of HIFAR, because of LEU fuel supply logistics.

7. If it is necessary to use 45% fuel, the need for additional safety analysis and work should be accepted, with consequent delays to pre-existing programs.

Reactor Operating Cycle

8. The present operating cycle of 28 days, including four days shut-down for fuel movements and maintenance, is a reasonably optimum compromise of conflicting requirements and should not be altered unless the pattern of usage of HIFAR alters.

Fuel Element Loading

9. Given the above recommendations and making reasonable assumptions concerning the relative cost components of LEU fuel elements, it is economically beneficial to use fuel elements with more ^{235}U rather than the amount as now used in the HEU elements. The plan for conversion to LEU should proceed on the basis that fuel elements will have 200 g ^{235}U LEU and there will be an increase of power to 13 MW.

10. Consideration could be given at a later stage to using fuel elements with ^{235}U loading other than 200 g if they can be shown to be more economic; no safety problems are foreseen in raising the additional power to maintain thermal flux levels.

Program

11. It is essential that endeavours should be made to obtain an answer from the US authorities as soon as possible about further supplies of HEU for one year or two years to avoid running out of fuel for HIFAR.

12. In the event that the US Authorities decline to make further HEU fuel available then urgent recourse should be made to investigating any other offer of HEU (e.g. 45%) ^{235}U fuel.

13. The Minister should be advised that tenders could soon be called for LEU fuel to ensure HIFAR's continued operation and that the annual fuel cost may rise by 40 to 45%. These figures can only be confirmed when better data are available.

14. Consideration should be given, at the time of ordering the first batch of LEU fuel, to split the order between the preferred bidder and the next preferred bidder.

15. It should be accepted that to prevent a hiatus in HIFAR operation, tender action for the procurement of LEU would have to be commenced in July 1986 should no further HEU be available and this is considered to be impractical.

1. INTRODUCTION

When the DIDO class reactor HIFAR was designed in the early 1950s, the advantages of using high enrichment uranium (HEU) for the fuel were well appreciated and included

- ease of manufacture because there is less uranium to be alloyed or distributed in the fuel element for a given ^{235}U loading, and
- suitability for compact cores with high neutron flux to thermal power.

At that time HEU was commonly used with 90% or more ^{235}U. Since then there has been growing concern for possible diversion and misuse of such material.

It has long been realised that moderate reductions in the percentage of ^{235}U in HIFAR fuel made little difference to manufacture of fuel, operation and utility of the reactor or the economics of operation; over the years, the percentage of ^{235}U has been progressively reduced to about 60%. At this level, however, fabrication of an efficient, compact nuclear weapon is still possible and it has become accepted (INFCE 1980a, INFCE 1980b) that it is only when the ^{235}U percentage falls to about 20% or less (LEU) that the production of a nuclear weapon becomes significantly difficult and the device becomes inordinately large.

In 1978 the USA, as the principal vendor of HEU, announced a program to eliminate the use of HEU fuel in research and test reactors except where it could be shown that the reactor could only perform its required functions with fuel of that enrichment. Under the Reduction of Enrichment for Research and Test Reactors (RERTR) program, studies were carried out on LEU fuel fabrication technology and neutron physics of LEU cores. These studies showed that reactors of, inter alia, the HIFAR design could operate on LEU albeit with economic penalties and either increased power to maintain the flux or reduced flux at the existing power.

The United States Nuclear Regulatory Commission (NRC) having published an earlier policy statement (NRC 1982), on 8 July 1984 published a Proposed Rule to reduce to the maximum extent possible the use of HEU in domestic and foreign research and test reactors (NRC 1984). It became apparent that the success of the program was leading towards an NRC Final Rule limiting the future release of HEU to cases where it was needed for a unique purpose that could not be accomplished without the use of HEU fuel; the Final Rule has now been issued (NRC 1986) with minor changes due to representations made to the NRC following promulgation of the Proposed Rule.

To prepare in a timely manner for conversion to LEU, a meeting was held at the AAEC Research Establishment on 20 February 1986 to discuss the strategy for HIFAR fuel supply and it was agreed that the Manager, Engineering Services and Operations (MESO) would convene a Working Party to examine the technical factors and recommend a suitable strategy.

A meeting was held by MESO on 25 February and attended by representatives of AAEC's Nuclear Technology, Health and Safety and Applied Physics Divisions, Australian Institute of Nuclear Science and Engineering (AINSE), CSIRO Division of Energy Chemistry, the AAEC Regulatory Bureau, Technical Secretariat, Commercial Products Unit and Reactors Department.

At this meeting a Working Party consisting of representatives of Reactors Department, Nuclear Technology Division, AINSE (representing, by agreement, HIFAR Users including AINSE and AAEC Neutron Scattering Groups, Commercial Products Unit, Neutron Activation Group, etc.) and the Regulatory Bureau (as an observer) was set up and subsequently the following terms of reference for the Working Party were accepted:

(a) OBJECTIVE

The purpose of the Working Party is to ensure that technical and other matters relating to the conversion of HIFAR to operate on LEU fuel are considered in a timely way so that forward ordering of LEU fuel can commence in time to maintain adequate fuel reserves at Lucas Heights.

(b) THE REPORT

The Working Party is required to report on 30th June 1986 to the Deputy Director with a strategy compatible with the current usage of HIFAR neutron flux and reactor availability. The economics of meeting these needs should be considered in the context of operating convenience and safety. Any proposed changes to the reactor core and its operating parameters should be documented and justified. (Smith 1986)

The Working Party consisted of

Mr A.C. Higgins, Manager, Engineering Services and Operations, Chairman

Mr R.W.S. Carlson, Observer

Dr R.L. Davis

Mr D.B. McCulloch

Mr A.C. Wood

Mr N.S. Stewart, Secretary.

In Mr McCulloch's absence overseas, Mr G.S. Robinson substituted for him.

The Working Party has met nine times from March to June 1986 and presents this report in fulfilment of the objective.

2. REASONS FOR CONVERSION

2.1 Background

The first formal moves towards a general reduction in the level of enrichment of uranium fuels available for use in research reactors derived from Working Group 8(c) of the International Nuclear Fuel Cycle Evaluation (INFCE) in the late 1970s. The main intentions were to reduce, as much as possible, the world traffic in HEU replacement fuel, then running at about 1250 kg ^{235}U per annum, and to minimise HEU fuel stockpiles at research reactor sites.

The Working Group 8 report endorsed the principle of seeking such enrichment reduction (INFCE 1980b Summary, para 4.3) with an important proviso, namely, "In assessing the practical feasibility of utilizing lower enriched fuel in existing research reactors, the agreed criteria are that safety margins and fuel reliability should not be lower than for the current design based on highly enriched uranium and that neither any loss in reactor performance, e.g. flux-per-unit power, nor any increase in operating costs should be more than marginal".

Largely at the instigation of the United States, RERTR programs have been undertaken in many countries throughout the 1980s. A major part of these programs has been directed towards meeting the intent of this proviso. A status review is given in Section 4.

As the United States is the major supplier of enriched uranium for research reactors, its export policies have tended to determine fuel supplies throughout the Western world. It has also recently finalised its policy on the use of HEU in US research reactors (NRC 1986).

2.2 Reactor Conversion Outside the USA

All new research reactor core designs in recent years (e.g. the Indonesian 30 MW medium power reactor) have been based on the premise that fuel of greater than 20% ^{235}U enrichment would not be available. A similar situation has prevailed for major modifications and upgradings proposed for existing research reactors. An exception is a current paper study for radical reconstruction of the Munich, FRG reactor as a high illumination beam reactor. The proposed concept would not be workable with any LEU fuel configuration likely to be practicable. However, the proposal does not appear likely to be implemented.

Reactor operators requiring replacement fuel have for some time been essentially restricted to LEU wherever the technical requirements of the reactor are sufficiently low that they could be met with fully qualified LEU fuel technology. These reactors are mainly in the low or moderate power group (say 2 MW or less).

For higher power or more highly-rated reactors where LEU conversion could not be effected with such qualified fuels without unacceptable performance or economic penalties, US policy has been to restrict export licences for the supply of HEU fuel to a quantity, which, with existing stocks, would be sufficient to permit operation of the reactor concerned to, but not beyond, the end of 1987. This policy assumed that LEU fuel suitable for conversion of any reactor requiring a fuel density of less than approximately 5g U cm^{-3} would be fully qualified in time to permit reactor licensing revisions, fuel ordering and delivery, etc. to be completed, and core conversion to start, at the latest, in early 1988. Submission of a plan for conversion is also a condition of grant of the HEU export licence. Possible slippage of these dates is considered in following sections.

Similar policies are apparently being followed by other potential HEU suppliers. In particular, all recent supplies of research reactor fuel from the USSR to operators in Comecon countries have been, as far as is known, of 20% ^{235}U or lower enrichment; it is of interest to note that most operators in these countries are considered to have little real knowledge of the technical specifications of their fuel, but take what is supplied and use it in the prescribed manner, regardless of other considerations.

2.3 HIFAR Conversion

In recent years, the enrichment of HIFAR fuel obtained from the UK has decreased slightly from 80% ^{235}U to 75% and then 60% as reprocessed uranium was used. It is probable that no more fuel of this last enrichment will be available from the UK.

The most recent batch of 104 fuel elements of 60% ^{235}U was manufactured in the UK from uranium purchased in the US in 1984. To obtain an export licence for this material, it was important for the Commission to have participated in the RERTR program and to show a commitment to conversion to LEU. In particular, the Commission submitted a schedule for the conversion to LEU in which operation with LEU from early 1988 was envisaged. An important part of this plan was completion in the United States LEU test program for U_3Si_2-Al fuel including a full core test in the Oak Ridge Reactor (ORR). As the ORR test has slipped back about one year (see Section 4.3), it is possible that the US would approve further HEU for use in HIFAR.

2.4 Timing of Conversion

The HEU fuel available at Lucas Heights, together with deliveries of fuel on order, will permit HIFAR to operate to early 1988. From early 1988, it will be necessary either to have LEU fuel available, as was envisaged in the schedule submitted to the United States authorities in 1984, or to obtain an agreement for HEU to be used for a further one or two years. The US authorities will be approached in the near future for an "in principle" approval for an additional two years' supply of HEU; it is hoped that an answer will be forthcoming shortly. Because there is no guarantee that the response will be favourable it is necessary to prepare plans for the various possibilities so as to eliminate, as far as possible, any risk that HIFAR might have to shut down for lack of fuel.

3. REQUIREMENTS

3.1 The Role of HIFAR

HIFAR is a high flux source of neutrons operated by the Commission to meet national needs including research and development, and the production of radioisotopes.

3.2 Requirements for the Operation of HIFAR in support of Research and Development - Neutron Scattering

HIFAR was designed in the early 1950s and has been operating for over 27 years at its original design power of 10 MW. It currently provides beams of thermal neutrons of sufficiently high intensity for the conduct of research of international standing, undertaken by scientists from many parts of the Australian research community including post-graduate students working for higher degrees. There are, however, fast neutrons in the beams and thermal neutron leakage into the reactor building which together reduce the quality of the beams and, hence, the rate at which results can be obtained. At present, the number and size of the neutron scattering facilities combined with the flux and operating time available, just provides an adequate basis to meet existing demand, but the advice of Australian Institute of Nuclear Science and Engineering (AINSE) and that of the AAEC neutron scattering group is that any deterioration in that basis would have adverse effects on Australia's international standing in neutron scattering research. Indeed, the Australian Science and Technology Council recently recommended that the HIFAR neutron beam facilties be improved (ASTEC 1985).

For these reasons, any changes to the fuel, its arrangement and the mode of operation of HIFAR because of the introduction of LEU should be made without reduction to the existing annual, integrated thermal neutron beam flux; thus should the reactor operating time be reduced due to more shutdown time, the flux must be increased to compensate for lost beam time.

The AINSE and AAEC staff engaged in neutron scattering research suggest that the present 28 day operating cycle including a four day shutdown is satisfactory and permits many experiments to be carried out in one operating period. A shorter operating cycle would increase the number of interrupted experiments; consequently, these would require re-calibration on start-up leading to a loss of effective beam time - necessitating an increase in flux to compensate.

Taking the above factors into consideration, the Working Party is of the opinion that the change to LEU should not result in any deterioration of the capability for carrying out neutron scattering research.

3.3 Requirements for the Operation of HIFAR in Support of Research and Development - Neutron Activation

The Working Party has established that the effectiveness of the neutron activation work carried out at Lucas Heights would not be adversely affected by a 20% to 30% reduction in neutron flux. This work does not, within broad limits, make demands on the operation of HIFAR.

3.4 [illegible]irements for the Operation of HIFAR in Support [illegible] sotope Production

3.4.1 Production of fission product molybdenum 99

The production of ^{99}Mo from the fission of ^{235}U is limited by the transfer of heat from the irradiation (rocket) can and not by the absolute reactor flux level.

The ^{235}U content, in terms of enrichment (currently 1.8%) and mass (currently 45 g of UO_2), is set for a particular maximum flux level and can be varied if that flux level changes in order to achieve the same ^{99}Mo yield per target can.

The ^{235}U mass required per can is approximately inversely proportional to the neutron flux level. At present about 330 g of ^{235}U is irradiated each year for the Commercial Products Unit and, for example, a drop of 14% in flux levels would incur an extra ^{235}U consumption worth up to $12 000 per year. Thus, a reduction in flux levels at the irradiation cans can be retrieved by changing the material to be irradiated but there is a cost penalty.

3.4.2 Production of n γ molybdenum 99

A reduction in the neutron flux activation rate - say up to approximately 5% - would not significantly affect the current production for the Commercial Products Unit. However, if the Technetium gel Generator is satisfactorily developed, the n γ production of ^{99}Mo will become more important and a flux reduction from the present levels could affect production. n γ ^{99}Mo is produced mainly by the capture of epithermal neutrons.

It has been shown (see Appendix 2) that the epithermal flux is only depressed by about 4% to 5% at mid core (using LEU at 10 MW), is hardly depressed at all in the D_2O moderator and falls off a few per cent in the graphite. It is desirable that the epithermal flux should not be reduced. At present it is not foreseen that increased usage of n γ ^{99}Mo would provoke a change to the operating cycle but Commercial Products Unit states that a four day shutdown starting on Tuesdays would be beneficial.

3.4.3 Production of iridium 192

At present, the activities of the ^{192}Ir sources produced by the Commercial Products Unit are barely adequate to satisfy the needs of the customers. A reduction of 10% in achieved activity would seriously affect the marketability of the product; a recent fall in activity of that amount resulted in the loss of the major New Zealand customer for a period of three months. The total market is currently worth about $150 000 per year and is growing. If this source of revenue is to be maintained, the activation flux must not be reduced.

3.4.4 Other radioisotopes

The production of other radioisotopes for the Commercial Products Unit is not critically dependent upon reactor flux levels. However, any reduction in the achieved activity as, for example, caused by a reduction in flux could cause customers to go elsewhere for their supplies. As an example, high radioactivity cobalt 60 sources for teletherapy are already being purchased from Atomic Energy of Canada Limited by some former customers because due to activity limitations the AAEC cannot supply sufficiently high activity sources. It should be noted, however, that these sources only generate $50 000 per year in income from a market that is static in size so they are not critical to the commercial viability of the Commercial Products Unit.

3.4.5 Possible installation of a flux trap

A flux trap is a device to increase the thermal flux level in a reactor core by providing a volume that has an increased moderator-to-fuel ratio. This effect can be achieved by removing a fuel element near the centre of the core. A study of the removal of the B3 element (near the centre of the core) showed a 10% increase in fuel consumption, an increase of up to 60% in the activity of fission product ^{99}Mo but less than 20% increase in ^{192}Ir activity (Harrington 1984). The study was based on HEU fuel but results with LEU are expected to be similar.

Although the installation of a flux trap would enhance the flux available at a given power for the production of radioisotopes, it would not alter the flux available for neutron scattering work in the neutron beams and would increase the usage of fuel elements.

3.4.6 Operating Program

Commercial Products Unit would prefer an operating program which has a minimum total shutdown time and schedules the shutdown towards the latter end of the week rather than the beginning. The present 28 day cycle which includes a four day shutdown, is satisfactory for commercial and medical radioisotope production.

3.5 Requirements for the Operation of HIFAR in Support of Commercial Neutron-Transmutation Doping (NTD) of Silicon

During the last two years, the Commission has invested a considerable sum of money and effort in the development of rigs and equipment for the NTD of silicon and in trial irradiations to satisfy potential customers. The irradiation rigs are located in the graphite reflector. A reduction in flux would reduce the capacity for producing NTD silicon. At present there is an excess of capacity of some 15% but AAEC is only supplying part of the needs of one firm; any reduction in flux level would limit the ability of the AAEC to develop further income in the future.

3.6 Requirements for the Programming of HIFAR to Facilitate Maintenance and Operational Aspects

The present operating cycle of 28 days, including a four day shutdown has evolved as a compromise between conflicting needs. Some of these tend to increase the length of the operating cycle, some to reduce it, and others place further restraints upon the selection. They include:

- the preferences of the users
- maximisation of the return on the Commission's investment in the reactor
- minimisation of the fuel cost
- the need for maintenance access.

The needs of the current users are covered in some detail in Section 3.2 to 3.5. At the risk of oversimplification, it may be said that user's needs are best served by the closest practicable approach to continuous operation which, in turn, leads to the longest operating cycle that can be sustained by a shutdown of one working week. Also, some users require additional shutdown time to install or commission in-pile equipment, so from time to time the shutdown week must include dedicated user time.

Much of the operating cost of the reactor is fixed; in the short term at least, it is independent of reactor operating time. It is believed that this will remain true even when the higher fuel cost of LEU (which is a variable cost) is taken into account. It follows that the cost of an extra operating day is less than the cost of an average operating day. On the other hand the value to the Commission of an extra operating day will normally approach the average value. Consequently, the return to the Commission is maximised when the reactor availability is highest. As the availability tends to rise with increased cycle time, this in turn encourages a longer cycle.

On the other hand, it can be shown that fuel burn-up is maximised as the reactor refuel cycle is shortened. As fuel burn-up controls the number of elements renewed and, in the absence of a significant return from reprocessing the spent fuel, the reactor fuel cost is directly proportioned to that number, it follows that fuel costs are minimised by reducing the length of the operating cycle. The effect is non-linear and its magnitude is dependent, among other factors, on the rig reactivity burden and the length of the cycle. The potential gains from changing the present burden and cycle are not large.

A further consideration is that with the present operating rules the minimum practical shutdown for an effective fuel change is three working days, due mainly to the need to allow a 48-hour decay or cooling period before reactor fuel unload starts.

Experience has shown that in a normal operating year, there is a need for the reactor to be shut down for 39 days for maintenance, repair and minor modifications. However, maintenance needs are best met by frequent access to the reactor which not only reduces the outage time of some plant but also tends to reduce the size of the peaks of the work cycle. On the other hand some occasional maintenance tasks require three or four days continuous reactor outage.

Other restraints on the choice of cycle arise from the need for shutdowns to coincide with the working week, the need to allow radioactivity to decay before starting some shutdown tasks, and the effects of fission-product poison on the ability to carry out low-power measurements before and during the fuel changes. Finally, the operating cycle must be scheduled some months in advance so that users' programs and major reactor works can be planned and synchronised with reactor operations.

These considerations indicate that the optimum operating cycle will lie between the extremes of a six-week cycle with a five-day shutdown and a two-week cycle with a three-day shutdown. The former has the disadvantage of lower fuel burn-up and a potential loss of weekend production. The latter has the disadvantage of reduced operating time and the occasional need to extend shutdowns on an ad hoc basis to accommodate maintenance and installation work.

An analysis carried out (Bezimienny 1986) shows that if it is assumed that there is no change in the forecast demand for radioisotopes,

- a reduction of operating days would cause a loss of revenue greater than the saving in fuel element costs;
- an increase in operating days would increase revenue more than the increase in fuel element costs;
- a reduction of the operating cycle to 21 days would theoretically be feasible but, to maintain the number of operating days, it would allow no margin for delays; and
- extension of the operating cycle beyond 28 days would increase operating (fuel) costs.

The present four-week cycle is considered to represent the best compromise between these two extremes.

3.7 Summary

Arguments have been advanced that conversion of HIFAR to LEU should not result in any diminution of either the levels of neutron flux available or the annual total flux available for neutron scattering work.

In the case of radioisotopes, the only critical ones are iridium 192 and cobalt 60. Although neither of these is a large revenue earner, their production and sale is a useful part of the Commercial Products Unit operations. Other isotopes can be produced in spite of a modest (15%) reduction in flux, although in the case of molybdenum 99 there would be a consequent swing away from the n γ process towards production by means of fissioning ^{235}U which produces unwanted waste fission products. There would be an increase in price for more highly enriched ^{235}U target material and such a change would not favour the introduction of the gel generator.

Neutron activation work would not be affected.

NTD silicon would only be slightly affected at present but the future development of sales might be limited and more irradiations would be interrupted by shutdowns.

There is no case for increasing the length of operating cycle. There is some flexibility for reducing it to three weeks but the economic gain (fewer fuel elements used) is not great; it is estimated to be about $A55 000 per year now rising to perhaps $A100 000 per year when operating on LEU fuel. A strong argument against reducing the operating cycle to three weeks is that to maintain the total operating time, the duration of the shutdown must be reduced to three days; this leaves virtually no margin for recovering from problems that may arise since the three days are fully taken up with two days for fuel element decay heat reduction and one day for fuel movements.

A neutron flux trap in the core would increase flux for some isotope production at the expense of additional fuel consumption but it does not enhance the flux in neutron beams.

The Working Party considers that conversion to LEU should not result in any diminution of either the levels of neutron flux available or the annual total flux in any facility and that the operating cycle should be retained as at present.

4. REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS STUDIES

4.1 General

There have been two main strands in RERTR studies. The development, extensive testing and satisfactory demonstration of new fuel materials of much higher uranium density than was previously used were essential to enable the conversion of the higher power reactors (say, greater than 2 MW) to the use of LEU. Extensive studies of fuelling strategies and their implications for safety and operations were also required for both representative 'generic' reactor types and for each individual reactor affected. It has been generally accepted that changes to fuel element geometry should be avoided whenever possible when converting to LEU fuel.

Fuel development and testing have been sponsored primarily by the US Department of Energy (DOE) in collaboration with the principal commercial fabricators of fuel for research reactors in the USA, UK, FRG and France. Countries fabricating fuel only for their own research reactors (e.g. Denmark, Argentina) have also been involved to a lesser extent in this aspect of the RERTR program.

The International Atomic Energy Agency (IAEA) has played some part in the co-ordination of fuel development activities, but its major contribution has been in assisting the wide dissemination of the derived information. It has performed a major co-ordinating role in reactor performance and safety assessments in relation to LEU conversion. It has also, through the preparation of suitable guidebooks on important aspects of conversion and the organisation of expert missions and training courses, provided substantial assistance to developing member-states in formulating their LEU conversion requirements.

The Commission, as Australia's representative, has participated actively in IAEA-coordinated RERTR activities almost since their commencement and has made a recognised contribution to the program. As a consequence of this involvement, the Commission has prompt access to evolving fuel development and test data, which is important to ensure that the best decisions can be made in relation to the timing and strategy for the conversion of HIFAR.

4.2 Fuel Qualification

Satisfactory qualification of a new fuel material in relation to its economy, performance and safety is a multi-stage, highly technical undertaking. Because the irradiation behaviour component is extremely important, there is little scope for compressing the timescale, and a program extending over several years cannot be avoided.

It is also necessary that statistically significant data on fabrication under commercial line conditions, and the performance of elements made under those conditions be establisned, as well as demonstrating satisfactory results from laboratory scale experiments. A maximum feasible level of material standardisation is also desirable to minimise manufacturing cost overheads.

Only a half-dozen or so materials could be considered as serious potential candidates for the new fuels. Furthermore, it is only within the last two years or so that one of those originally thought less likely to meet requirements has emerged as a clearly favoured contender for conversion of the large majority of research reactors world-wide which, owing to their power rating, consume significant quantities of fuel. This new fuel is a silicide in aluminium, U_3Si_2-Al, which provides a maximum practical uranium density of approximately 5.0 g cm^{-3}. Only a few high performance, special purpose research reactors could not be reasonably satisfactorily converted to LEU with this fuel, when it is fully qualified. As there is a clear desire by fuel manufacturing companies to standardise on one fuel type rather than produce a range of fuels, this is the favoured fuel even for reactors such as HIFAR which do not require such a high uranium density.

Tests of U_3Si_2-Al fuel in miniplates and full-size fuel elements have been essentially completed and a full core test in ORR has begun. The miniplate tests on material from manufacture on a laboratory scale have been very successful. The uranium densities used in these tests have been increased from the original 3.8 g cm^{-3} to 5.5 g cm^{-3} and have shown excellent post irradiation examination (PIE) results for irradiation up to more than 2×10^{21} fissions cm^{-3}. The corresponding depletion of the ^{235}U (% burn-up) was above 90% in some of these tests.

Six fuel elements (2 each from each of the fuel manufacturing companies NUKEM, CERCA and Babcock and Wilcox (B&W)) with 20% enriched U_3Si_2-Al at 4.8 g U cm^{-3} have been irradiated in ORR to an average burn-up of up to 75%. Local burn-up reached 96%. Some of the PIEs have been completed and given good results. Some large bubbles were formed in particles which initially were predominantly U_3Si. Specifications and production techniques have been modified to reduce the amount of U_3Si in current fuel production.

The full-core test in ORR was originally scheduled to begin early in 1985 and last for 18 months as the HEU elements were gradually replaced by LEU elements. The fuel for this test, which is similar to that described above, was obtained from the same three manufacturers. Completion of the test is considered by many countries to be important for full qualification of the fuel.

Commencement of the test was delayed until January, 1986, primarily because of production difficulties encountered by one of the fuel suppliers. These have been resolved and only a few control elements are still to be delivered. About half the core has now been converted, and a representative sample (a dozen or so) discharged LEU elements should be accumulated by about mid 1987. Initial PIE results should also be available by about that time.

Three fuel elements with 20% enriched U_3Si_2-Al have been manufactured by NUKEM for each of the DR3 (Riso, Denmark) and FRJ-2 (Julich, FRG) reactors. For the DR3 test elements, the electron-beam welding technique used for HEU elements has been retained; while for the FRJ-2 test elements, a new roll-swaged fabrication technique was used.

4.3 Reactor Fuel Cycle

The preparation of guidebooks to the conversion of research reactors from HEU to LEU fuel for both light water (IAEA 1980) and heavy water (IAEA 1985) reactors has been co-ordinated by the IAEA. The guides deal mainly with studies of changes in fuel requirements and the effect on reactor performance, though they also contain early information on fuel development and qualification.

The chief concern for heavy water reactors is that the extra ^{235}U loading required to compensate for the large increase in ^{238}U when converting from HEU to LEU fuel must be accurately calculated. To this end, benchmark calculations of a DIDO-class reactor were undertaken for the guidebook by five participants (Argonne National Laboratory (ANL), AERE, HARWELL, AAEC, Japan Atomic Energy Research Institute (JAERI) and Riso). The results, which also included changes in neutron fluxes and reactivity coefficients on converting to LEU fuel, were generally in good agreement. This comparison increased the confidence that could be placed in the participants' calculations of their own reactors.

Early AAEC calculations for HIFAR (IAEA 1985; Harrington & Robinson 1985) concluded that an LEU element with about 160 g of ^{235}U matched the reactivity of the standard HEU element with 150 g of ^{235}U; that is, the same number of fuel elements would be required. The main effect on reactor performance was a 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. Alhough these results were for a U_3O_8-Al fuel element, neutronics calculations are little affected by a change from U_3O_8 to U_3Si_2. These results were generally in line with those for other DIDO-class reactors, though the higher power levels and rig burdens of the latter made detailed comparison difficult.

A later study (Harrington & McCulloch 1985) of the same fuels examined in more detail the effects on irradiation facilities. Briefly the results indicate 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.

Studies of the reactor fuel cycle performed for this working party are given separately in Section 6.

5. SAFETY DOCUMENTATION REQUIRED

The conversion of HIFAR to LEU fuel is a major modification in the terms of the HIFAR Authorisation (Regulatory Bureau 1983); the fuel material is being changed from an alloy of uranium and aluminium, to a dispersion of uranium silicide in aluminium, there are changes to the relative levels of fast, epithermal and thermal neutrons in the fuel element and the moderator immediately surrounding it, and there are changes to the behaviour of the fuel in conditions of high burn-up and/or high temperature.

The representative of the Regulatory Bureau who is an observer of the Working Party is of the opinion that, on the basis of indications now available, a satisfactory case for operating HIFAR with LEU should be able to be made.

The Safety Documentation should follow the three stages usually required in safety submissions, with Commission approval being sought for each stage after Regulatory Bureau review. The three stages may be briefly described as follows:

Stage 1 - Submission seeking approval in principle.

The submission should discuss the possible impact of the use of LEU fuel on LOCA, reactivity, and fuel transfer flask accident sequences and their consequences. Possible changes in the degree of compliance with REGBUR Memo 1 and any likely impact on the Commission decision to lift the land use restrictions should be mentioned.

This stage is to assure the Commission that there are no foreseen safety impediments to the conversion program.

Stage 2 - Detailed safety case.

A detailed proposal of how the core conversion process is to proceed is required, taking into account the results of Oak Ridge Reactor (ORR) in-pile tests on the proposed fuel element and giving details of estimated, calculated or measured effects on the physics and other parameters of HIFAR together with the measurements and experiments to be conducted in HIFAR to verify that, in HIFAR's particular case, the conversion can be safely made.

Stage 3 - Confirmation that forecasts affecting safety have been validated.

The documentation will present the results of all tests in HIFAR and seeks approval to operate routinely at power with the new fuel, with an appropriate set of Limits and Conditions.

The Working Party has taken advice and prepared a table of contents for the Stage 2, Detailed Safety Case (see Appendix A). The table of contents should not be regarded as definitive but rather as a reasonable approximation. The Working Party estimates that Stage 2 Safety Submission will require the expenditure of about 2 person-years of effort by professional and technical staff from Nuclear Technology Division, Reactors Department and by the members of the Working Party, in addition to the work already done. Stages 1 and 3 will be less costly, perhaps one third to one half of a person-year each. The effect on other programs of the dedication of this effort to the conversion of HIFAR to LEU has not been evaluated.

6. FUEL CYCLE CALCULATIONS

6.1 General

Neutronics calculations of HIFAR operation with U_3Si_2-Al fuel of 19.75% enrichment have been undertaken for the Working Party. The calculations were similar to previous AAEC calculations outlined in Section 4 but concentrated on the effect of ^{235}U loading on fuel consumption rates and neutron flux levels. No hard data on the production costs for LEU fuel elements are at present available but relative fuel costs have been derived from simple assumptions considered likely to reflect general trends in relative costs. Details of the study are given in Appendix B.

Because preliminary calculations indicated that the extra aluminium in a roll-swaged fuel element caused a 10% increase in fuel consumption rates, it was assumed that electron-beam welded elements would be retained. The neutronics calculations are based on matching the excess reactivity of LEU fuel at shutdown with that of standard HEU fuel. Operation with current and possible higher rig burdens have been considered. The results have been interpreted in terms of the 28-day operating cycle.

6.2 Comparison of Three LEU Fuel Loadings

Comparative fuel cycle data for standard HEU and LEU fuel with ^{235}U loadings of 150, 170 and 200 g per element are summarised in Table 6.1. The preliminary cost data are based on costs per element of LEU fuel relative to HEU fuel of 1.46, 1.61 and 1.83, respectively, for the three fuel loadings (see Appendix B). The fuel consumption rates are given for two power levels. The first is for the normal 10 MW operation and the second for the approximate power level required to maintain flux levels throughout the reactor. The criterion of maintaining flux levels results in the same core thermal flux, with other fluxes being slightly increased.

Table 6.1

FUEL CYCLE DATA

	HEU	LEU		
^{235}U per element (g)	150	150	170	200
U density in meat (g cm^{-3})	0.54	2.17	2.46	2.90
Burnup (10^{21} fissions cm^{-3})	0.50	0.39	0.58	0.85
For 10 MW operation:				
Fuel elements per year	46	58	40	27
Relative fuel cost	1.0	1.86	1.40	1.08
For operation with no flux reduction				
Power (MW)	10	11.4	12.0	12.9
Fuel elements per year	46	68	49	36
Relative fuel cost	1.0	2.17	1.71	1.42

Note: These numbers of fuel elements per year should be read in relative terms and in practice, the acatual numbers are affected by operating parameters.

The data are given only for the current rig burden but the general trend is the same with a higher rig burden. For 10 MW operation, comparison of 200 g LEU fuel with HEU fuel gives 8 to 13% reduction for various beam facilities and 6, 16 and 20% reduction for the activities of (n, γ) Mo, Ir and fission product Mo respectively. The corresponding figures for the 170 g LEU element are 6 to 9% for beams and 5, 12 and 15% for activities. The fluxes and activities at higher power levels are, to a close approximation, proportional to power.

It is clear that considerably lower fuel costs are associated with the use of high fuel loadings of ^{235}U. The preliminary nature of the cost data should not unduly affect this conclusion; although the relative cost of LEU fuel and HEU fuel may change when firmer data are available, variation with ^{235}U loading is unlikely to change much.

It may be noted that the uranium density and the average discharge burnup in Table 6.1 are quite modest compared with those being tested in the fuel qualification program. The average ^{235}U depletion has reached 65% for the 200 g element, but the low fission density relative to those successfully demonstrated in the RETR fuel program U_3Si_2 - Al tests is the significant result.

6.3 Additional Calculations for a 200 g LEU Element

Because the 200 g LEU element gives the lowest fuel costs and also represents the biggest change from the current fuel cycle, additional calculations have been performed for this case.

Calculations of flux peaking were limited to a consideration of the worst (artificial) case, which occurs with a new fuel element in the central C3 position. Operation with a complete core of LEU elements gave very similar results to standard HEU elements. Both gave peak element powers of about 650 kW for 10 MW operation. The worst case with a core of mixed fuel (new 200 g LEU element in C3 of equilibrium HEU core) gave 750 kW, but such a situation could be easily avoided. The limiting condition on fuel element power is the margin to excursive flow instability. This margin remains very large even for the worst mixed-core case at 13 MW operation.

For 10 MW operation, the reactivity loss per cycle was about 5.2% for both LEU and HEU fuels. For 13 MW operation, the cycle reactivity loss increased to 5.9%. These figures were derived from changes in average core state. In practice, the small number of fuel elements changed per cycle could lead to an increase in the reactivity to be controlled by the coarse control arms. If necessary, this could be reduced by including a burnable poison in the fuel elements as this is current practice for DIDO and FRJ-2.

7. ANALYSIS

7.1 Introduction

HIFAR will convert to using LEU in the near future. Whether the date for the introduction of LEU is early 1988, early 1989 or early 1990 makes little difference except for the urgency of action because no justification has been adduced for believing there will be a major change in the requirements of reactor users during the next 5 years.

7.2 This section develops in a logical sequence the most appropriate proposal for the operation of HIFAR using LEU. The most important parameters to be considered are

reactor operating power
neutron flux available for reactor users
reactor operating cycle
fuel element loading (grams ^{235}U per element)
fuel cost.

7.3 Reactor Operating Power

HIFAR currently operates at 10 MW. The HIFAR Safety Document (HSD 1972) shows that HIFAR can operate safely at 15 MW. Other DIDO class reactors are operating at Harwell in UK at 25 MW. Subject to detailed consideration, the Working Party believes that a suitable safety case could be made for HIFAR to operate at any power up to 15 MW without major upgrading beyond that which is planned in the HIFAR Refurbishing program.

7.4 Neutron Flux available for Reactor Users

The Working Party considers that the flux available for neutron scattering should not be decreased, particularly in view of the recent ASTEC recommendation (ASTEC 1985). Although a reduction in flux levels would probably lose some markets for radioisotopes, the production of molybdenum 99 for technetium-99m for medical purposes could continue (at some extra expense, in the case of fission product ^{99}Mo, estimated as $12 000 for a 14% reduction in flux).

Studies have shown that if LEU fuel elements with 150 g ^{235}U were substituted for HEU fuel elements with 150 g ^{235}U and the reactor operated at the same power, there would be a flux reduction of about 12%. For isotope production only, this flux loss could be recouped by using a flux trap though it would increase fuel consumption by about 10%. Because a flux trap would only improve flux for some radioisotope production, the Working Party does not recommend a detailed consideration of the use of a flux trap at this juncture.

7.5 Reactor Operating Cycle

Although the duration of shutdown could be reduced from the present four days to three days, this allows no margin for contingencies. The neutron diffraction work requires the same integrated flux as at present. Radioisotope production would be inconvenienced by longer shutdowns. An increased number of shutdowns brings some penalties in lost time because of the need to recalibrate rigs at each start up. At present the amount of shutdown time closely matches that required for maintenance.

The Working Party believes that a 28-day operating cycle including a four day shutdown, is close to the optimum.

7.6 Fuel Element Loading (grams ^{235}U per element)

At present the HEU elements in HIFAR each contain 150 g ^{235}U with a uranium density in the fuel 'meat' of 0.54 g cm^{-3}. The type of fuel meat used has a reasonable maximum uranium density of 1.6 g cm^{-3} for fabrication purposes. An LEU element of the same geometry and containing 150 g ^{235}U will have a uranium density of 2.17 g cm^{-3}. This is the reason for the development of uranium silicide fuel which, subject to confirmatory tests, should be proved to a reasonable maximum uranium density for fabrication purposes of 5.0 g cm^{-3}; such fuel is satisfactory up to irradiations of at least 2.10^{21} fissions cm^{-3}.

As noted in Section 6.2, to use 150 g LEU elements with the power at 10 MW results in a reduction in neutron flux of some 4 to 12% depending on the facility or radioisotope concerned; because of the poor burn-up and increased fabrication cost, the annual fuel cost for HIFAR would increase to 186% of present cost. The Working Party does not recommend this course of action because it is uneconomic and would adversely affect the neutron diffraction work.

To use 170 g or 200 g LEU elements with the power at 10 MW is more economic because of the higher percentage burn-up obtainable; in fact, the annual fuel cost in the latter case would only be 110% of the present costs. The adverse effects on neutron diffraction work would be greater than for the 150 g element. The Working Party does not recommend either course of action.

Where there is to be no reduction to any flux available to users, the power must be increased; use of a 150 g fuel element will require the power to be increased to 11.4 MW. However, the fuel cost for this operation would be 217% of present costs. If the fuel weight is increased to 170 g or 200 g, higher powers are required; but because a higher burn-up is attainable, the fuel elements with greater ^{235}U weight are more economical.

On the basis of the assumed LEU fuel element cost algorithm, further fuel cycle cost reductions in the 'constant flux' option would be available if the fuel element loading were increased to even more than the 200 g ^{235}U. This would, however, mean a further increase in reactor power, a corresponding further reduction in thermohydraulic safety margins and very high ^{235}U depletion in the discharged fuel, assuming that current rig reactivity burdens apply. Furthermore, although results from laboratory-scale LEU fuel element production have suggested that difficulties and rapidly increasing fuel plate rejection rates (and hence costs) would not arise until densities of 3.5-4.0 g U cm^{-3} are approached for U_3Si_2 - Al fuel, it is not prudent to assume at this time that these high densities are attainable without additional cost penalties under routine production conditions. Certainly, it has not yet been demonstrated that plates formed to the small radius of curvature necessary for HIFAR-type fuel elements can be made economically and will perform satisfactorily (maximum density of approximately 3.1 g U cm^{-3} in prototype FRJ-2 and DR-3 elements).

The Working Party believes that the 200 g element (2.9 g U cm^{-3}) is a sensibly conservative compromise, for the operation of HIFAR at 13 MW (core power) with a heat flux which gives a good margin to flow instability, a maximum density which is comfortably below the maximum proved in development tests and a fuel cost which is 142% of the present costs. Possible economies from the use of fuel elements with higher ^{235}U loadings can be considered later in the light of accumulated commercial manufacturing experience and routine irradiation results with U_3Si_2 - Al fuels. It will be recalled that from the earliest days of the INFCE Working Party, it was known and emphasised that the conversion to LEU would lead to greater fuel costs, although the magnitude of these was unspecified.

The Working Party considers that a 42% increase in fuel costs is concomitant with present political decisions and the avoidance of deterioration in neutron scattering work.

8. OUTSTANDING INFORMATION

It is considered that adequate technical information is already available from miniplate and prototype fuel element fabrication experience and irradiation trials to give high confidence that LEU conversion of HIFAR along the lines considered in previous sections will be feasible, and will not adversely affect reactor safety margins or experimental/ production uses of the reactor in any significant way. It is, however, important to confirm that U_3Si_2-Al fuel elements fabricated in numbers and conditions similar to those which will be applicable for normal commercial production, will perform to the same standards demonstrated by the prototype elements made under laboratory-or pilot-scale conditions. Because of delays in the commencement of the ORR experiment, it is unlikely that even the minimum of data which might be considered as providing reasonably assured confirmation will be available much before mid 1987. Any unexpected adverse finding as the ORR demonstration proceeds would significantly defer that projected assurance date.

The relative economics of the conversion options considered must be regarded as indicative only, because adequate realistic commercial cost data are not available. This is likely to emerge only as more manufacturing experience with the new LEU fuels accumulates over the next few years. Meanwhile, it may be necessary to review and amend the detailed conclusions of the present evaluation from time to time as better relative cost data become available.

9. STRATEGY AND SCHEDULE FOR IMPLEMENTATION

The timing for the implementation of LEU conversion is governed to a large extent by Government policies. The Australian Government is committed to lowering HIFAR fuel enrichment as soon as practicable and would be unlikely to agree to any increase above the current 60% even as an interim measure. It is assumed, however, that the Australian Government would accept a delay of a year or two in the implementation of LEU on the basis that delays have occurred in the proving of LEU fuel and that the manufactuerers' experience in line production is still very limited.

The overriding consideration is the policy of the US Government since it controls the supply of both HEU and LEU. The Working Party believes that the Commission would benefit from a delay of two years in the implementation of LEU to allow fuel manufacturers to gain more experience in commercial line production. The LEU fuel elements which have so far satisfied post-irradiation examination (PIE) have been produced as 'specials' and more fabrication problems may arise as commercial line production is implemented. Production fuel elements are at present being loaded into the ORR but a full core will not be achieved until late 1986 and PIEs of the first few of these as expended elements will not be available until mid 1987.

Because the Oak Ridge test program is approximately one year behind its original schedule, the Working Party believes that this constitutes sufficient justification to defer the conversion of HIFAR by one year and an application to the US Government to this effect might be expected to succeed. However, since there is available 17 kg of HEU from the material purchased for the Critical Facility, which represents nearly two years' of supply, there is a possibility the US Government might agree to the use of all this uranium as HIFAR fuel. This decision would defer conversion to late 1989 and LEU fuel manufacture would occur during late 1988 and early 1989. Deferring manufacture to this time would give more confidence that teething problems in fabrication would have been overcome.

A request is already underway to the US Government for the agreement "in principle" to use the 17 kg of HEU on hand for HIFAR fuel. If this request is agreed to then tenders should be called from four nominated suppliers, namely UKAEA, NUKEM, ATLAS and BABCOCK and WILCOX to supply us with approximately 100 fuel elements at 60% enrichment. Our specification should require the alloy process to be used, as safety approval from the Regulatory Bureau would be necessary if manufacturers elect to use the aluminide process instead. Resources are not available to undertake the necessary safety assessment. Some of the nominated suppliers may decline to tender on this basis but the UKAEA certainly would tender.

In addition, the specification should also call for standard AAEC fuel element hardware to be used rather than different hardware held in stock by some of the suppliers for use on fuel elements for other DIDO-type reactors. Figure 9.1 shows projected fuel element stocks assuming that tenders are invited for 100 fuel elements of HEU by about August 1986 and for LEU fuel by mid 1988.

A second option arises from a possible US Government decision to disallow the use of all of the 17 kg of HEU but to permit the use of part of it equivalent to one year's supply.

Such a decision could arise from acknowledgement that although the US testing program is late, it is not two years late. Figure 9.2 shows projected fuel stocks, assuming that 60 HEU fuel elements are ordered by August 1986 and that tenders are invited for LEU by about September 1987. This September 1987 date would allow a few months assessment of PIE results from the commercial line LEU fuel which should be available in mid 1987.

A third option arises from a refusal by the US Government to allow us any additional HEU. Such a decision could compromise the continuity of operation of HIFAR. It would require tenders to be invited for LEU fuel by August 1986, well before the availability of the Oak Ridge PIE results and, even under fairly optimistic assumptions about production time for the new LEU fuel, our fuel stocks would be down to about 20 elements before the LEU was supplied. In addition it is understood that the fuel manufacturers still have not formalised standard Quality Assurance procedures for the manufacture of LEU fuel. The Commission should proceed on this time scale only as a last resort.

It is clearly important that early advice be received from the United States on our request to use the critical facility stocks of HEU, because an unfavourable response would require urgent tendering action to avoid a hiatus in HIFAR operation. Figure 9.3 indicates projected fuel stocks in this scenario.

The Working Party proposes that, in the event that the US Government refuses the use of the critical facility HEU, a fall back position be adopted. The UKAEA has indicated that it has on hand some uranium of 45% enrichment sufficient to manufacture 40 fuel elements. This is of United Kingdom (UK) origin. Although a transition to fuel of 45% enrichment is not particularly favoured by the Working Party because of the effort required in safety evaluation, its use is nevertheless a better alternative than closing HIFAR down owing to insufficient fuel being available. It is proposed that as a fall-back position UK approval be sought to purchase the 40 fuel elements of 45% enrichment from the UKAEA should approval be refused for the use of HEU. Fuel stock projections from this scenario are indicated in Figure 9.2.

In the scenarios indicated by Figures 9.1 and 9.2 consideration should be given to splitting the order between the preferred and the next preferred bidders. If the preferred bidder is the lowest tenderer, then this action would obviously cost more, but the benefit would be that if there were problems associated with a particular manufacturer's fuel (either with its quality or delivery time) we could fall back on the use of the alternative manufacturer's fuel. A small cost benefit analysis should be undertaken at the time the order is being placed to determine whether the benefit outweighs the costs.

A schedule has been prepared (Figure 9.4) which indicates the timing of the conversion of HIFAR to LEU assuming the scenario whereby the US agrees to the use of critical facility fuel. This is the preferred program not only from the economic viewpoint, but also because it would allow maximum experience to be gained by the manufacturers of LEU fuel before our fuel order is placed.

Explanatory Note for Figures 9.1, 9.2, 9.3 and 9.4

Figure 9.1 shows the scenario where not less than 100 additional HEU fuel elements are procured before ordering LEU fuel elements.

Figure 9.2 shows the scenario where additional 60 HEU fuel elements are procured before ordering LEU fuel elements.

Figure 9.3 shows the scenario where a direct conversion from HEU to LEU is made when the current stock of HEU fuel elements is used up.

The following assumptions are made:

a) Current fuel consumption of 60 fuel elements/year will continue for at least another year.

b) After 6 July 1987 it is envisaged that the fuel consumption will drop to 52 fuel elements/year.

c) Mixed core consumption will be at the rate of 43 fuel elements/year.

The following assumptions have been made on the advice of Technical Services Section and used in the graphs:

For Figures 9.1 and 9.2 -

d) Tenders for HEU fuel elements will be invited within two months, i.e. by the end of July 1986.

e) Tenderers will submit their tenders within two months from the date of invitation.

f) Review of tenders will be completed and Ministerial approval received within two months from the receipt of tenders and the orders will be placed.

g) The contractors shall commence deliveries of HEU fuel elements within nine months of the receipt of order.

For Figures 9.1, 9.2 and 9.3 -

h) The contractors will require about 12 months from the receipt of order to commence delivery of LEU fuel elements.

Abbreviations

PIE:	Post Irradiation Examination
HEU:	High Enrichment Uranium (> 20% ^{235}U)
LEU:	Low Enrichment Uranium ($\leq$ 20% ^{235}U)

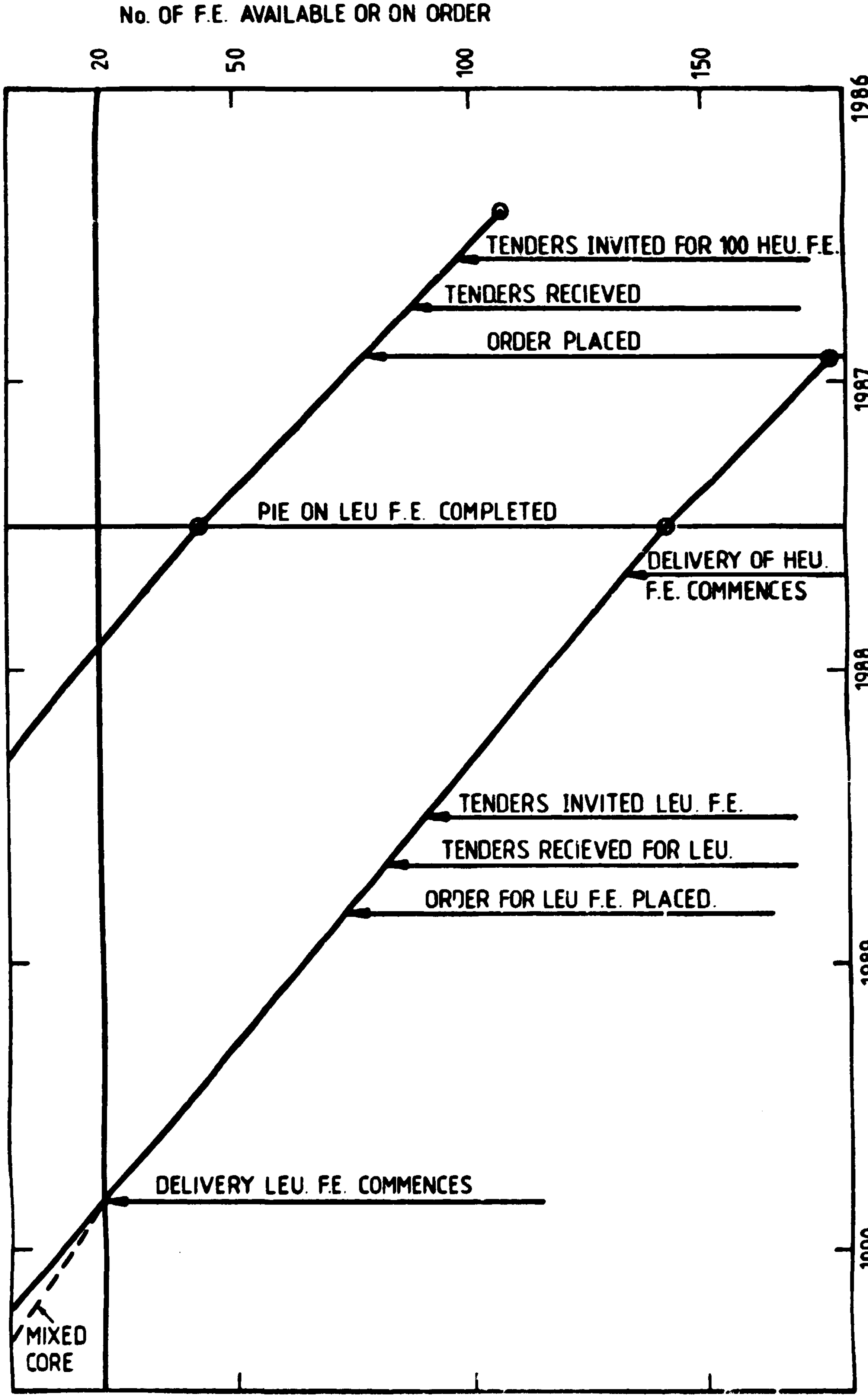

FIGURE 9.1 ASSUMES 15 kg (100 FUEL ELEMENTS) FURTHER HEU. AVAILABLE

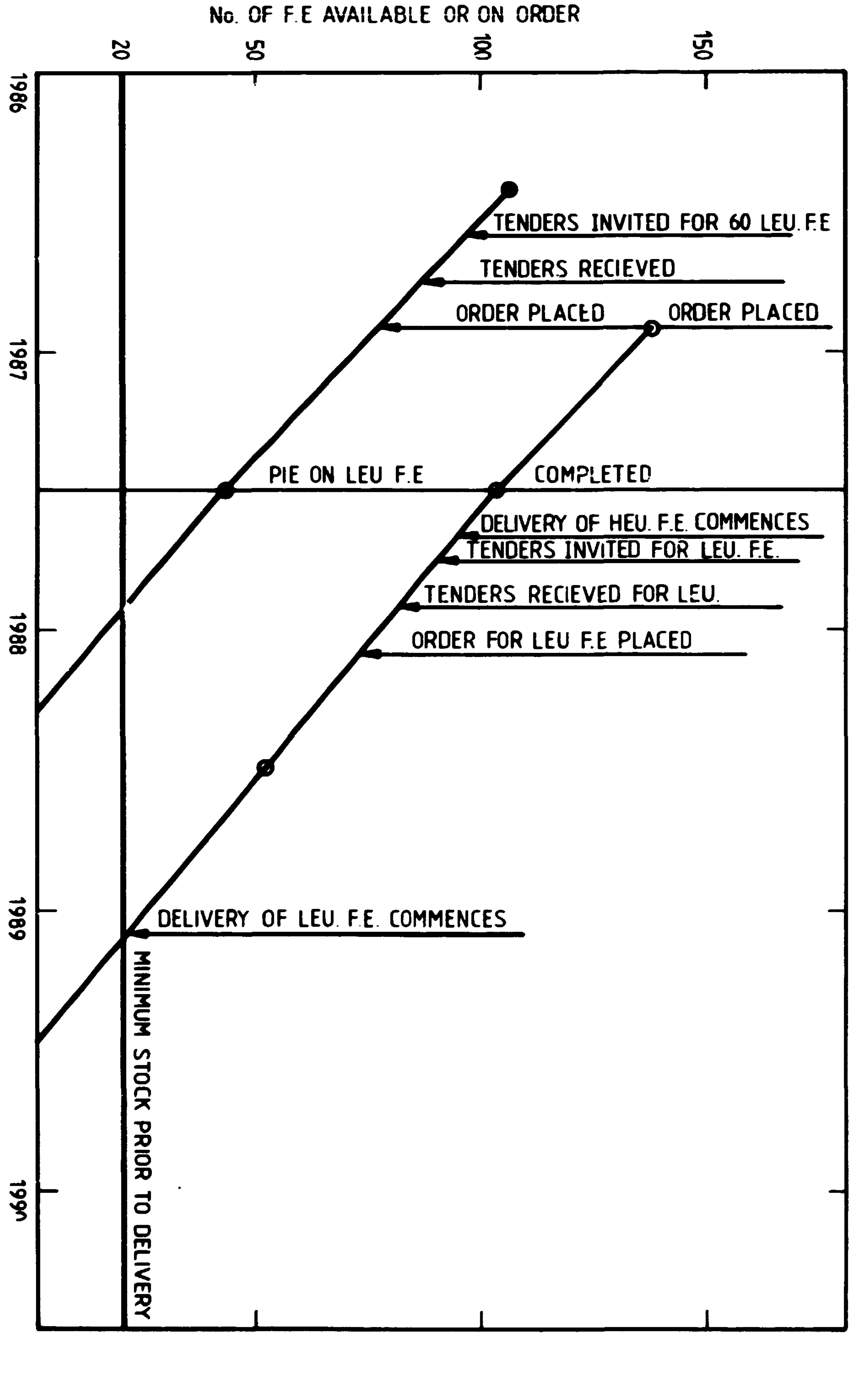

FIGURE 9.2 ASSUMES 60 FUEL ELEMENTS (1 YEARS SUPPLY) OF FURTHER HEU AVAILABLE

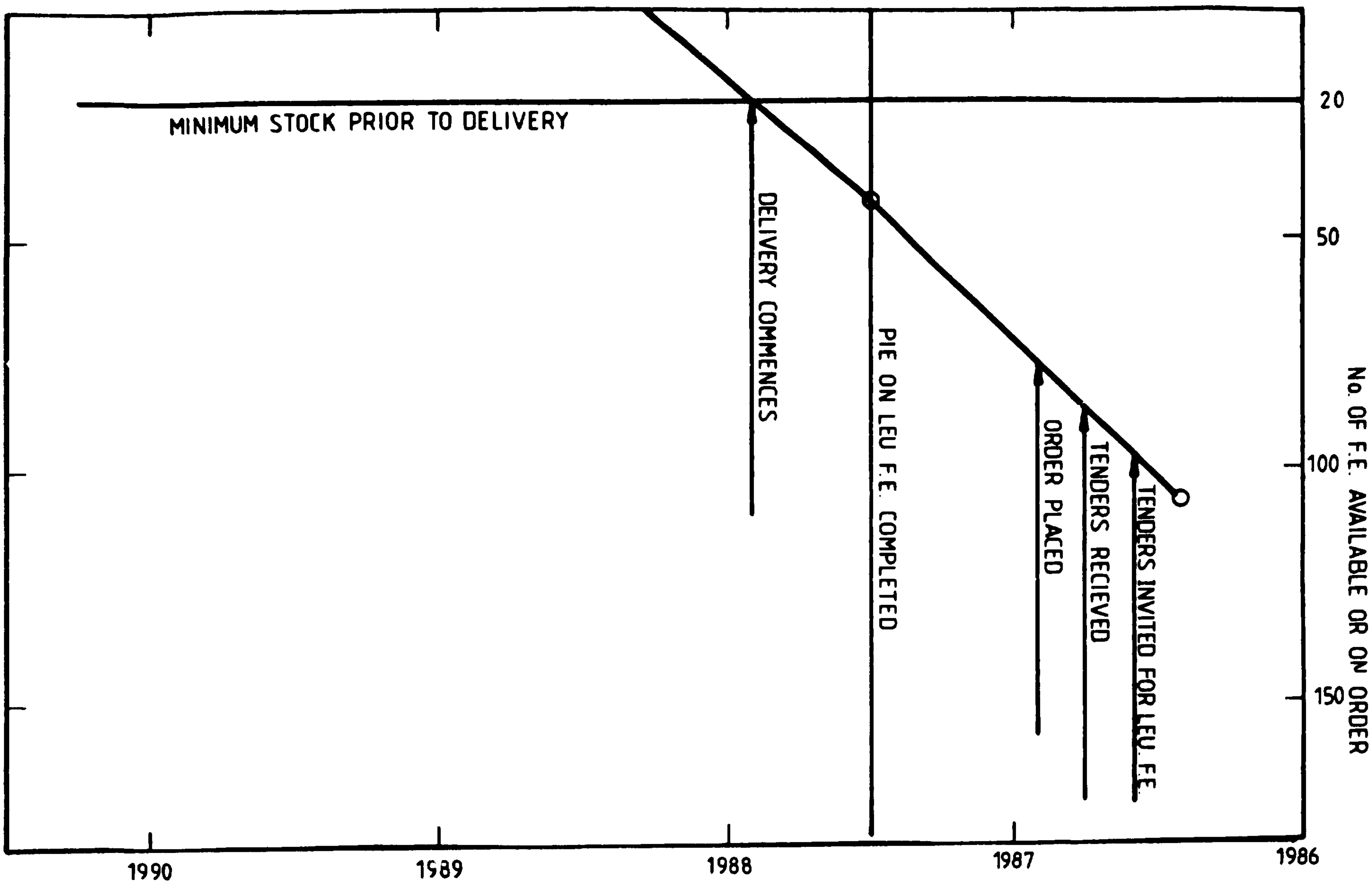

FIGURE 9.3 ASSUMES NO FURTHER HEU AVAILABLE

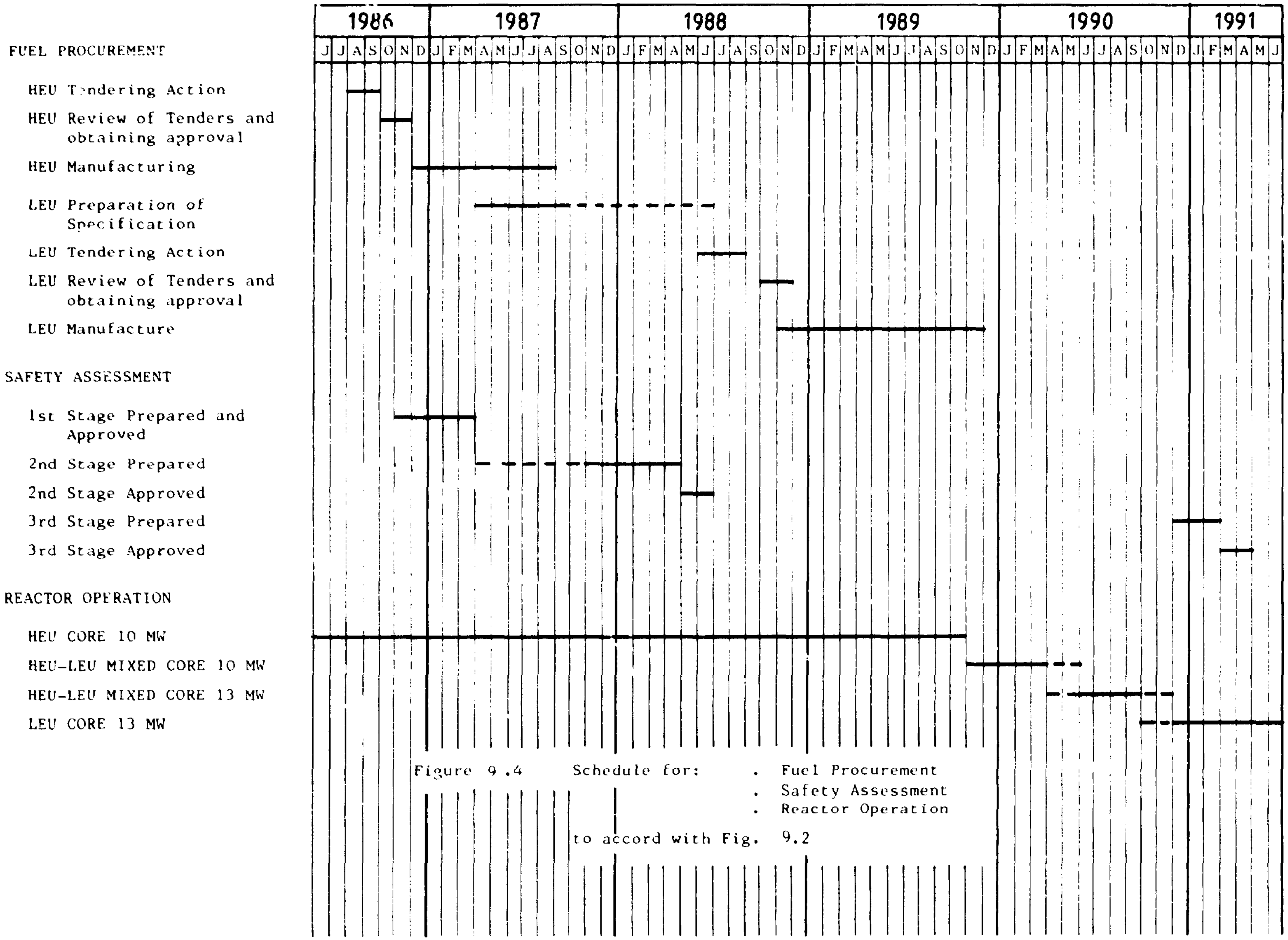

Figure 9.4 Schedule for:
- Fuel Procurement
- Safety Assessment
- Reactor Operation

to accord with Fig. 9.2

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APPENDIX B

CALCULATIONS OF HIFAR FUEL CYCLE WITH LEU FUEL

B.1 INTRODUCTION

Calculations of the fuel cycle of the HIFAR reactor have been performed to compare the performance of LEU fuel with the standard HEU fuel of 80% enrichment. The study has been mainly concerned with the effect of the ^{235}U loading per element on fuel consumption rates and neutron flux levels. Relative fuel costs have been deduced from simple assumptions based on preliminary cost information. The LEU fuel adopted for this study was U_3Si_2-Al fuel of 19.75% enrichment.

B.2 REACTOR MODELS AND MAJOR ASSUMPTIONS

Reactor modelling has followed the same general approach as previous AAEC studies of conversion to LEU which has been detailed by Harrington & Robinson (1985). In brief, few-group macroscopic cross sections for a cell consisting of a section through a fuel element have been obtained from a cell burn-up calculation. Global calculations with these cross sections have been performed in RZ geometry to obtain axial bucklings and finally in an XY model which includes detail of in-core and reflector rigs and facilities. These calculations have been performed with a uniform burn-up throughout the core. The adequacy of this approach was established previously (Harrington & Robinson 1985).

Because preliminary calculations indicated that the extra aluminium in a roll-swaged fuel element caused a 10% increase in fuel consumption rates, it was assumed that electron-beam welded elements would be retained. Thus, identical fuel element geometry was used for the HEU and LEU fuel.

As in previous studies, fuel cycle data for HEU fuel was taken to be an average of HIFAR operating programs 266 to 286. Where necessary, data were obtained from the HIFUEL program (Robinson 1982) 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 is per cent reactivity in a core containing 3.2 kg of ^{235}U. Calculated values of reactivity, ρ, have been 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 have been performed to establish for a given LEU fuel element the core-average burnup which gives the same excess reactivity at end-of-cycle (1.6%) as HEU fuel of a given burnup. Two situations have been considered: the standard rig burden for which the HEU burnup is 40.5 MWd and an increase from 2.3% to 5.3% in the in-core rig burden 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 burnup 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), 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.

B.3 FUEL COST DATA

To compare fuel costs for LEU and HEU fuel, it has been necessary to make a number of assumptions that are consistent with the preliminary cost data which are available. The assumptions are

- Cost of ^{235}U per gram 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 uranium density range, LEU fuel plate rejection rate is constant.

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

B.4 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 B1. For each element type, data are presented for both the standard rig burden and a high rig burden. 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.

It can be seen that the maximum densities required are very modest compared with the 4.8 g cm^{-3} being qualified in the RERTR programs. Core fissile mass has been included in the table because it affects the reactivity scale. The average discharge burn-up values are for 10 MW operation; there would be a slight reduction at higher power. The discharge burn-ups in terms of fission density are also modest compared with those already demonstrated in the RERTR program.

For operation at 10 MW and operation with no flux reduction, there are considerable savings in fuel cost through the use of high ^{235}U loadings. These savings become even more pronounced as the rig burden is increased from the current low value.

Some detail on neutron fluxes and isotope activities for 10 MW operation with the current rig burden is given in Table B2 and Figures B1 to B5. Results at higher power levels may be taken to be directly proportional to power. Figure B1 gives a plot of fluxes along the X-axis, i.e. through the C3, C4, C5 fuel positions, at the core midplane for HEU fuel. In the 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. Figures B2 to B4 give the flux ratios for 150 g, 170 g and 200 g LEU fuel relative to HEU fuel.

The results for fluxes at various beam facilities and isotope activities are given in Table B2, and a selection of these results is plotted in Figure B5. The effective isotope cross sections of Harrington and McCulloch (1985) were used to derive these activities. It can be seen that fluxes at the beam facilities and (n, γ) Mo activity in particular show much less variation than the core thermal flux.

Absorption coefficients are also given in Table B2, and the variation in core average values may be compared with the $1/(\text{fissile mass})^{0.7}$ ratios. The agreement validates the reactivity worths used throughout the study.

The power fractions in each ring of a fuel element have also been calculated for the four fuel types and proved to be practically independent of fuel type. The maximum 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.

B.5 ADDITIONAL CALCULATIONS FOR A 200 g LEU ELEMENT

Because the 200 g LEU element gave the lowest fuel costs of those elements considered, additional calculations have been performed for this case. The use of this element also represents the biggest change from the current fuel cycle.

Flux peaking in a new fuel element has been calculated for standard HEU and 200 g LEU fuels. The results are basically for a new element in the C3 position, which is the worst case. The results of seven cases are given in Table B3. All cases except number 2 were performed in RZ geometry. 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 is an attempt 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 is intended to be 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 can be seen that peaking with the 200 g LEU fuel differs little from that with standard HEU fuel. The extreme case 5 could be easily avoided in the change-over. The limiting condition on fuel element power is the margin to excursive flow instability, and this has been investigated for 13 MW operation.

For operation at 13 MW with two coolant pumps, the normal inlet coolant temperature has been calculated to be 48^{o}C (Parsons 1986). An analysis of HIFAR flow instability power by Romberg, included in the IAEA guidebook (IAEA 1985), gives a value of 2400 kW for this temperature. Applying the uncertainty factors on coolant flow rate and fuel loading from the HIFAR Safety Document (HSD 1972) reduces this value 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, are extremely large.

The loss of reactivity over a fuel cycle has been calculated for HEU fuel at 10 MW and 200 g LEU fuel at 10 and 13 MW, and the results are given in Table B4. These results were obtained using the AUS code system (Robinson 1975) for cores having uniform burnup. To validate these results, they have been compared with those given by Harrington & Robinson (1985) which were derived by using the HIFUEL code to follow HIFAR operating programs 266 to 286. This gave a reactivity loss of 5.71% for HEU fuel and 5.79% for a 170 g LEU fuel element. Also, analysis of HIFAR measurements for programs 266 to 286 gave a reactivity loss of 6.0% using the standard HIFAR CCA calibration and 5.0% using that of Harries (1978). It is concluded that the results in Table 4 are reliable and indicate no significant reactivity problems.

TABLE B1. 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 B-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 (δk/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 B-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 B-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

Figure B-1. Fluxes at Core Mid-plane for HEU Fuel

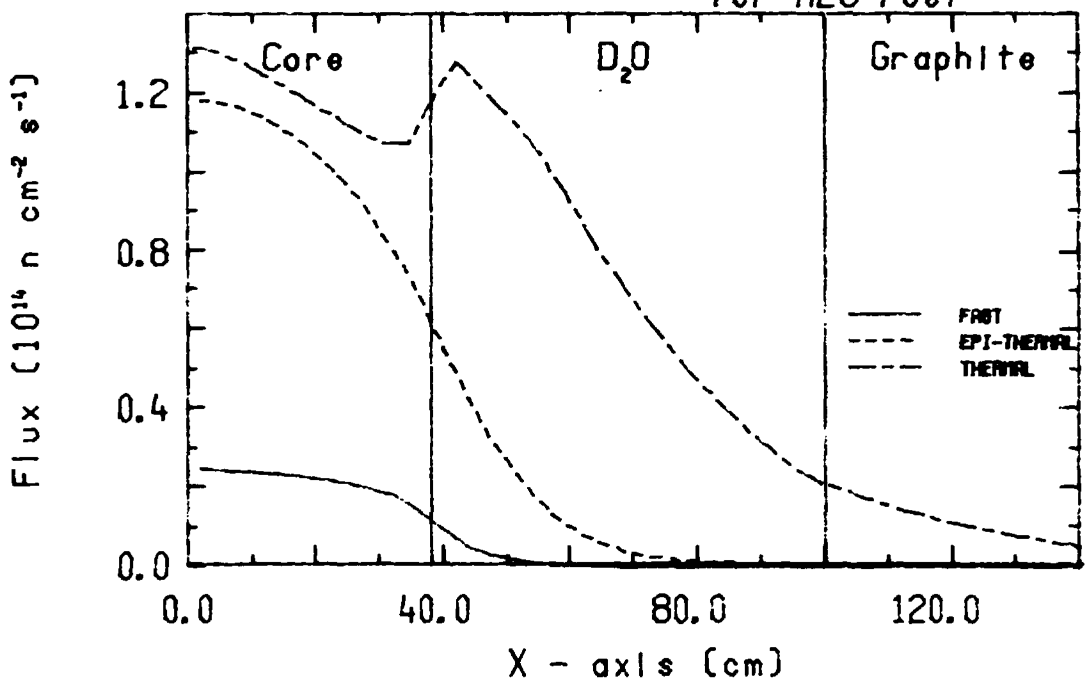

Figure B-2. Flux Ratios at Core Mid-plane 150g LEU / HEU Fuel

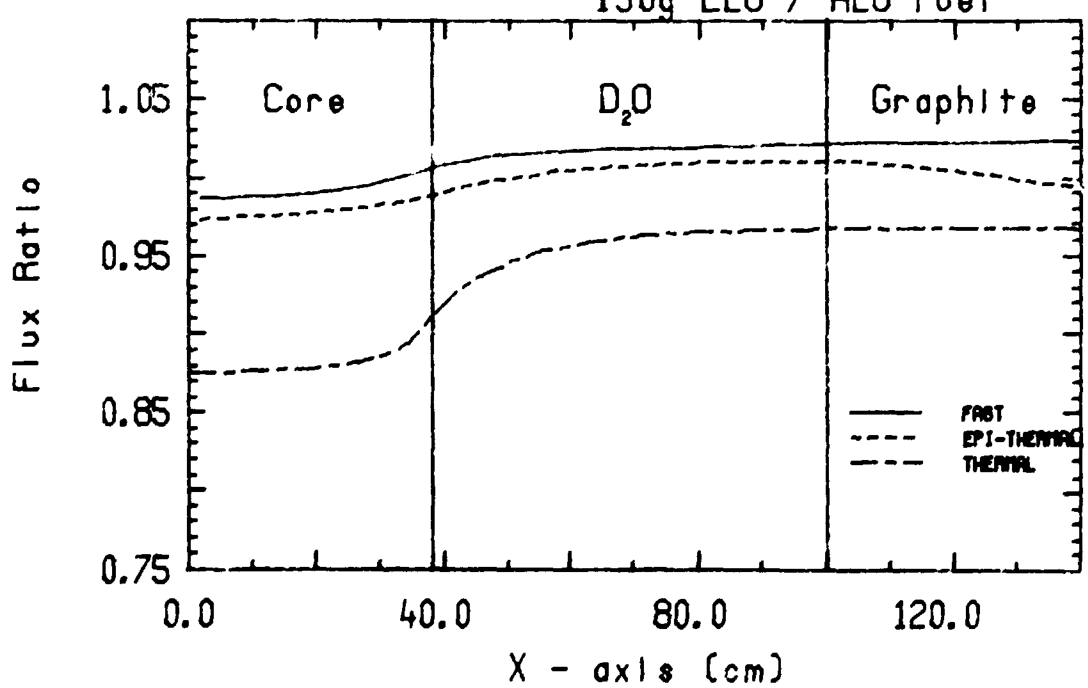

Figure B-3. Flux Ratios at Core Mid-plane
170g LEU / HEU Fuel

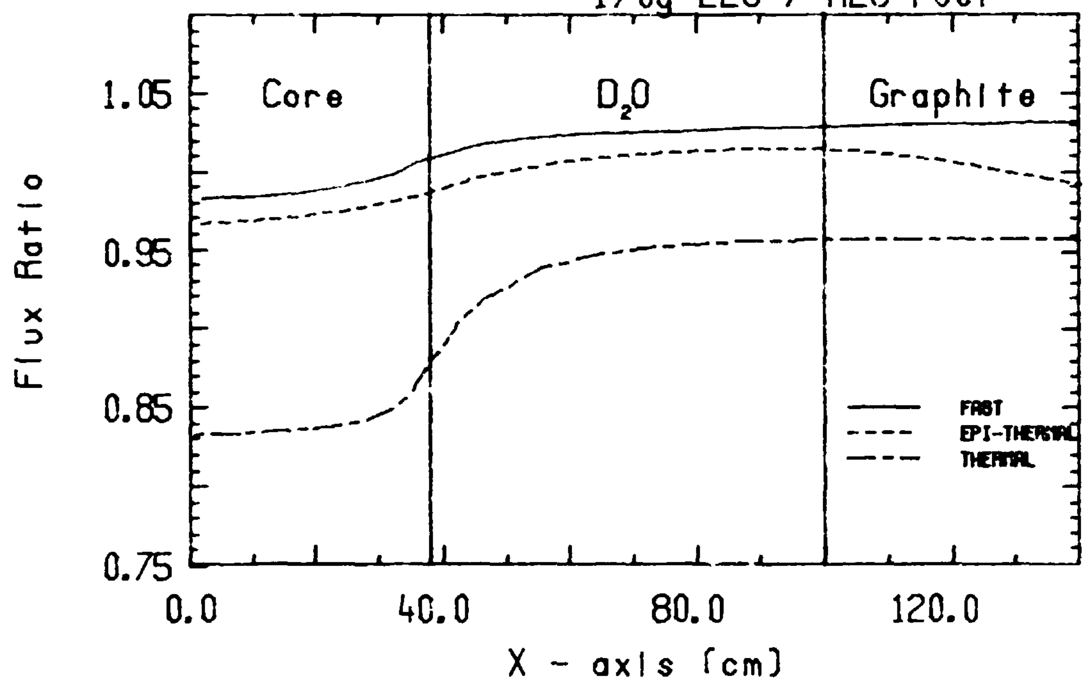

Figure B-4. Flux Ratios at Core Mid-plane
200g LEU / HEU Fuel

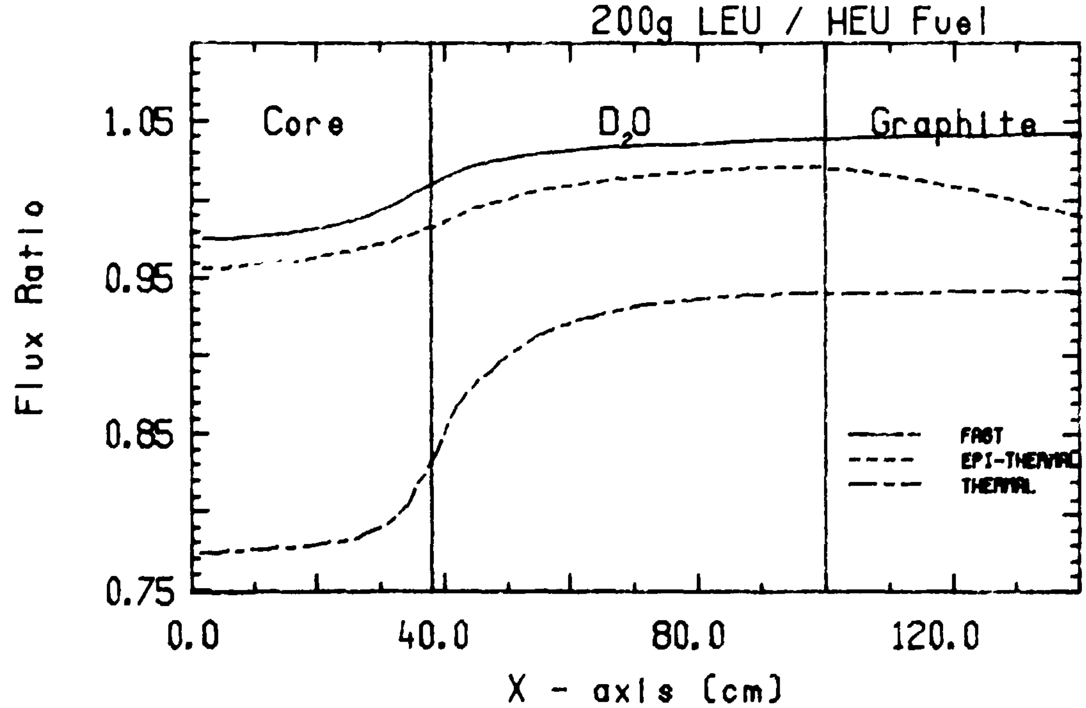

FIGURE B-5. FLUX AND ACTIVITY VERSUS FUEL COST