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A PRELIMINARY ASSESSMENT OF THORIUM AS A FUEL FOR THERMAL REACTORS

CRRP-1221

by

M.F. DURET and M.J. HALSALL

Chalk River, Ontario

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ABSTRACT

This report presents a preliminary survey of the contributing factors to total fuel cost, for a variety of potentially economic fuel cycles. U^{238} and Th^{232} are considered as fertile materials with enrichments of U^{235}, U^{233} and plutonium. The total fuel cost comprises

(a) a fuel supply cost which is derived from a manufacturing cost and the fuel burnup,

(b) a spent fuel credit, and

(c) inventory charges.

The interrelation of these three factors and their dependence on reactor flux, fuel burnup, the heat rating of the fuel and the interest rate are considered for each combination of fertile and fissile material.

Results show that inventory charges, spent fuel credit (hence processing costs) and fabrication costs have an important effect on the fuelling cost. In addition, using highly rated thorium-based fuels will affect reactor capital costs. Further, more detailed studies of reactor design, fuel design and fuel management schemes are now required to verify the attraction of using thorium as a reactor fuel.

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INTRODUCTION

Nuclear power is growing rapidly. In Canada nuclear power is generated by irradiating natural uranium as long as the fuel reactivity will allow. The spent fuel is stored. This fuel contains about 0.4% plutonium, of which about 69% is fissile. To indicate the 'real' worth (as opposed to the economic value) of this fuel in terms of familiar numbers we note that CANDU, a 200 MW electrical station produces about 90 kilograms of plutonium a year. About 70% of this plutonium, if separated, can be fissioned in a single further irradiation of about 3 n/kb. If the plutonium burnup rate is 90 kg/year it will produce (at a station efficiency of 30%) a further 60 MW of electrical power, i.e. 30% of the reactor power producing it. If this plutonium is used to prolong the irradiation of natural uranium to 3 n/kb the total power obtained by burning 90 kg/year is 160 MW(e) greater than would be obtained by burning natural uranium alone. The importance of plutonium to the overall power program will thus depend on how it is used.

The real problem of course is economic and other fuels may compete very effectively. In this report we compare various combinations of the fissile materials U^{235}, U^{233}, plutonium and the two fertile materials U^{238} and Th^{232} in thermal reactors having a neutron economy similar to that of CANDU. We assume that fuel burnup is limited only by reactivity. The basis for this comparison is the fuel cost so that attention must be paid to factors affecting this cost such as the manufacturing cost, interest on fuel inventory and processing costs. The operating fuel cost depends on manufacturing cost and the burnup. The inventory charges depend on the manufacturing cost and the fuel rating. The processing contribution to power cost depends on the concentration of fissile material in the fuel at the end of the irradiation and its value which is determined

to some extent by its radioactivity and the consequent handling difficulties. The interrelation of these costs with reactor parameters is shown schematically in figure 1. All costs in this report are in US dollars.

A single once-through fuel cycle followed by processing has been considered. The effect of further recycling is taken into account by ascribing a value to the irradiated fuel.

METHOD OF CALCULATION

Reactivity

Changes in fuel composition with irradiation are calculated in the burnup program BOT. A thermal reactor with cross sections specified using the Westcott formulation is assumed. For the uranium cases the spectrum parameters chosen have been based roughly on the spectrum in the Douglas Point CANDU reactor. For the thorium cases three U^{235} concentrations were run on LATREP for a 37-element rod design having roughly twice the fuel rating (MW/kg) of the Douglas Point Reactor fuel in order to form estimates of r-value and neutron temperature. The 2% and 2.5% enrichment results are plotted in figure 2 as a function of irradiation. BOT assumes a constant r-value so the value 0.09 was chosen as being representative of the major part of the irradiation. This value is perhaps a little low for the more highly enriched cases but will not affect the overall picture. The neutron temperature was taken to be 175°C and the standard flux 5×10^{13} $n/cm^2/sec$, although thorium has been considered in a range of fluxes for comparison. Irradiation of fissile and fertile material are computed independently and normally these results can be added in any ratio to correspond to a given enrichment. However, when plutonium is used to extend the burnup of natural uranium the Pu^{240} effective cross section will depend on whether the plutonium enrichment is

intimately mixed with natural uranium or is in the form of spikes. This occurs because of the large amount of resonance absorption in Pu^{240} and its dependence on the self-shielding occurring in this resonance. We have assumed that the enrichment is introduced in such a way that irradiations of fissile and fertile materials may be calculated independently. The reactor in which this burnup occurs is characterized by $\bar{\eta}$, a number which indicates how much greater than the total neutron absorption the total neutron production must be to provide for leakage, reactivity control and neutron losses in structural materials. From the calculated fuel properties for a given irradiation the enrichment required to make the reactor critical during this irradiation can be determined. Thus if a fuel is to be irradiated to an irradiation ω and the integrated neutron yield and absorption during this irradiation in the fertile materials are Y_s and A_s and in the fissile materials Y_f and A_f, then

$$\frac{Y_s + NY_f}{A_s + NA_f} = \bar{\eta}$$

is an equation which can be used to determine N, the required enrichment. If the fertile and fissile materials are placed in different fluxes, their irradiation proceeds at different rates but the equation is still true providing the proper integrals are used. The BOT program has been incorporated into a control program which calculates the enrichment required for a given irradiation and makes an estimate of the fuel costs.

Cost of Fissile Materials

U^{235}

The cost of U^{235} depends on how it is to be used. As a starting point we use quoted U.S. prices for uranium hexafluoride from a

diffusion plant. The cost per gram of U^{235} is \$12.03 if it is bought in the form of 93% enriched material. At lower enrichments the cost per gram of U^{235} is lower but the cost of converting the hexafluoride to UO_2 becomes more important so that the cost reaches a minimum of about \$10.61/gm at an enrichment of about 2.2%[2]. For enrichments lower than this it pays to mix this material with Canadian natural uranium oxide. For higher enrichments material from the diffusion plant is cheaper. The resulting cost per gram of U^{235} as a function of enrichment is plotted in figure 3. For thorium fuels only mixtures of thorium and 93% U^{235} have been considered, although there might be an economic advantage in using lower enrichments.

U^{233}, Plutonium

Since these fuels are obtained only by irradiating other materials their cost cannot be obtained without reference to the nuclear power complex which is producing them. This will vary from one country to another; it may include fast and thermal breeders, and it will certainly change with time as experience is gained with handling reactor fuels. There may be some degree of economic 'insulation' between different countries however, each country preferring to develop an integrated system of producing and using fissile materials internally rather than depending on a foreign source of fissile material to expand or change its power program. Thus, 'costs' of fissile material may be expected to vary from one country to another and will reflect the line of reactor development chosen. In Canada it seems reasonable to estimate the relative worths of fissile materials by adding small amounts of each to natural uranium and comparing the resulting incremental burnup.

The regular BOT program without its control program was used for this purpose. The first case run (for comparison purposes) was

natural uranium in a reactor with an $\bar{\eta}$ of 1.06. The burnup obtained was 8400 thermal MWd/t so that this reactor is not very different from the Douglas Point reactor in neutron economy. Subsequent cases were run on BOT with compositions of 1 U^{235} + 137.8 U^{238} + 0.1X where X represents an atom of U^{233}, U^{235} or plutonium of various isotopic compositions. These compositions are the result of irradiating natural uranium to various irradiations. The incremental burnups obtained are plotted in figure 4 as a function of the irradiation of the natural uranium from which the plutonium is extracted and compared to that obtained for the pure fissile isotopes U^{233} and U^{235}. Two sets of curves are shown. The lower curve (curve (a)) which refers to 0.1 atom of plutonium has been divided by the fractional fissile content to determine the burnup increment per fissile atom of plutonium, plotted in the same figure (curve (b)). The neutron spectrum in which the plutonium is fissioned was characterized by the parameters T_n = 150°C and r = 0.07 which one would expect to find in a well-thermalized reactor spectrum. Reasonable changes in this spectrum will have only a small effect on the result.

Also shown in this figure are the effects of

(i) storing the uranium fuel for 10 years before reprocessing and using it (curve (c)),

(ii) processing after a five-year storage and then storing for a further five years before using it (curve (d)).

In the first case the plutonium becomes poorer because of the loss of Pu^{241} during the storage interval. In the second case, in addition to the loss of Pu^{241}, there is five years' worth of Am^{241} in the fuel, adding to the parasitic absorption.

For U^{235} and U^{233} the incremental burnups are 2295 and 2756 thermal MWd/t. The incremental burnup per fissile plutonium atom is very nearly constant at about 2300 MWd/t (see figure 4). Assuming

as a first approximation that the relative worths of the three fissile materials are proportional to the incremental burnup obtained and assigning a value of \$12.03 to pure U^{235} we obtain:

U^{235}	\$12.03/gram
U^{233}	$\$12.03 \times \frac{2756}{2295} = \$14.45$/gram
Plutonium	$\$12.03 \times \frac{2300}{2295} = \$12.06$/gram of fissile plutonium.

The U.S. guaranteed prices[3] per gram of U^{233} and fissile plutonium are \$14.00 (less a penalty depending on the U^{232} content) and \$10.00. In practice the plutonium should be somewhat less valuable than estimated above since usually some Pu^{241} will be lost and some Am^{241} will grow in during the interval between removal from one reactor and insertion in another. Plutonium is also somewhat more costly to handle than U^{235} because of its toxicity and α-activity. The difference between \$12.06 and \$10.00 may well reflect the American experience with the handling difficulties associated with plutonium. Similar considerations apply to U^{233}. The difficulties in handling U^{233} arise partly from its α-activity but mostly from the hard γ rays from daughter products of U^{232}.

Fast neutrons produce a Th^{232} (n,2n) Th^{231} reaction. Depending on the hardness of the reactor spectrum the equivalent thermal cross section lies between 10 and 50 millibarns. Th^{231} decays with a half-life of 25.6 hours to Pa^{231}. The cross section for the reaction Pa^{231} (nγ) Pa^{232} is about 200 barns and Pa^{232} decays with a half-life of 31.7 hours to the comparatively stable but α-active U^{232}. Taking the U^{232} capture cross section to be 100 barns and neglecting the short half-life of its precursors and the burnout of Th^{232}, the U^{232} concentration at an irradiation ω is simply

$$U^{232} = 200\ (1 - e^{-\omega/10})^2$$

in parts per million of Th^{232}. We have assumed here a relatively thermal spectrum where the (n,2n) reaction has a cross section of only 20 mb.

At irradiations which are likely to be of interest, i.e. in excess of 3 n/kb the total uranium concentration in thorium has reached an equilibrium value of about 1.4×10^4 ppm. After processing to extract uranium from irradiated thorium the U^{232} contamination in ppm of uranium will be:

$$U^{232} = 14000\ (1 - e^{-\omega/10})^2 \text{ ppm of uranium.}$$

TABLE I

Irradiation in n/kb	U^{232} in ppm of equilibrium Uranium
0	0
1	130
2	460
3	940
4	1520
5	2170
6	2850

Table II lists the penalty due to handling difficulties for U^{233} contaminated with U^{232}. As can be seen from Table I the U^{232} concentration at irradiations of 4 n/kb is high enough so that the maximum handling penalty will be incurred. A higher cross section for the Th^{232} (n,2n) Th^{231} cross section will lead to higher concentrations of U^{232} and the maximum penalty will be incurred at lower irradiations. Anticipating results to some extent we have assumed the full penalty for U^{232} contamination.

TABLE II

U^{232} in ppm of uranium	Penalty in US dollars
0	0.40
20	0.60
45	0.80
80	1.00
130	1.20
190	1.40
250	1.50
350	1.60
500	1.70
700	1.80
1000	1.90
1500 and above	2.00

From these considerations we adopt the following price scales for the fissile materials. As raw materials in manufacturing thorium fuel elements, U^{233}, U^{235} and fissile plutonium are assumed to cost \$14.00, \$12.00 and \$12.00 per gram respectively, as derived from their relative worths in improving the burnup of natural uranium. In determining the credit to be allowed for spent fuel we deduct \$2.00 from the above values for U^{233} and plutonium to allow for handling difficulties, and use \$12.00, \$12.00 and \$10.00.

Note that when a value is given to spent fuel, residual U^{233} or U^{235} in U^{238} must be discounted since it will not be recovered in a chemical process. In processing thorium fuel all uranium isotopes are recovered together with any plutonium which may have been used as enrichment.

Processing

The cost of processing irradiated uranium would at present be prohibitively high in Canada due to the small throughput. In the U.K. where several reactors are operating to relatively low burnups the throughput is sufficiently high to make processing economic and presumably this state of affairs will exist in Canada in the 1970's. The processing cost of $25/kgm selected for this study is based on estimates of processing cost by Nuclear Fuel Services[4]. U.K. processing may be even lower. An extra dollar was added for processing thorium since slight additional complications are expected in the chemistry of the extraction process. The processing costs for uranium and thorium were therefore taken to be $25.00 and $26.00/kgm though comparison cases were run with this reduced to zero.

Losses in processing have been neglected except that 98% of Pa^{233} has been assumed to decay to U^{233} before processing. Np^{239} is assumed to decay completely to Pu^{239} and the decay of Pu^{241} is neglected though this last effect could reduce the worth of the plutonium by $1/gm if there is a 5-year lapse between withdrawal of irradiated fuel and manufacturing new fuel and a further 5-year lapse before irradiation of this fuel begins (figure 4).

Manufacturing Costs

The method used for estimating manufacturing costs is not accurate but serves to point out one of the major problems likely to be encountered when using thorium as a fuel.

Estimates of manufacturing costs have been made as a function of pellet diameter for natural cluster-type fuel bundles of UO_2 similar to those in the Douglas Point reactor[5]. These estimates may be expressed roughly in the form

$$A + B\ S/M$$

where the volume term A probably arises mainly from the cost of UO_2 and the S/M term mainly from Zircaloy. The constants in this expression are:

$A = \$22.22/kg\ U$

$B = \$0.102/cm^2$ where S/M is expressed in cm^2/kg.

The fuel rating also depends on S/M. When the heat rating of the fuel is limited by the heat transfer coefficient the heat which may be taken from the fuel is proportional to the surface area while the amount of fuel is proportional to M so that the fuel rating is proportional to S/M.

Thus we express the cost of fabricating natural uranium fuel as:

$$F_U = 22.22 + \frac{25.93 \times MW/kg}{MW/kg \text{ for CANDU}} \quad \$/kgm.$$

for UO_2 fuel bundles.

For ThO_2 bundles with a somewhat lower density we write

$$F_T = \frac{10.5}{9.5} \left\{ 22.22 + \frac{25.93 \times MW/kg}{MW/kg \text{ for CANDU}} \times \frac{9.5}{10.5} \right\}$$

More explicitly

$$F_U = 22.22 + 1546 \times \frac{MW(th)}{kg}$$

$$F_T = 24.56 + 1546 \times \frac{MW(th)}{kg}$$

For enriched fuel the cost of the enrichment is just added to F_U or F_T neglecting any complication which might be required to handle enriched material in the manufacturing plant. The fuel ratings used in these formulae are averaged over the fuel irradiation.

The precise form of these fabrication costs, especially that for thorium, has a considerable effect on the final power cost and

should be considered in more detail. The difficulty in the case of thorium is the large thermal cross section which necessitates a high enrichment to achieve criticality. Thus the same weight of thorium fuel in the same flux as uranium fuel would have at least twice the heat rating with correspondingly higher fabrication costs. This point will be discussed later.

Inventory Charges

One final cost contribution which has been included is the interest charge on fuel inventory. In the case of uranium fuels interest charges have been made on the basis of the cost of fabricated natural uranium even in cases where enrichment is considered. The reason for this is that a reactor of the type considered ($\bar{\eta}$ = 1.06) loaded initially with natural uranium would be well over critical so it would not be reasonable to charge interest against the cost of enriched fuel. For the thorium cases interest has been charged against the fuel composition which is required to make the reactor critical. This treatment of the inventory charges is only approximate and a detailed fuel management study is required to determine these charges more accurately. In addition, other capital charges will depend on the fuel rating and enrichment and a proper treatment of the capital contributions to power cost will involve a study of the reactor design as well as fuel management problems. In this preliminary study a simple treatment of fuel inventory is sufficient to indicate where differences between fuelling with thorium-based fuels and natural uranium will arise.

Nuclear Data

Nuclear data in this calculation are based on the 1960 Westcott compilation[6] with revisions to the U^{235} and Pu^{239} data summarized by Critoph[7]. A recent estimate of $\nu(Pu^{241})$ by Westcott (ν = 2.966)

has been used but the capture and fission cross sections are taken to be proportional (as a function of energy) as in the 1960 Westcott compilation.

RESULTS

Figure 5 compares Th^{232} and U^{238} using U^{235} as the fissile material. Curve (a) shows the result of enriching natural uranium to prolong fuel life. At a flux of 5×10^{13} the fuel rating for natural uranium is 0.0167 thermal MW/kg giving a manufacturing cost of $48.00/kgU. This fuel is similar to that for the Douglas Point reactor. As U^{235} is added both manufacturing cost and burnup increase. The increase in manufacturing cost is primarily due to the cost of the added fissile material. The change in average fuel rating as enrichment is added is small, so the fabrication costs change very little, as can be seen by comparing curves (a) and (b). Curve (a) includes the manufacturing cost and shows how the burnup depends on the fuel costs. In curve (b) fabrication costs have been omitted leaving only the cost of refined natural UO_2 ($21.50/kgU) and extra U^{235} required. Curves (c) and (d) are corresponding results for Th^{232} and U^{235}. Here thorium dioxide has been assumed to cost $21.50/kg of thorium. Evidently a large capital investment is required to provide a given burnup using thorium as a fertile material. However, the incremental fuel supply cost which is inversely proportional to the slopes of the curves at any point is much better for Th^{232} than U^{238}. This is due to the superior nuclear properties of U^{233}. However, with thorium the flux is important and curve (e) shows the effect of flux on burnup. Here fabrication costs have been omitted so curve (e) is to be compared with curve (d).

The fuel supply cost is inversely proportional to the slope of a line drawn from the origin to any point on the curves. Thus at any

point where the slope of the curve is greater than that of a line joining the point to the origin, fuel supply costs will be reduced by enriching further.

Figure 6 shows how costs are modified when credit for spent fuel is taken into account. Curves (b) and (d) are the result of subtracting the net value of this spent fuel from the cost of the manufactured fuel. With the processing costs used here it does not pay to process natural uranium fuel until it has reached a burnup of 7000 MWd/t, i.e. processing costs more than the extracted plutonium is worth. Beyond this point the burnup per dollar invested increases. For Th^{232}-U^{235} fuel the difference due to processing (curves (c) and (d)) is much more striking since the concentration of U^{233} in the fuel is much higher and U^{233} is more valuable than the plutonium in U^{238}.

The comparison is still not complete. There will be a considerable time lag between providing manufactured fuel for the reactor and recovering fissile material from spent fuel. During this period interest must be paid on the inventory of fuel in the reactor. The conventional way of treating this problem is to capitalize the cost of fuel required to make the reactor critical (plus, possibly, a small inventory to allow a few months' operation). The fuel supplied to the reactor to maintain reactivity is an operating cost. This we call the fuel supply cost. Thus, interest is paid on the fuel required to make the reactor critical and the total fuel cost includes this interest and the difference between fuel supply cost and spent fuel credit. At equilibrium, spent fuel will be discharged as new fuel is provided. Since this fuel inventory is a non-depreciating item in the capital cost, low interest rates may be appropriate. For these studies we have used 5%.

These points are brought out more clearly in figures 7 - 14 where we have plotted fuel costs directly. Except where noted these

costs include inventory charges and credit for spent fuel. The curves in these figures all have the same general form. The fuel required to achieve criticality with thorium is very expensive compared to natural uranium because of the high initial concentration of fissile material. In addition, fabrication costs are higher than for natural uranium because of the high heat ratings which must be achieved to keep inventory charges low. Thus for low ultimate burnups the fuelling costs for a thorium-fuelled reactor are prohibitively high. However, the incremental burnup per additional dollar invested is large so that the fuel cost decreases rapidly with increasing burnup. Eventually an accumulation of fission products and capture product poisons will cause the cost to rise again. Figure 7 indicates the relative contributions of fuel supply cost, inventory charges and spent fuel credit to the total fuel costs for U^{238} and Th^{232} using U^{235} as the fissile material. Clearly, inventory charges and spent fuel credit are major contributors to the total fuel cost for Th^{232}.

Use of Various Fissile Materials

For the purposes of this general survey it has been assumed that any fissile material introduced will be irradiated in the same spectrum and for the same length of time as the fertile material. For U^{235} and U^{233} used as enrichment with thorium, this is probably a reasonable assumption to make since these fissile materials would very likely be intimately mixed with thorium. The η values for U^{235} and U^{233} fall to 1.06 after about 4.0 and 4.7 n/kb respectively and so would have received about their optimum irradiation when the thorium fuel was removed for processing. Plutonium (or Pu* as it will be called, being plutonium which has been extracted from natural uranium at a burnup of about 8400 MWd/t) has an η value of 1.06 at about 1.7 n/kb so it would be unreasonable to irradiate it much further since it would be acting as a parasitic absorber and producing little

power. A better way of using Pu* with thorium might be in the form of spikes. With bi-directional fuelling these spikes could be pushed through the reactor faster than thorium bundles. The main difficulty here would be that initially all the power would come from the plutonium slugs and finally it would mostly come from thorium. This problem has not been considered in this report and Pu* has been treated in the same way as U^{235} and U^{233}, i.e. as if in the form of uniform enrichment.

In figure 16 the burnup as a function of irradiation which would be obtained with each fissile material is plotted together with the contribution from thorium alone. The amount of fissile material is just sufficient to provide the irradiation indicated. Considering, for example, an irradiation of 4 n/kb:

Fissile Material	Power from Th	Power from Fissile Material	% of total from Fissile Material
U^{233}	19,500	15,500	44
U^{235}	19,500	19,000	49
Pu^{239}	19,500	29,500	60
Pu*	19,500	56,800	74

The better fissile materials provide more burnup of the fertile material.

Total fuel costs for thorium with different fissile materials are plotted in figure 8 as a function of burnup. Curves (a) and (b) with U^{235} and U^{233} as enrichment show similar costs. The Pu* curve (c) shows the consequences of using Pu* as a uniform enrichment where even at lower burnups (where $\eta(\text{Pu*}) > 1.06$) the cost is high compared with U^{235} enrichment. This is due partly to the higher fabrication costs necessitated by the high fission cross section of Pu^{239} and partly to the difference in price at which the plutonium is bought

and allowed for as a credit in spent fuel. At higher irradiations parasitic absorption in fission products becomes more important. While there is also a difference in cost and credit value of U^{233} this is compensated by a better η value of U^{233} so that the fuel costs are very similar for U^{233} and U^{235}.

Results for natural uranium enriched with fissile material are shown in figure 9. The behaviour is basically the same as with thorium but on a different scale. Natural uranium contains sufficient 'free' U^{235} for burnups of the order of 9000 MWd/t to be possible without further enrichment, so we do not have the problem of providing large quantities of enrichment to start up a reactor. Inventory charges are thus low and the total fuel costs are lower than those in figure 8. However, plutonium is not as good a fissile material as U^{233}, so that with U^{238} instead of Th^{232} as the fertile material minimum fuel costs are obtained at much lower burnups ($\sim$ 14000 MWd/t). U^{235} compares favourably with U^{233} when used to enrich natural uranium. This is primarily due to the low cost of U^{235} for these low enrichments (figure 2).

Variation of Flux

Figure 10 shows the dependence of the fuel cost on flux for thorium and natural uranium enriched with U^{235}. Several factors contribute to this variation.

(a) Xenon absorption increases with flux, reducing the effective η of the fuel. This is a small effect.

(b) For the same reason Np^{239} holdup in U^{238} and Pa^{233} holdup in Th^{232} become more important as the flux is raised. The Np^{239} effect is relatively small because of its short half-life (2.35 days compared to 27 days for Pa^{233}).

(c) In a high flux less fuel will be required to produce a given power output, although it will of course need to be changed more often. Therefore interest charges on the fuel inventory will be lower. In a thorium reactor containing very expensive fuel the inventory charges contribute a bigger percentage to the total fuel cost than is the case with uranium so there may be a greater incentive to go to higher fluxes even at the expense of increased absorption in Pa^{233}.

(d) The simplified formulation adopted for the fuel fabrication costs in this report is such that the advantage of increasing the flux to lower the inventory charge is outweighed by the extra fabrication cost incurred. If the flux is doubled in order to halve the inventory charges the heat rating of the fuel must also be doubled. This calls for very thin fuel pencils with a consequent high fabrication cost. Even with a flux of 5×10^{13} $n/cm^2/sec$ as in the Douglas Point reactor, the heat rating with a thorium fuel would be at least double that for uranium and a 37-element rod design would probably be required.

(e) If the flux in a reactor could be doubled, twice the power output would be obtained from the same reactor and the resultant savings in capital costs might be considerable. With natural uranium fuel, fabrication costs are a large proportion of the total fuel cost and so it is not worthwhile to increase the flux in the Douglas Point reactor above 5×10^{13} in an attempt to reduce capital costs. The cost of fabricating fuel with the necessary high heat rating would be prohibitively high. With a thorium fuel in which the fabrication cost represents a smaller fraction of the total fuel cost it may pay to increase the flux in order to save on capital costs.

The magnitude of the effects (a) and (b) can be seen in figure 15 which shows the ultimate irradiation in n/kb as a function of U^{235} enrichment. At zero irradiation in the thorium cases, an increase of enrichment from 1.780% to 1.783% is sufficient to overcome the extra xenon absorption penalty incurred when the flux is increased from 5×10^{13} to 10^{14} $n/cm^2/sec$. The subsequent divergence of the curves is caused by the Pa^{233} holdup.

The dependence of total fuel cost on flux is due primarily to the increase in manufacturing cost with increase in flux as can be seen by comparing figure 10 with figure 11 where the effect of fuel rating on the manufacturing cost has been omitted.

Processing Costs

At present in Canada no fuel processing is carried out on a commercial scale and processing costs in the U.S. are high enough so that it is barely worthwhile to process spent natural uranium. At $25/kg the cost of extraction of Pu* at 4 gm/kg is $6.25/gm. The fissile content is 69% so the cost of extraction is about $9/gm of fissile material compared to the value of $10/gm which we have assigned to it. In the thorium fuel cases 14 gms/kg of fuel of U^{233} are obtained for a processing charge of $26/kg. The extraction cost of U^{233} is thus only $2/gm compared with the value of $12/gm we have assigned to it. Thus processing will be an essential part of any thorium fuel cycle with the cost of processing contributing only a small fraction to the total fuel costs. Since the processing costs represent a much higher fraction of the cost of a uranium-plutonium fuel cycle, a reduction in the cost of processing could give the uranium-plutonium fuel cycle a big advantage. Figure 12 indicates the limiting size of this effect by showing fuel costs for thorium and natural uranium enriched with U^{235}. Separate curves compare results when the processing costs $26 and $25/kg are assumed, and

when these costs are zero. For natural uranium this represents a saving of about 50%, whereas for thorium irradiated to 40,000 MWd/t the saving is about 10%. As more reactors come into operation and the quantity of fuel to be processed increases, the processing cost will decrease significantly[4]. Spent fuel will be rejected from the Douglas Point reactor at a rate of 1 tonne every 12 days and the $25/kg cost is based on a throughput of 1 tonne/day. It is not likely therefore that a processing plant operating at 80% utilisation would be built in Canada until the installed capacity of nuclear reactors is at least 10 times that of CANDU, or 7000 MW (thermal).

Other Input Parameters

(a) Interest Rate

A rate of 5% has been used throughout. This could be rather low and if so would bias the results in favour of the thorium fuel. An increase from 5% to 7% in interest rate increases the fuel cost for natural uranium by 0.028 mill/kWh but a similar increase with thorium fuel adds 0.073 mill/kWh.

(b) Station Efficiency

A net station efficiency of 30% has been assumed. This is a typical value for the conversion of thermal to electric power in a large station. Any variation from 30% would merely introduce the same proportionality factor into both uranium and thorium fuel costs.

(c) Plant Utilization

A station has been assumed to be on power for 7000 hrs/yr (80%). The effect of this is to increase the effective interest rate from 5% to 6-1/4%. It is therefore more important for a thorium reactor than for a uranium reactor to operate for the maximum possible number of full power days in any given period.

(d) Neutron Economy

A higher $\overline{\eta}$ value indicates a reactor of poorer neutron economy. The value 1.06 which has been used throughout this study is a reasonable number to take for a large D_2O cooled and moderated system. The exact value chosen has a large effect on the attainable burnup for natural uranium. An increase in $\overline{\eta}$ from 1.06 to 1.08 reduces the burnup from 8400 to 6450 MWd/t. This reduction in attainable burnup of 23% is reflected in a correspondingly increased fuel cost. Figure 13 shows the total fuel cost curves for natural uranium and thorium, both enriched with U^{235}, with $\overline{\eta}$ values of 1.06 and 1.08. The penalty incurred by increasing $\overline{\eta}$ from 1.06 to 1.08 in natural uranium is about 0.3 mill/kWh compared with about 0.1 mill/kWh in enriched thorium or enriched uranium.

(e) Plutonium Price

The $12 (including handling charges) cost of plutonium assumed for most cases assumes a certain degree of economic coupling with the American nuclear power program. Another equally valid viewpoint would consider that plutonium inventories built up in Canada are similar to the tailings of a working mine and thus of no value until it becomes economic to use them. By the time a significant inventory of plutonium has been accumulated in Canada, processing costs may well be low enough to provide fissile plutonium at $6/gm. To assess the impact of this low cost, fuelling costs have been calculated for Pu^*-Th^{232} fuel assuming a supply cost of $6 per fissile atom and a credit of $4 for plutonium contained in the spent fuel. The results plotted in figure 14 compare the low fuel costs attainable with those obtained under similar conditions, assuming $12.00/gm of fissile plutonium. With this choice for the cost of plutonium figure 14 does not tell the whole story. In addition to giving low fuel costs, the value of

the fuel inventory will increase during the life of the reactor. The use of plutonium and thorium in reactors looks interesting and should be investigated further.

SUMMARY AND CONCLUSIONS

In these exploratory calculations cost estimates are not precise. Nevertheless some general conclusions can be made which do not depend on the precise costing methods used.

The high thermal cross section of thorium leads to a large amount of fissile material (or a small amount of thorium) to make a thorium-fuelled reactor critical (figure 17). This makes the fuel expensive and fuel costs with no credit for spent fuel are high (figure 7). However, the high cross section also leads to a high concentration of U^{233} at the end of the irradiation, and processing to recover this uranium is economic with present day processing costs. The effect of the spent fuel credit is to lower reactor fuelling costs so that they are comparable with a natural uranium reactor (figure 7). Lower processing costs will reduce fuel costs still more but would benefit natural uranium fuel costs more than thorium fuel costs (figure 12).

A thorium-based fuel is very much more expensive than natural uranium because it must contain more fissile material; this fissile material is more expensive than that in natural uranium and fuel ratings are likely to be higher than for natural uranium. High fuel ratings reduce inventory charges which are an appreciable fraction of the fuel costs (figure 7). Natural uranium is so cheap that, in spite of the large contribution of fabrication cost to the manufacturing cost (figure 5), inventory charges are a relatively minor contribution to the fuel cost. For thorium fuels we have the reverse situation. Here the fabrication charges are a much smaller fraction

of the manufacturing cost but the fuel itself is so expensive that inventory charges are high. Inventory charges may be reduced by increasing the fuel rating. However, increasing the fuel rating increases the manufacturing cost. For cluster-type fuel bundles the effect of rating on manufacturing cost is so large that an increase in fuel rating (and reactor flux) leads to higher fuel costs (figure 10). The increase in manufacturing cost more than compensates for the reduction in inventory charges. The contribution of fabrication charges to reactor fuel costs can be seen by comparing figure 10 with figure 11 where the fabrication costs are fixed at \$48/kg U. There is thus a large incentive to increase fuel ratings cheaply for thorium-based fuels, and different types of fuel channels and fuel management schemes must be investigated.

Using figure 4 the relative worths of U^{233}, U^{235} and plutonium were determined and an 'indifference' value ascribed to U^{233} and plutonium based on \$12/gm of U^{235}. This seems to be unrealistic, at least in Canada, where large amounts of relatively cheap natural uranium are available. While the calculations performed here are not exhaustive, they indicate that it is not worthwhile to irradiate natural uranium much beyond 14000 MWd/t in CANDU-type reactors. This sort of burnup may be obtained using an enrichment less than 2.2% (figure 15) and according to figure 3, U^{235} enrichments in this range may be obtained for \$10.61/gm. The costs used in this report have been based on guaranteed prices quoted by the AEC. In fact these prices may be high as far as indicating their worth in extending the burnup of natural uranium in Canada is concerned (figure 9). In any case a complete study of the use of Pu*-Th fuels in CANDU-type reactors must take into account heavier isotopes such as Am^{241} and Am^{243} which are potentially valuable materials and may affect the credit allowed for spent fuel appreciably. Nuclear data

for the heavier nuclides are not accurate and an effort to improve this knowledge would be useful.

There is no doubt that thorium-based fuels will be irradiated to much higher burnups than natural or slightly enriched uranium. However, the gain beyond about 40,000 MWd/t is small and for this sort of burnup fuel swelling is probably quite manageable. Some development work in this area will, however, be necessary.

Fuel costs for thorium-based fuels appear to be very nearly competitive with fuel costs from natural uranium CANDU-type reactors, even with the present low price of natural uranium. The effect of thorium-based fuels on reactor design and capital cost may be appreciable and for this reason more detailed studies are of immediate importance.

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3. Nuclear Industry, Feb. 1965, p. 21

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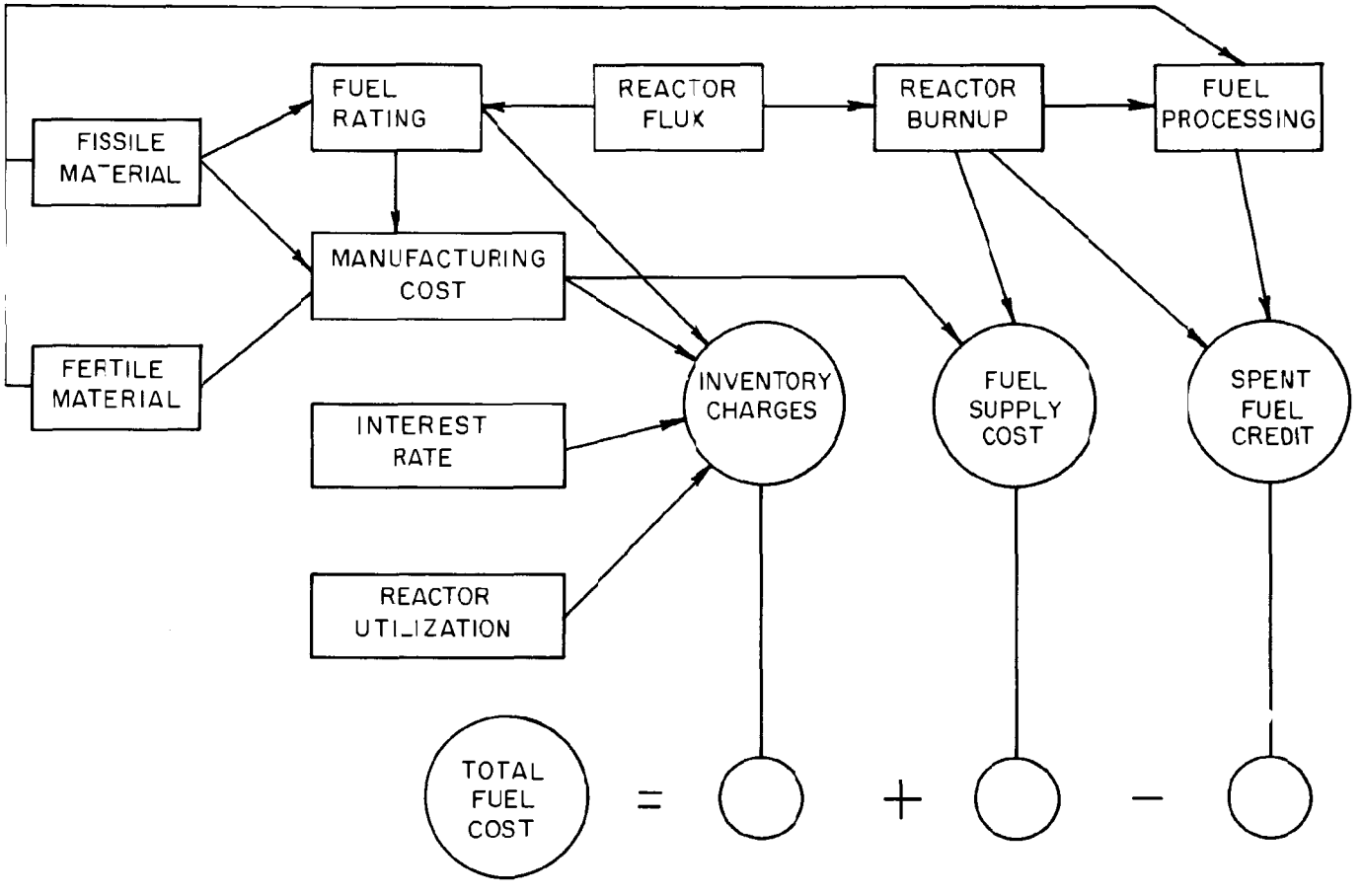
6. Westcott, C.H. AECL-1101

7. Chalk River Reactor Physics Handbook, Section B.I.7

FIG. 1

REACTOR PARAMETERS INFLUENCING FUEL COSTS



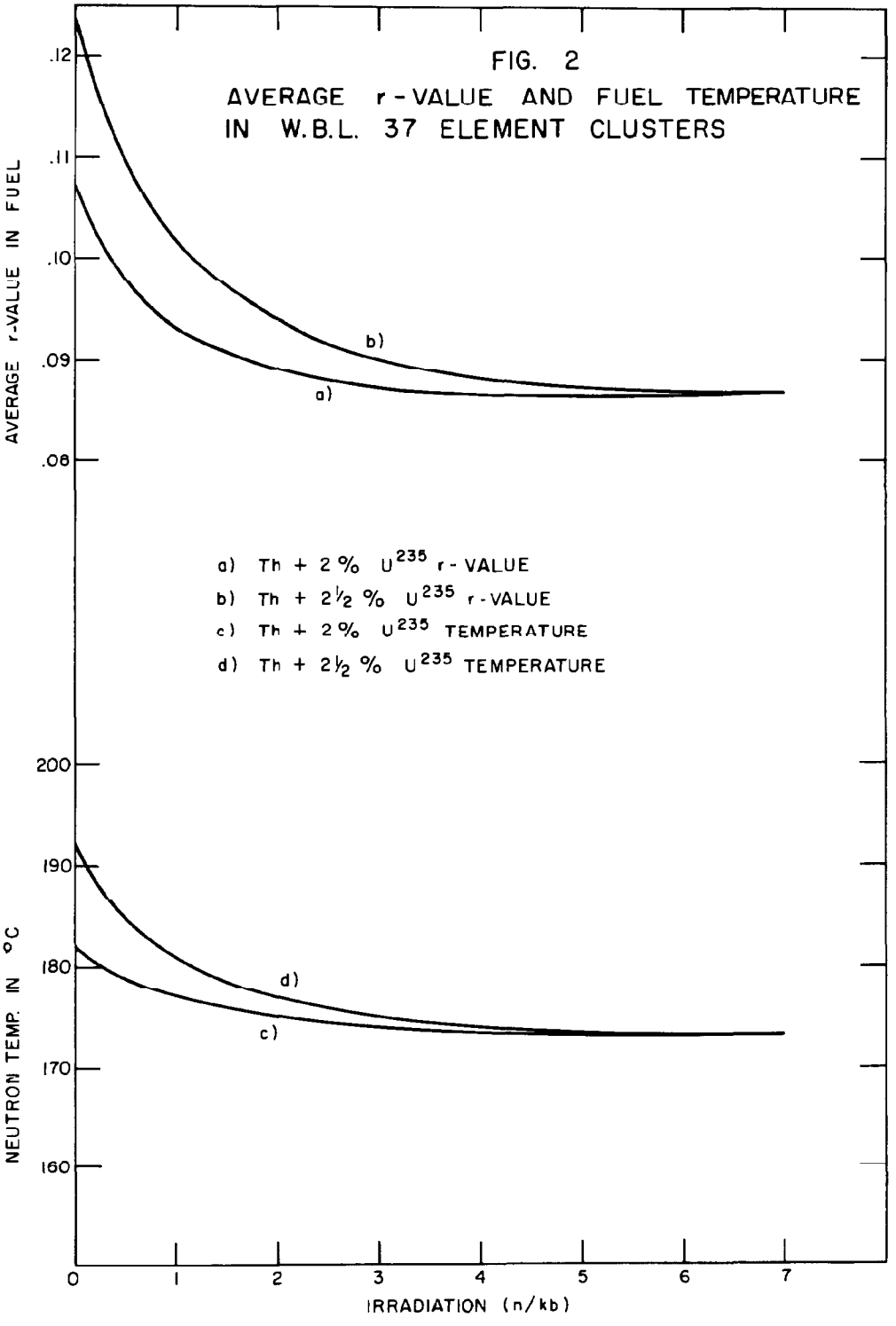


FIG. 2
AVERAGE r-VALUE AND FUEL TEMPERATURE
IN W.B.L. 37 ELEMENT CLUSTERS
AVERAGE r-VALUE IN FUEL
.12
.11
.10
.09
.08
b)
a)
a) Th + 2 % U235 r-VALUE
b) Th + 2½ % U235 r-VALUE
c) Th + 2 % U235 TEMPERATURE
d) Th + 2½ % U235 TEMPERATURE
NEUTRON TEMP. IN °C
200
190
180
170
160
d)
c)
0
1
2
3
4
5
6
7
IRRADIATION (n/kb)

FIG. 3

ENRICHMENT COSTS FOR CERAMIC GRADE UO_2

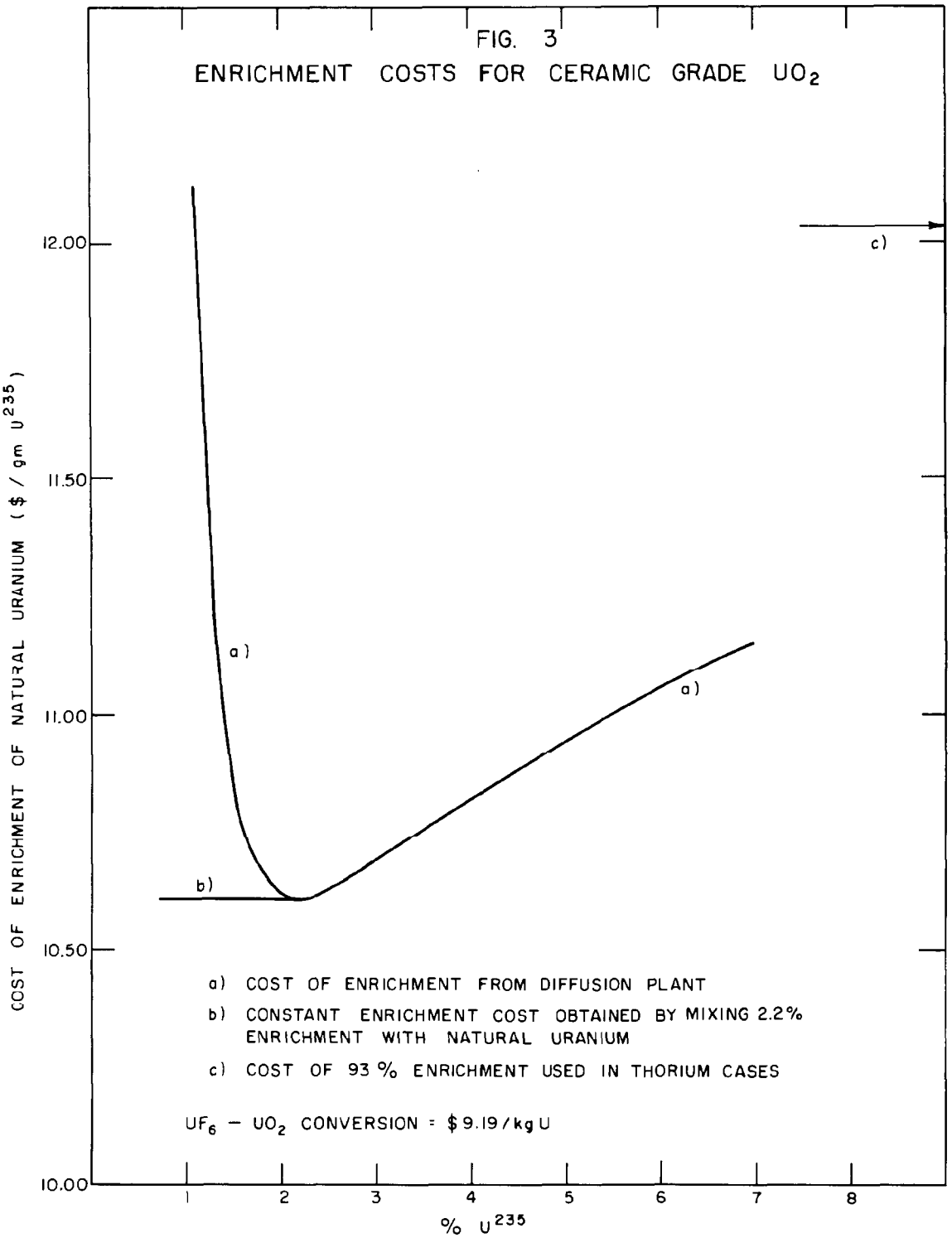


FIG. 4 INCREMENTAL BURNUP ATTAINABLE BY ADDING FISSILE MATERIAL TO NATURAL URANIUM

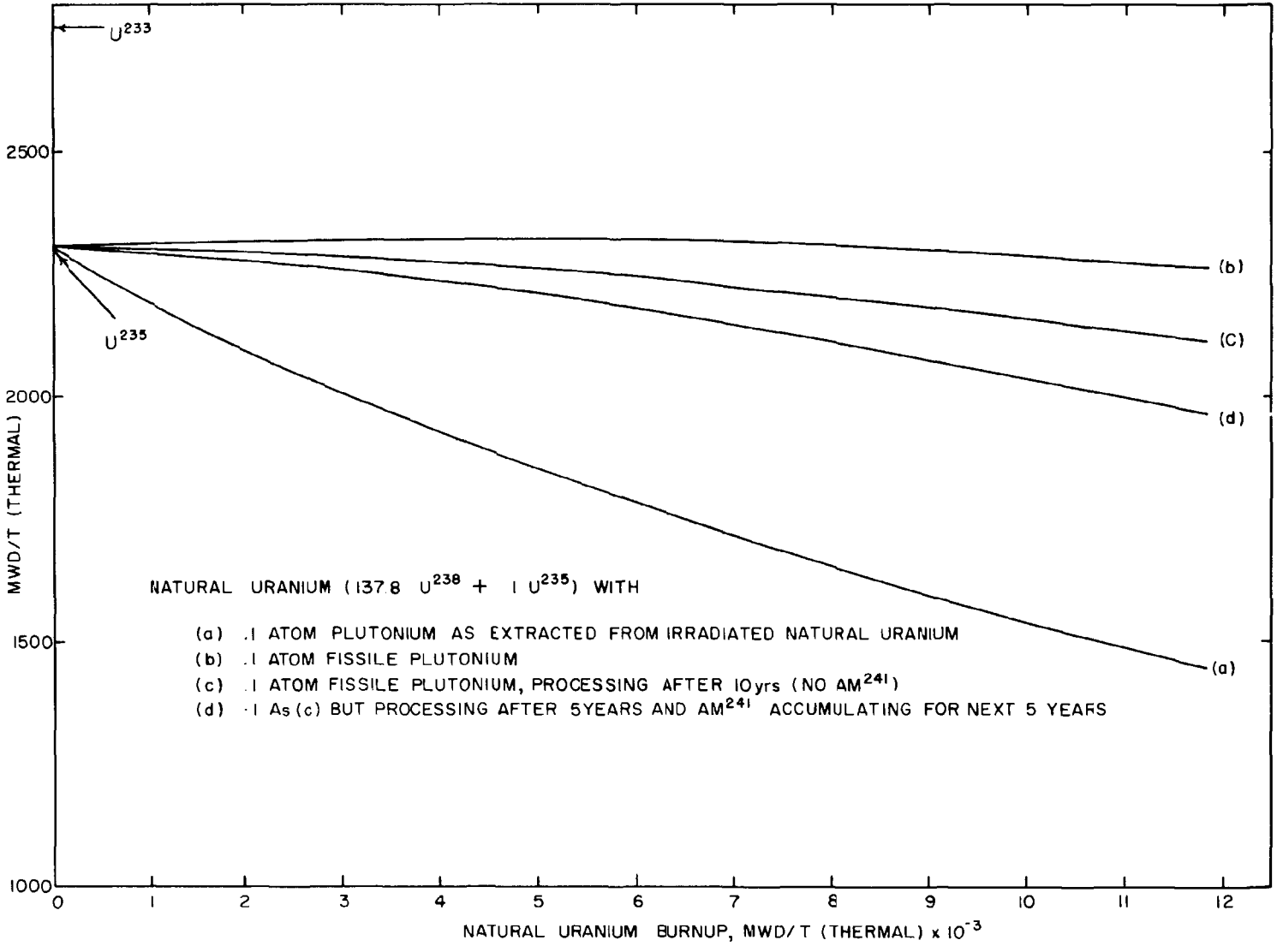


FIG. 5 URANIUM AND THORIUM MANUFACTURING AND FABRICATION COSTS

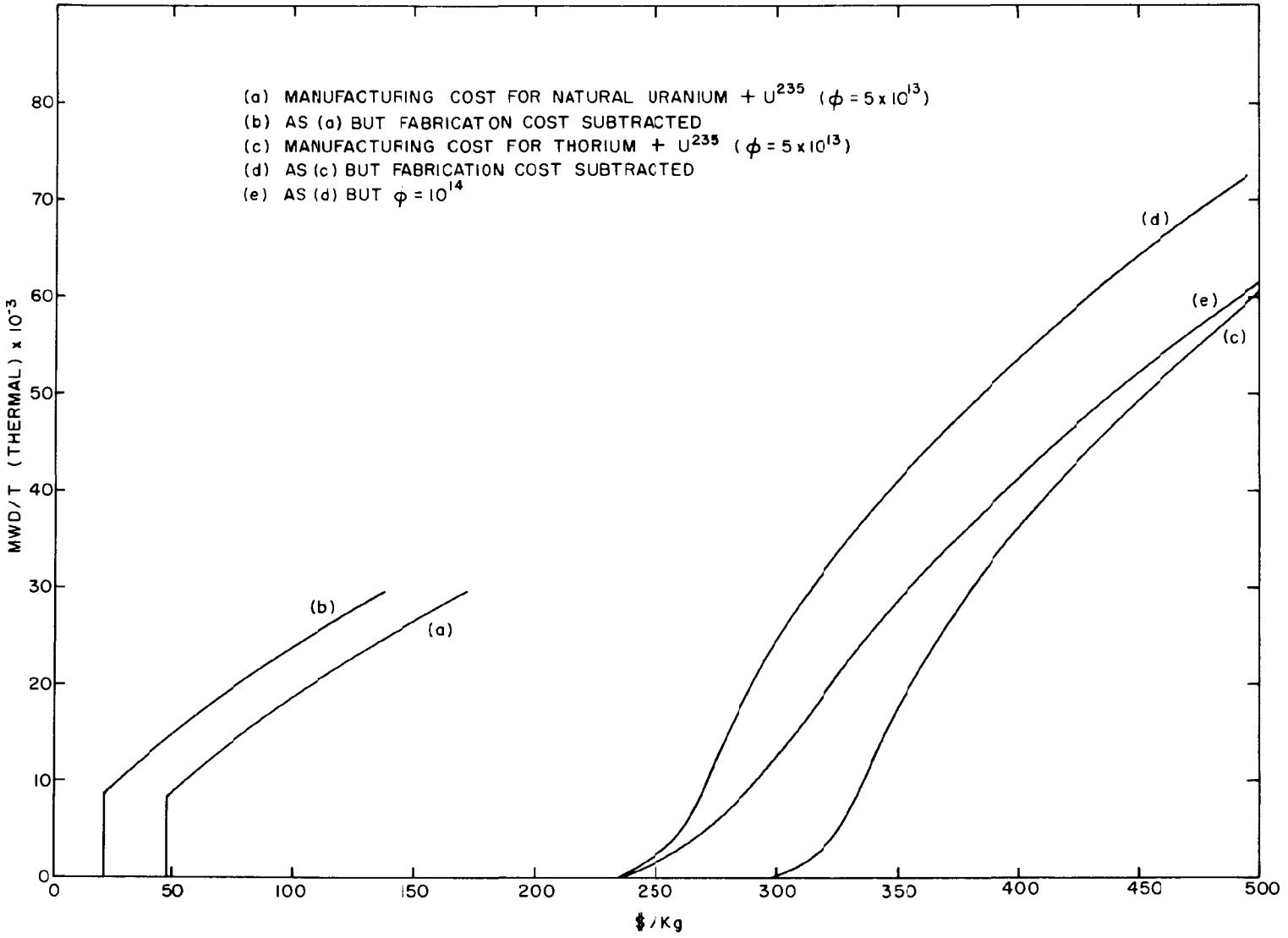


FIG. 6 SPENT FUEL CREDIT

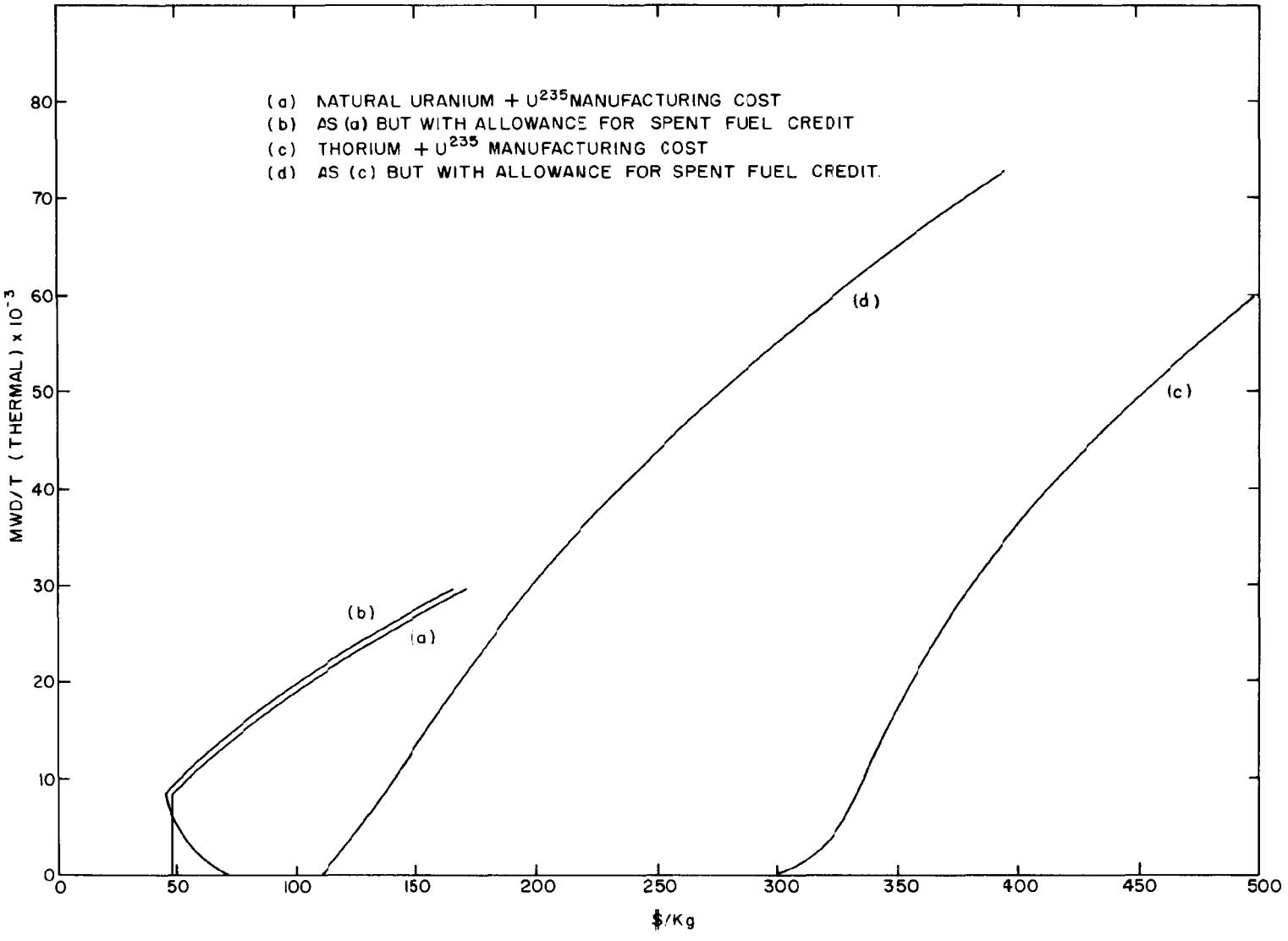


FIG. 7 SPENT FUEL CREDIT AND INVENTORY CHARGES

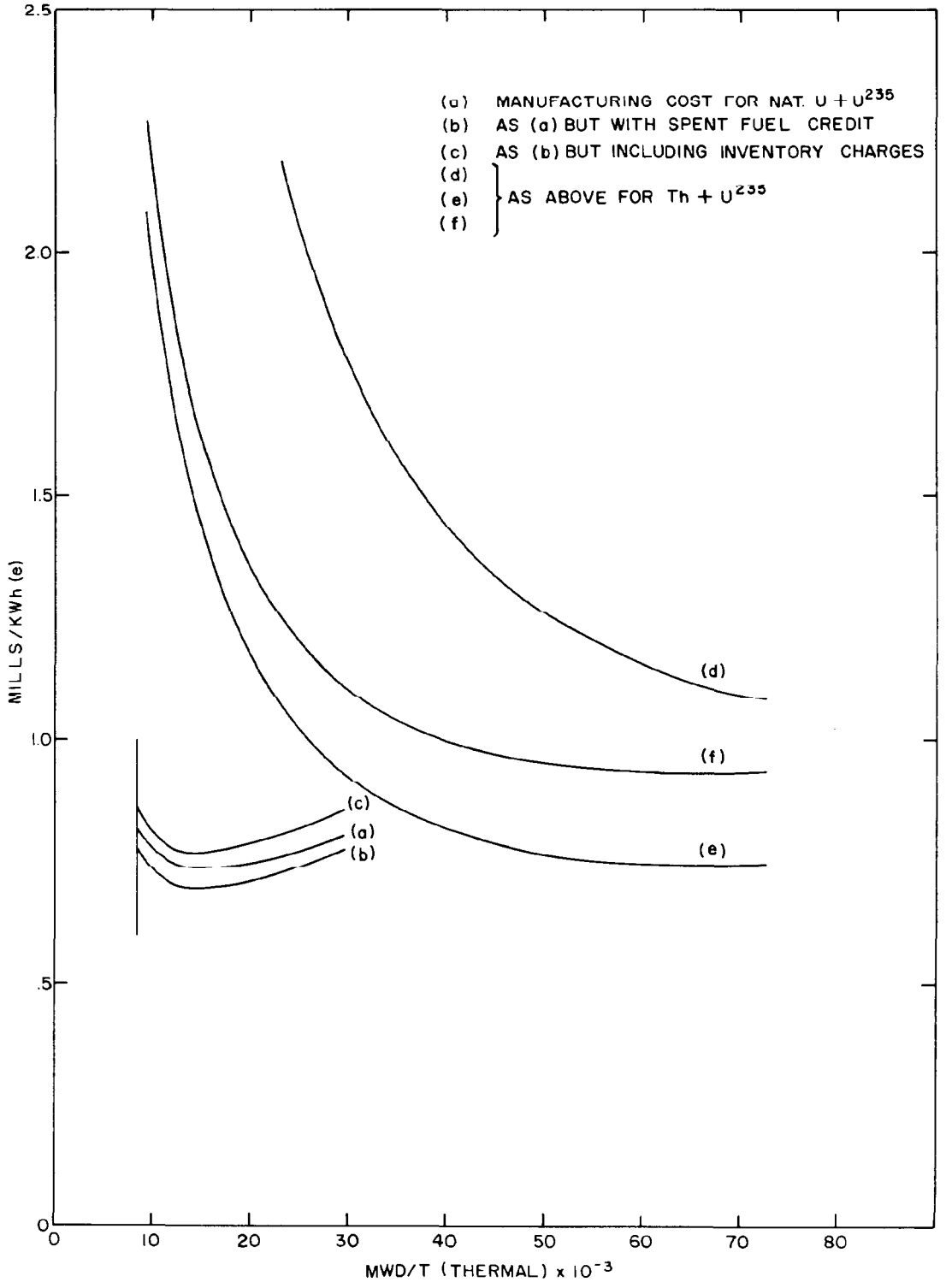


FIG. 8 THORIUM WITH VARIOUS FISSILE MATERIALS

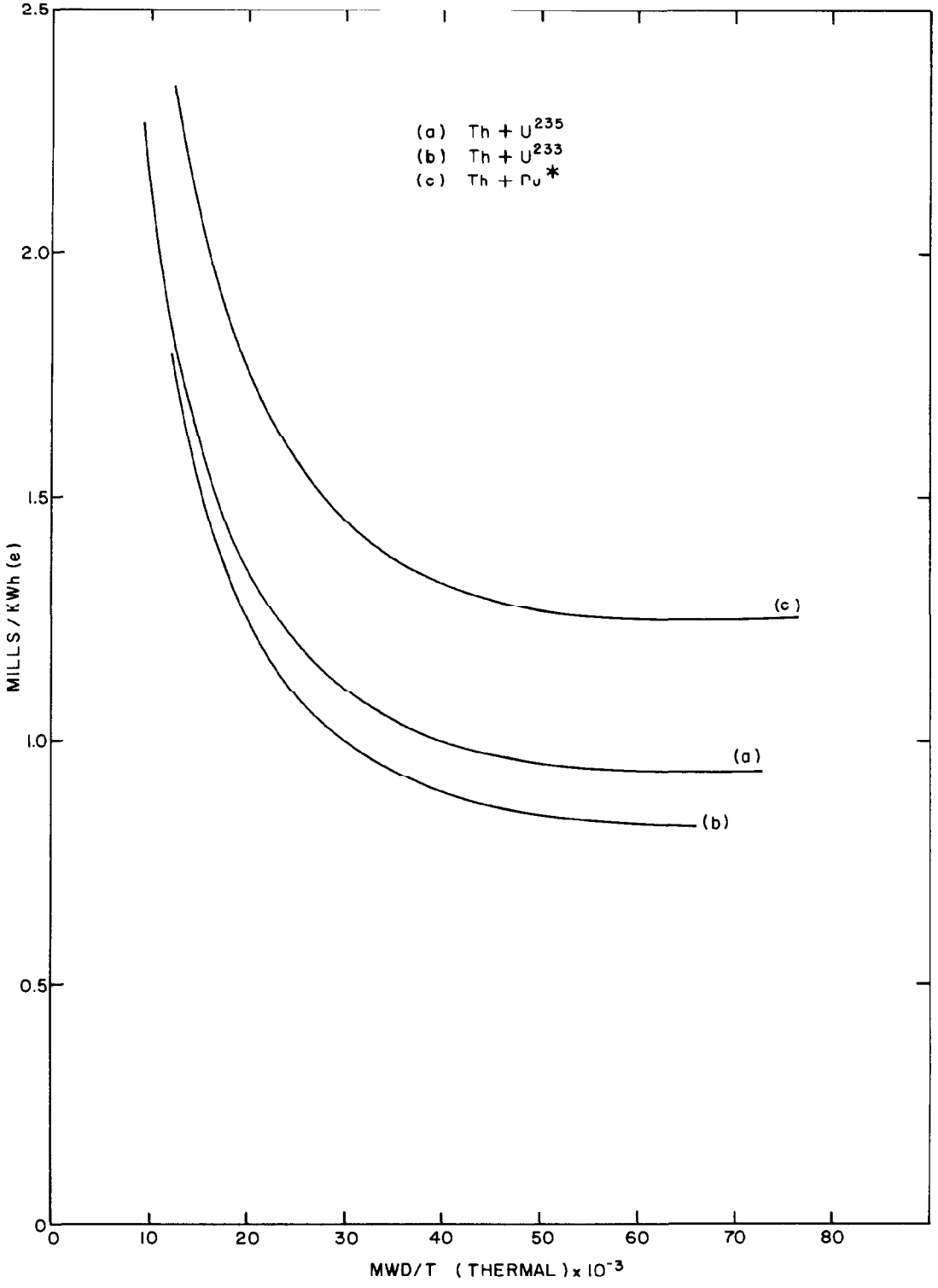


FIG.9 NATURAL URANIUM WITH VARIOUS FISSILE MATERIALS

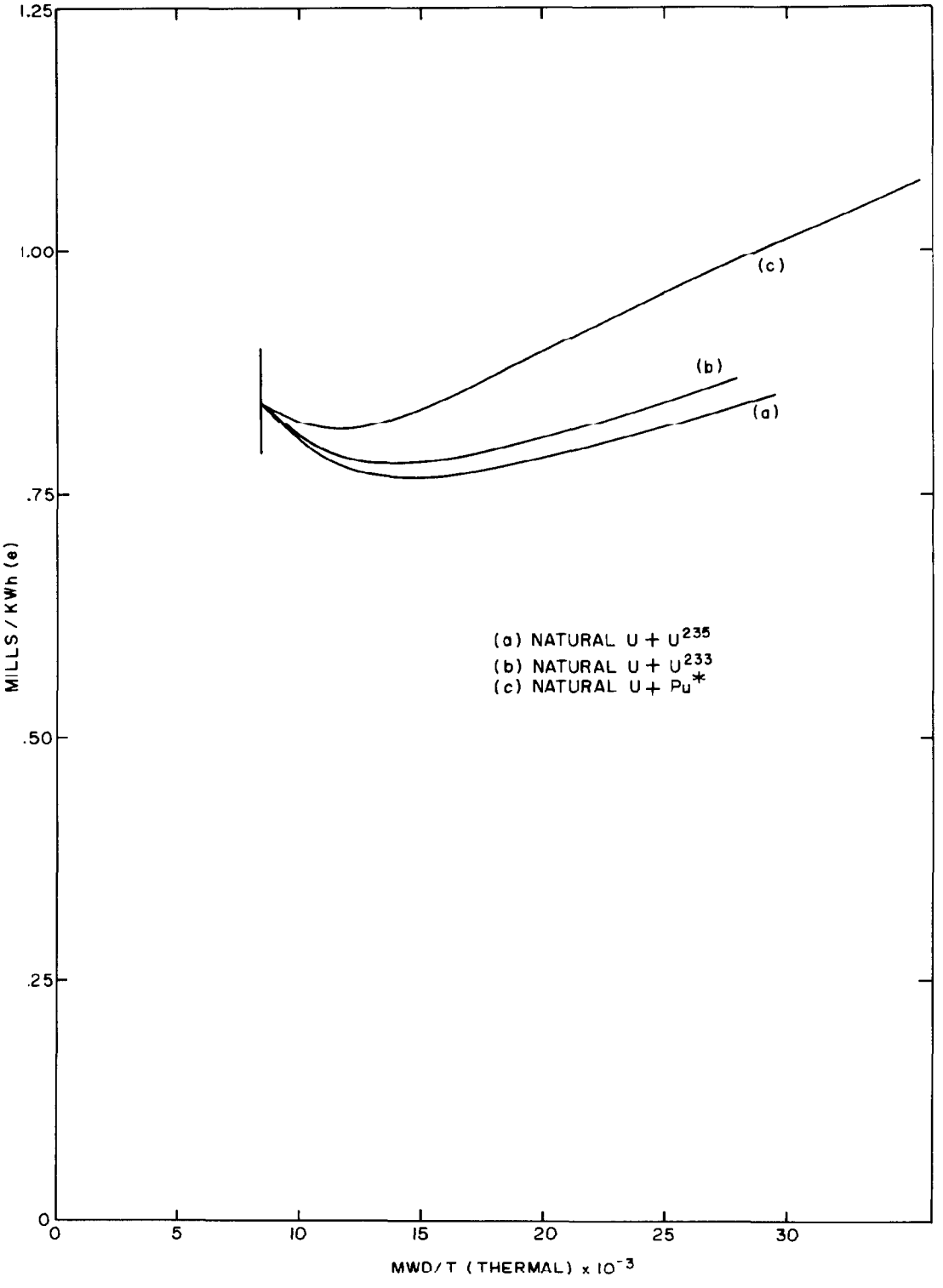


FIG. 10 EFFECT OF FLUX

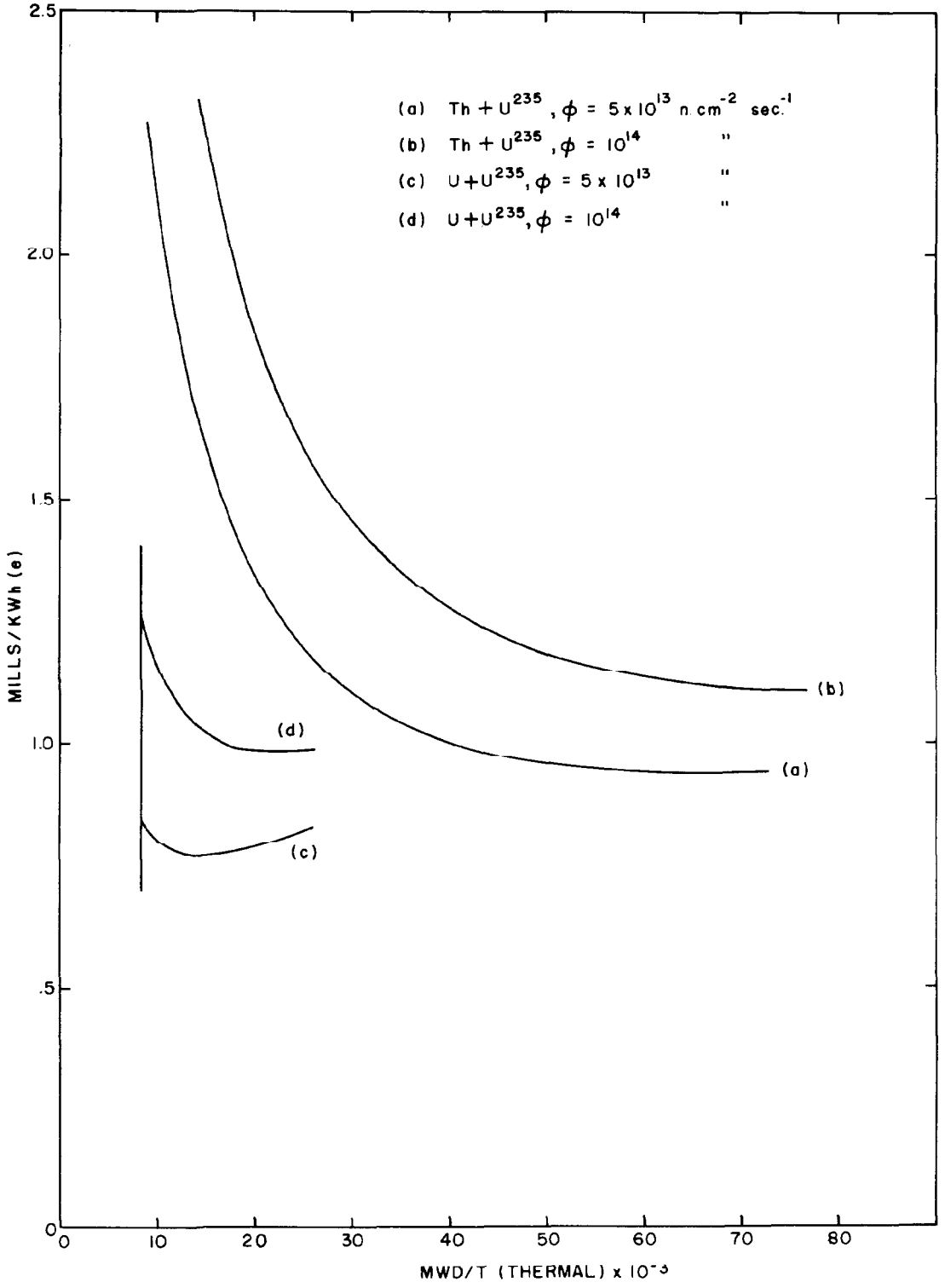


FIG. II EFFECT OF FLUX WITHOUT RATING DEPENDENCE

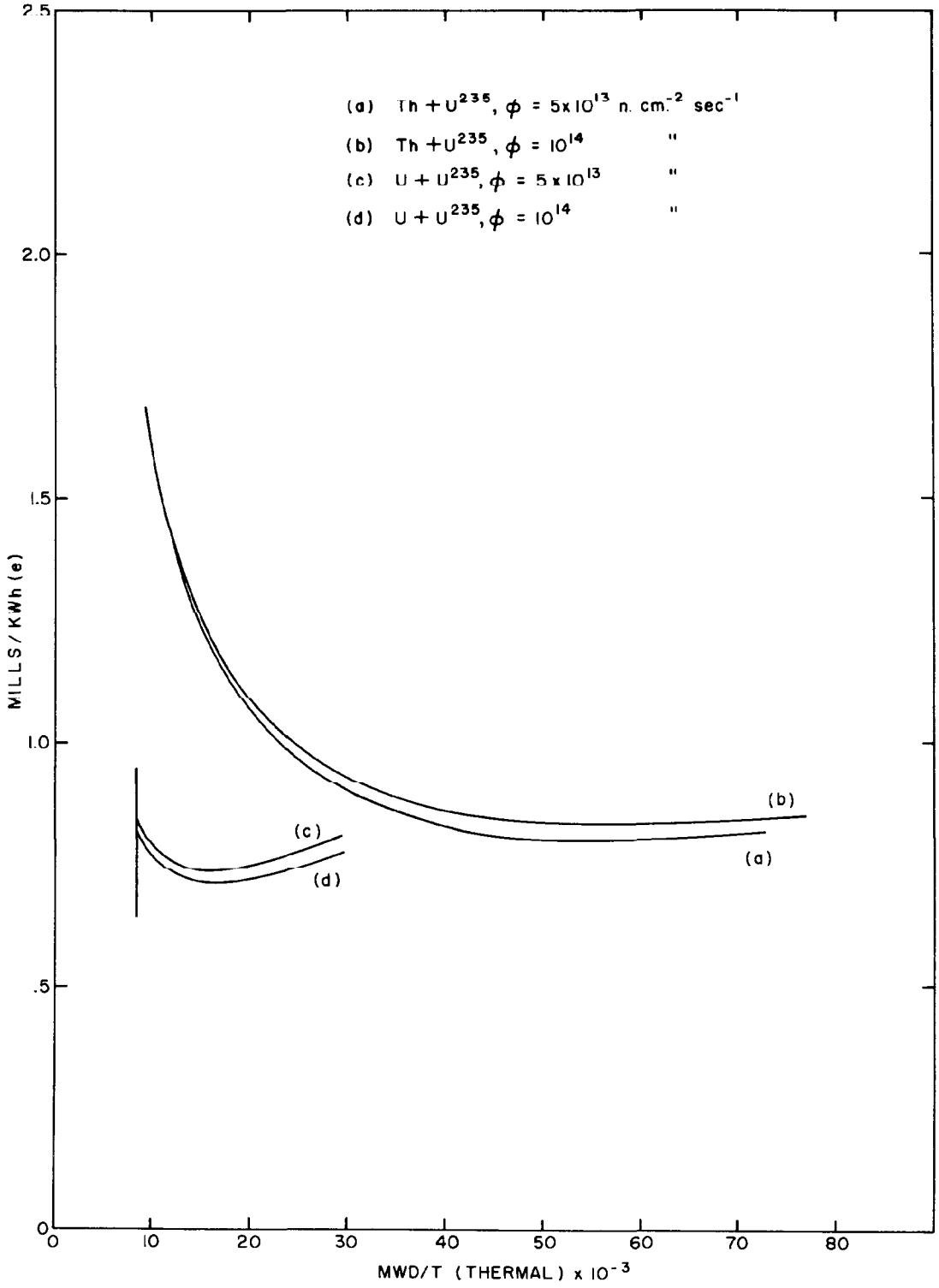


FIG. 12 PROCESSING COSTS.

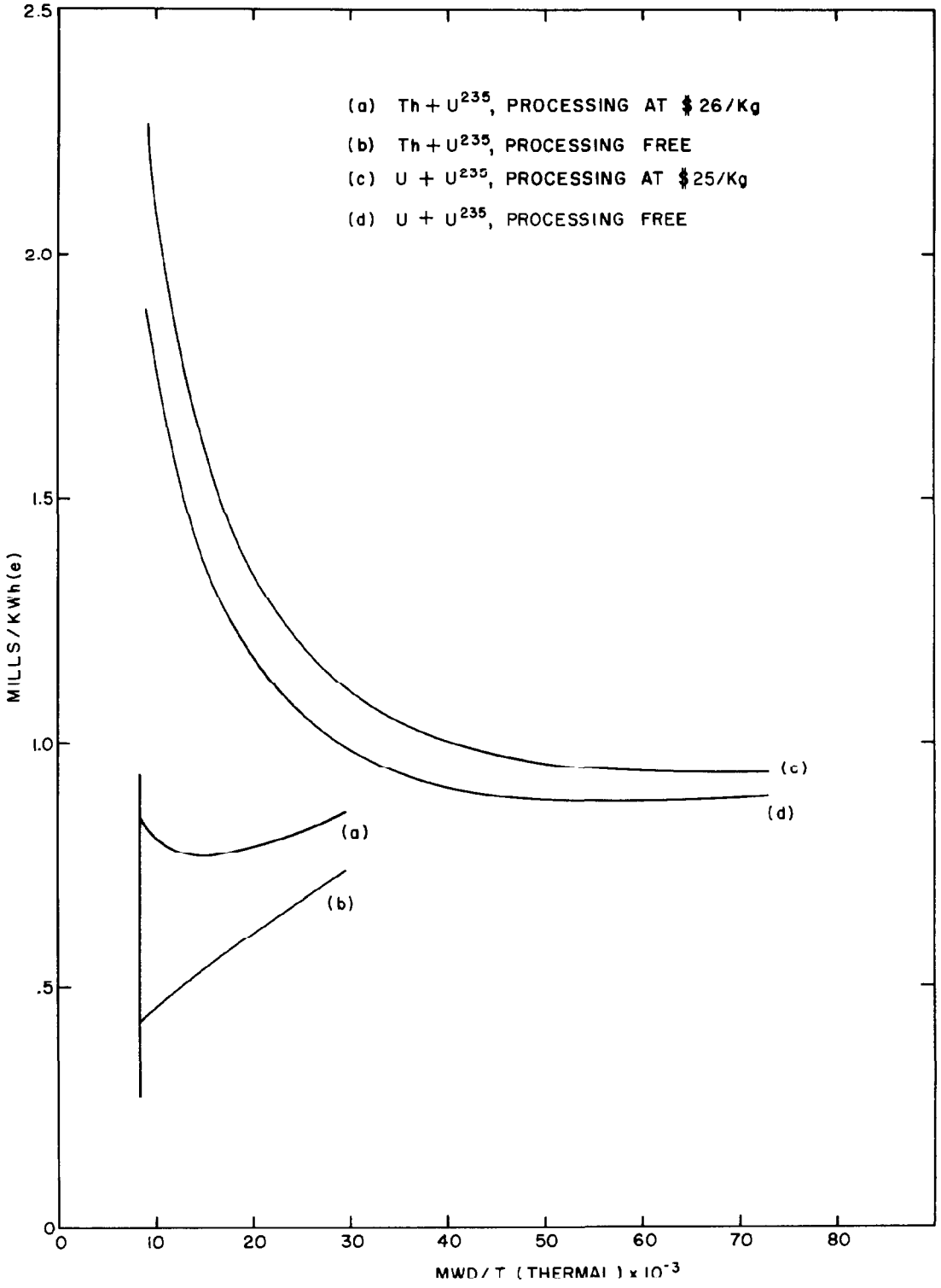


FIG. 13 NEUTRON ECONOMY

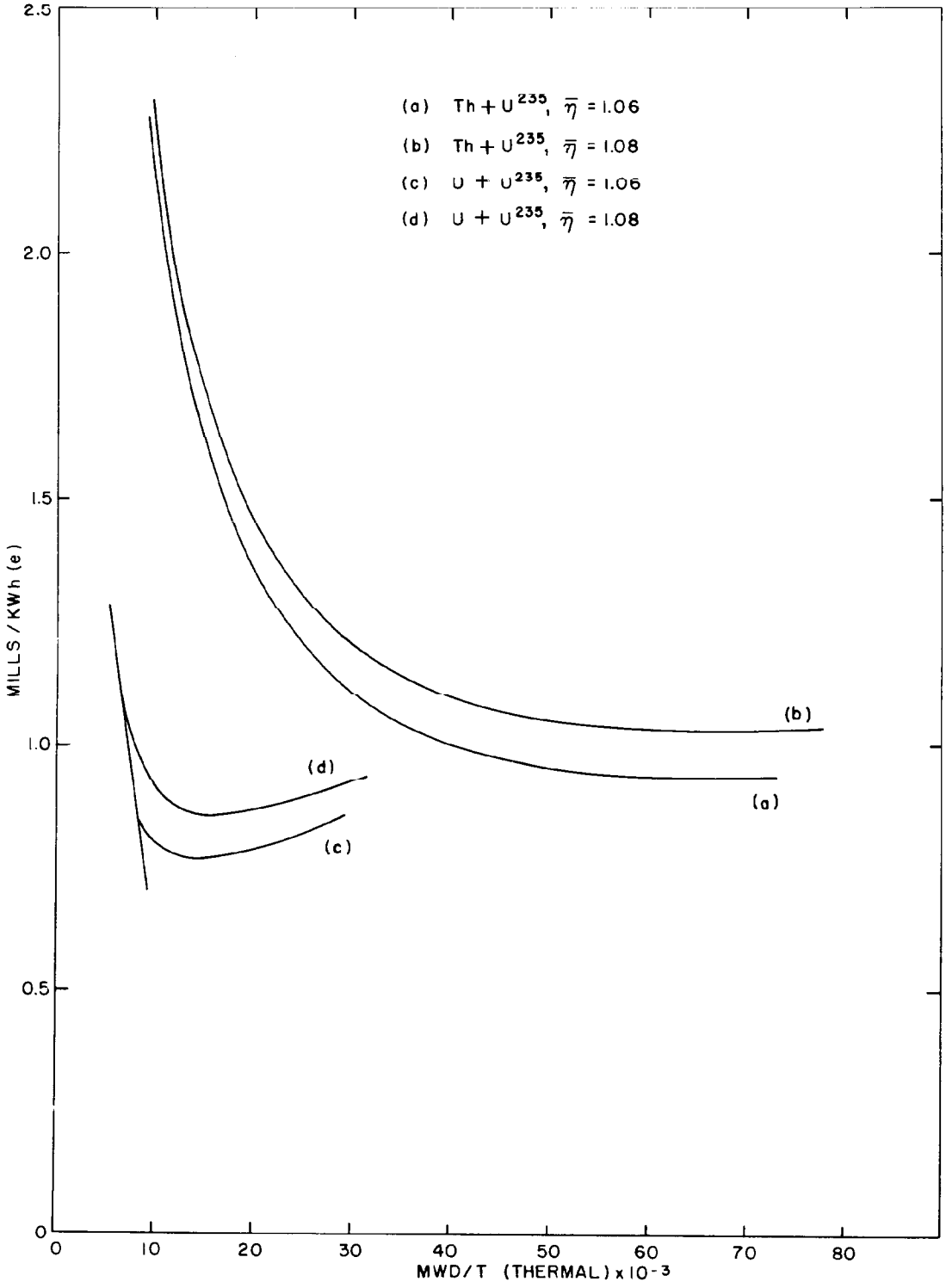


FIG. 14 PLUTONIUM PRICE

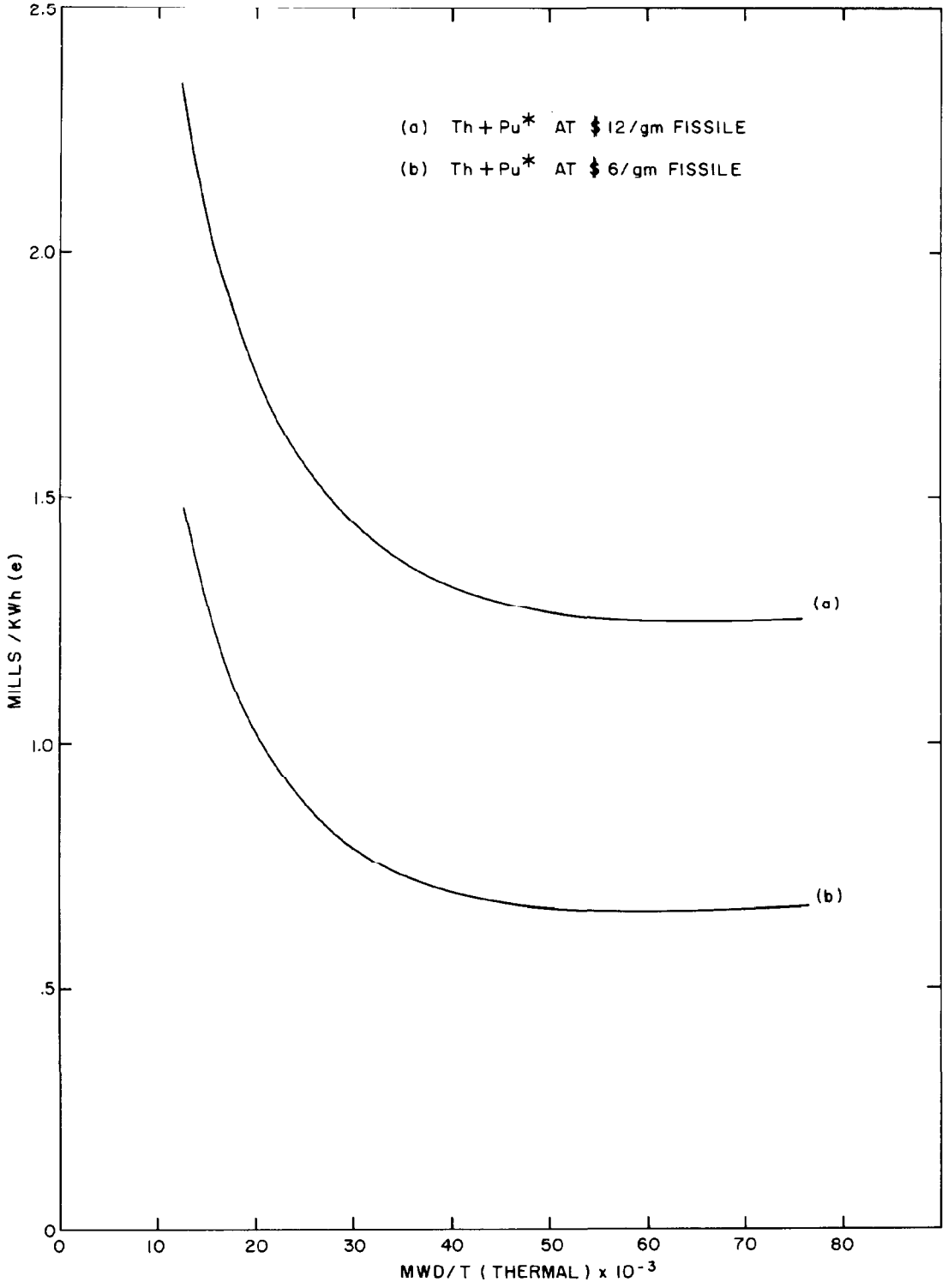


FIG.15 VARIATION OF BURNUP AND IRRADIATION WITH ENRICHMENT (U^{235}) AND FLUX

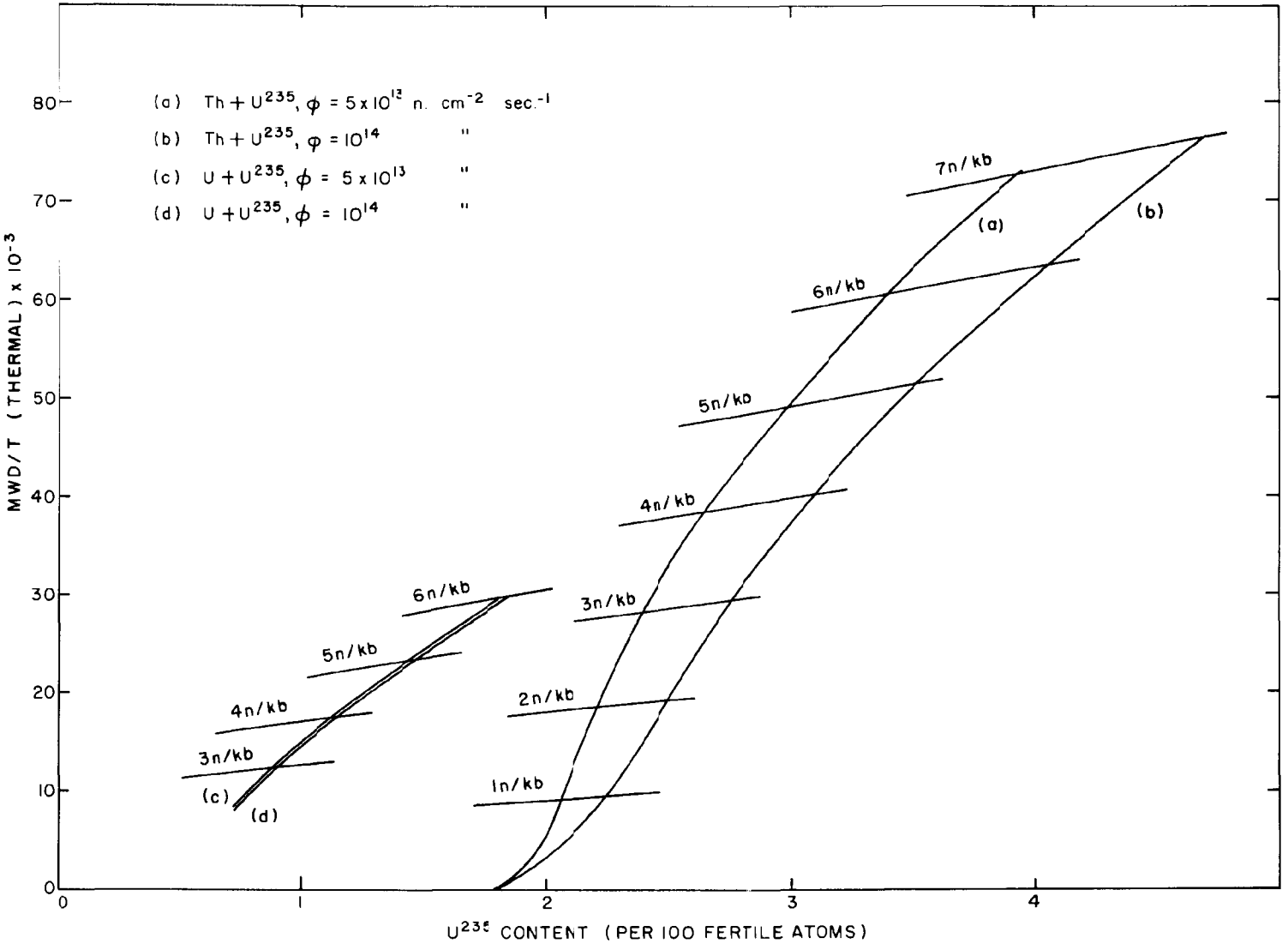


FIG. 16 BURNUP vs IRRADIATION FOR THORIUM + ENRICHMENT

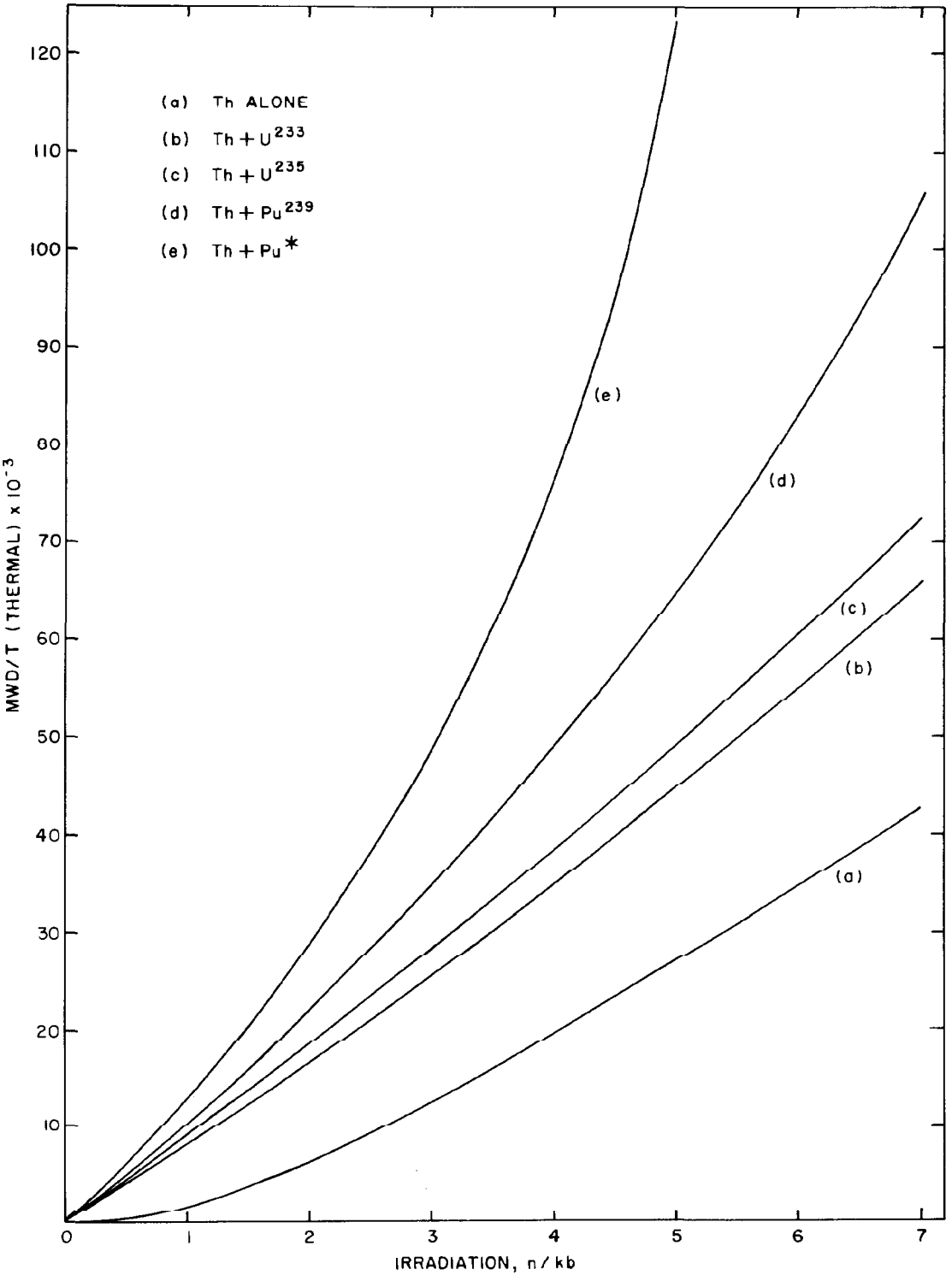
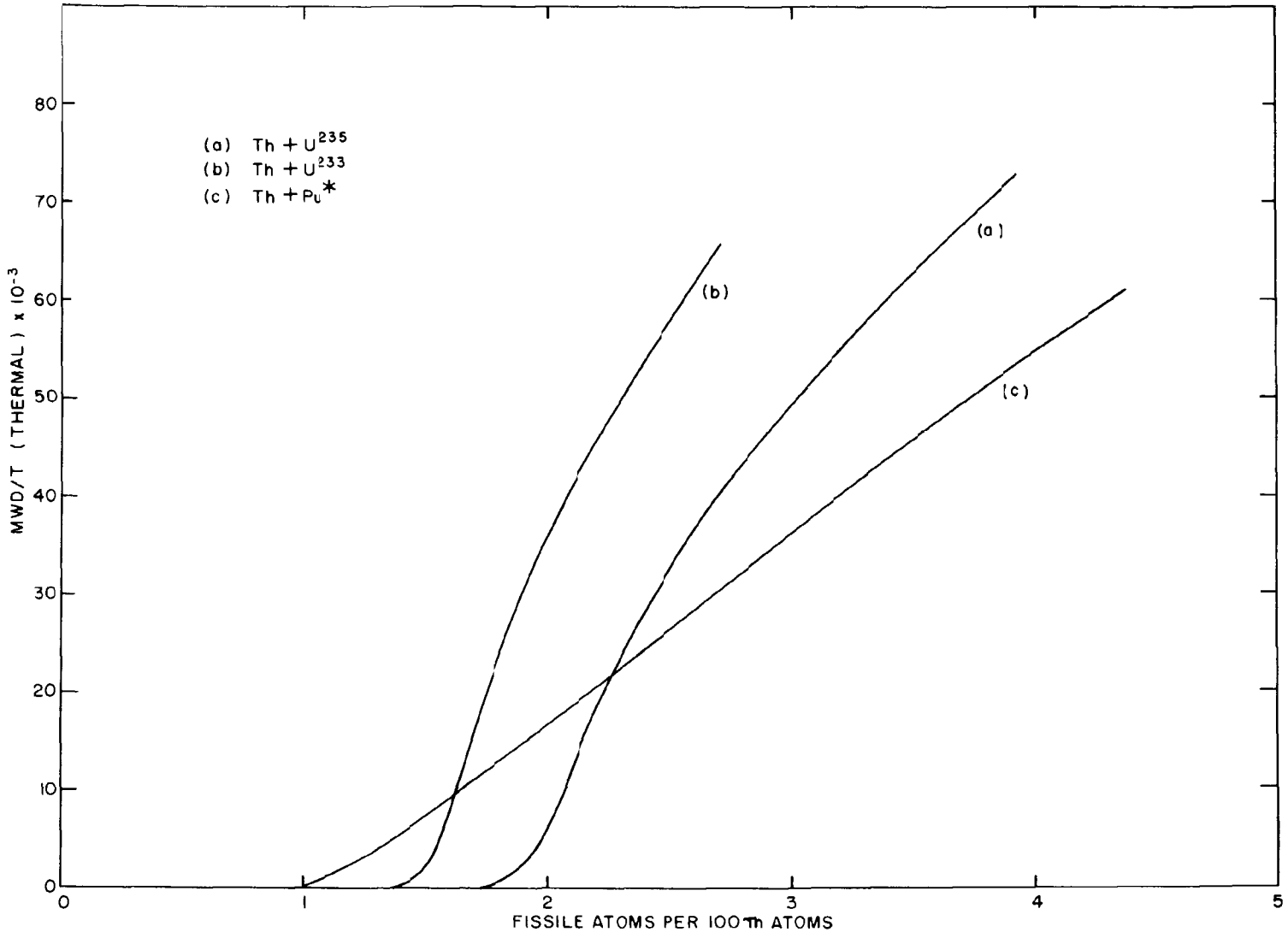


FIG. 17 BURNUP vs ENRICHMENT FOR THORIUM BASED FUELS



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