NUCLEAR FUEL CYCLE COST ANALYSIS USING PARAMETRIC VARIATION

by

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INTRODUCTION

Fuel cycle costs have been an area of nuclear power cost calculations in which investigators have relied on performance estimates to obtain reasonably adequate results. This is due to the variation in reactor types, fuel element configuration and composition, methods of fabrication and processing, and many of the economic variables involved. In addition, future technological advances and changing governmental policy concerning special nuclear materials and services have greatly affected the fuel cycle cost. Hence, it is important that as many of the values as possible involved in the fuel cycle cost be known.

Economics of the fuel cycle cannot be treated with precision in a general quantitative investigation. Factors such as reactor size, fuel enrichment, flux distribution, moderator, coolant, and others have a large effect on the final fuel cycle cost. This study is an investigation into the various parameters involved and a mathematical derivation of their relation to the total fuel cycle cost. From these relationships, a computer program has been written and some of the parameters varied to give an overall picture of the effect of these parameters on the final fuel cycle cost. This method is a compromise between knowing the core perform-

ance for a particular design and setting up a set of standard values that could be used in all estimates. In the first case, there is some doubt as to the actual operating parameters for any specific core, as well as the economic conditions that will prevail. The second case is subject to changing economic conditions and is relatively inflexible with respect to the choice of values that predict the performance of a reactor design. The parameter variation approach gives greater flexibility in solving the problem without an exact knowledge of core physics. Also a study of the effects of changing economic conditions on the fuel cycle cost can be made.

In this study many parameters are varied to determine the differential change in the final costs. The computer program was written for batch irradiation only. Cases for both private ownership of nuclear fuel and the present use charge method were also incorporated into the program.

The study of plutonium buildup and the costs of enriched uranium were made separately in order that they could be studied in more detail. For example, plutonium concentrations as functions of flux-time were calculated for various values of cross sections (corresponding to various temperatures) and resonance escape and nonleakage probabilities. In the case of computing the enriched uranium costs using the ideal cascade equation, the effect of changing natural

uranium cost, separative cost, and optimum waste concentration were studied. The result of these studies are presented in the Appendixes B and C.

The results obtained in this study should facilitate the estimation of fuel cycle costs for the light-water power reactors under a variety of economic conditions. Marginal cost errors also can be estimated. This study then should help utilities in preliminary nuclear power cost estimates.

REVIEW OF LITERATURE

Studies on fuel cycle economics have been treated in several different manners. Some have treated a specific reactor in detail while others have been concerned with general calculation of representative or reference reactors. In this thesis, a general reference reactor was considered and several of the parameters governing the economics of this reactor were varied. This allows one to determine the relative effect of each parameter on the fuel cycle cost.

The AEC has sponsored many studies in the area of nuclear power economics (11, 12, 13, 14, 15, 16, 17, 18, 19, 20). The Guide to Nuclear Power Evaluation was particularly helpful in laying a background and providing a set of ground rules for cost calculation (16, 17, 18). Other studies provided information on various steps during the fuel cycle along with methods for computing the cost incurred at these steps (11, 12, 13, 14, 15, 19).

Periodicals provide current data about operating reactors and new developments in the field (2, 3, 4, 6, 7, 8, 9). Nucleonics, Power Engineering, and Electrical World are some periodicals that include articles on nuclear power economics.

Benedict and Pigford (1) was the source used for the plutonium isotope buildup equations and the cascade equation. References 4, 7, 8, 9, 13, and 19 were used to compile data used in computing the fuel loading equation. Reference 10

was used as a check to some of the equations developed in this study.

Mullenbach (5) has an interesting book which discusses the history and present state of the nuclear industry, both from a public and private point of view. Herron (3) gives an account of several methods of performing toll enrichment and computes some costs based on these methods.

In general, the literature is mainly concentrated in government reports and periodical accounts of new developments pertaining to reactor economics. However, with the increasing use of nuclear reactors by private utilities, several private studies are available which have included calculations for both present and future times.

FUEL CYCLE COST ANALYSIS

The fuel cycle is the most significant cost connected with a power reactor after the plant structures have been erected and the equipment installed. This is due not only to the many steps and diverse technologies involved in the physical nature of the fuel cycle but also to the many economic factors involved. In the following sections analyses of the various processes and costs are presented in sequence as they occur in the fuel cycle.

Fabrication Cost

The fabrication cost as considered in this study consists of the conversion cost of UF_6 to the fuel material and the fabrication of the fuel elements. It was assumed that UO_2 fuel is used in the reactor and that conventional techniques are used in the fabrication step.

Conversion step

The cost of conversion to UO_2 is generally a function of the enrichment and the quantity of fuel undergoing conversion. Figure 1 shows a plot of the unit cost of conversion of UF_6 to UO_2 powder as a function of enrichment for some batch sizes. This curve is based on average vendor prices as compiled for the SENN reactor in 1962 and reported in Reference 14. The conversion cost includes the cost for

withdrawal and packaging of the UF_6 from the AEC, the cost of UF_6 cylinder rental and isotopic assay, the cost of scrap recovery and recycle back to the AEC, and the cost of transportation of the UF_6 to the conversion site. The conversion cost does not include any charge for loss of fuel material during the conversion process nor use charge on the fuel inventory.

Fabrication

The fabrication cost includes the cost of all hardware, the shaping and machining of the fuel material, the cladding of the fuel, assembly of the fuel elements, and the inspection and testing of the final fuel assemblies. For the particular case of UO_2 pellet fuel, the pelletization cost is sometimes calculated separately. This cost includes the pressing and sintering of the UO_2 pellets and the grinding of the pellets to insure tolerance requirements. In this study, the pelletization cost is included in the cost of the fabrication of the fuel assemblies.

The fabrication costs vary considerably. Some of the factors which have a bearing on the fabrication price are:

1. Quantity of fuel assemblies per batch lot
2. Size of the fuel assembly
3. Complexity of design
4. Tolerance requirements

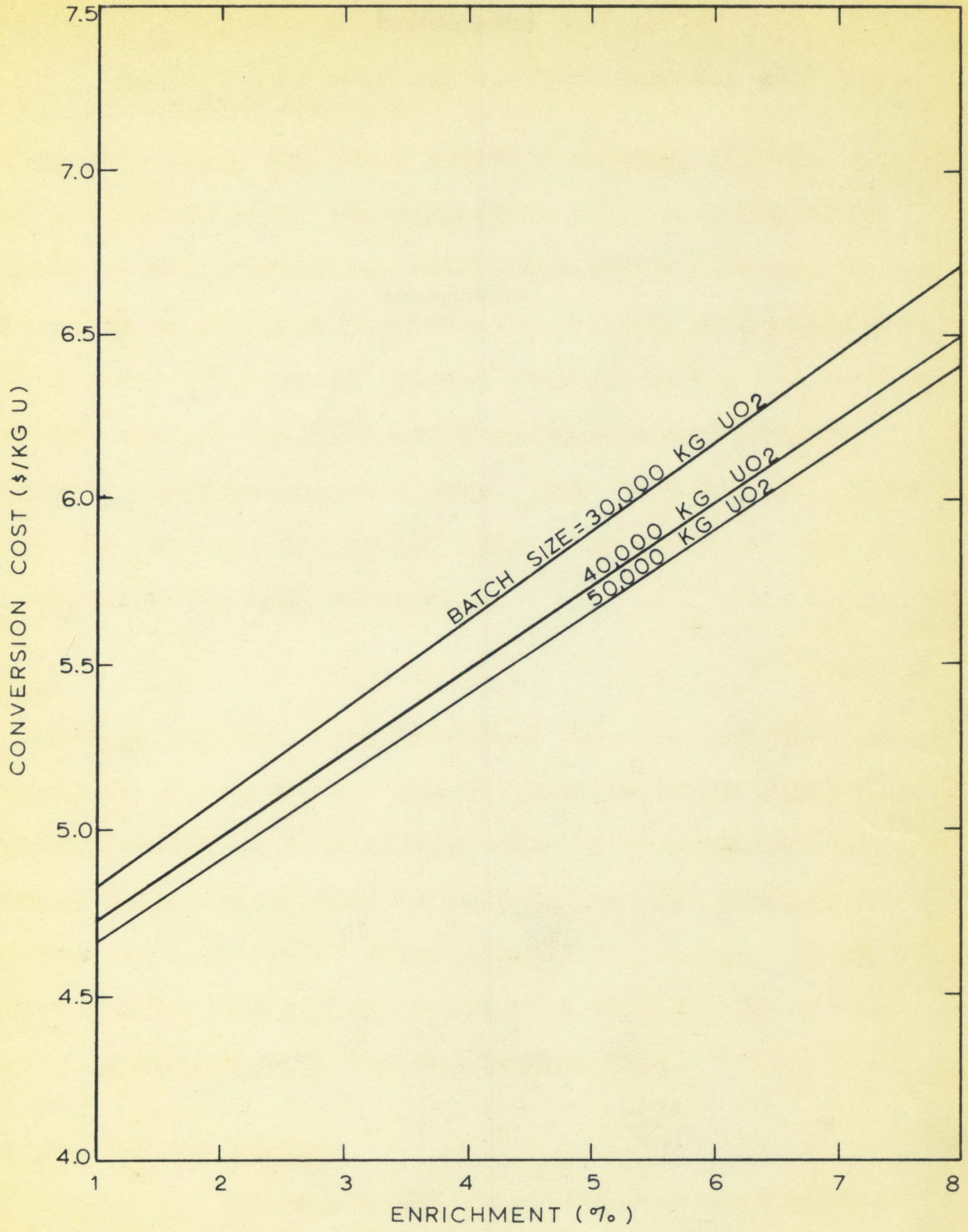

FIGURE 1 CONVERSION COST OF UF_6 TO UO_2 AS A FUNCTION OF ENRICHMENT AND BATCH SIZE

5. Specification requirements, and the type and rigidity of in-process inspection

6. Material requirements for cladding and other metal components

In this study the total fabrication cost includes all costs considered under the conversion step plus the costs incurred in the fabrication step. The costs incurred in the fabrication of the fuel elements are assumed to include the cost of scrap recovery of process overage during the fabrication step and any transportation costs incurred between conversion and fabrication sites. This cost does not include the losses incurred during the fabrication step as well as use charge on the fuel inventory.

Losses

Certain irrecoverable losses of the fuel material are incurred in the conversion and fabrication steps which must be accounted for as an expense. The AEC recommends some standard values to be used in calculating the fraction of fuel lost in each step. These are the following: 1% of the uranium passing through the conversion step and 1% of the uranium passing through the fabrication step.

Interest and use charge

During the conversion and fabrication steps considerable costs are incurred. The inventory of uranium must be financed in the case of private ownership of fissionable

material or a use charge rate charged if the fuel is leased from the AEC. The time factor which enters into the calculation of interest during the pre-reactor period depends mainly on the throughput rates for the conversion and fabrication processes. The AEC lists a value of 4 metric tons of uranium per month to be used for the calculation of the total fabrication time, i. e. conversion plus fabrication (16). Reference 14 gives a procedure for calculating fabrication time based on the quantity of uranium per batch size. This procedure presents a more realistic approach to present commercial practice in relation to batch size. The rule is given below, where X is batch size in metric tons.

$$\text{Time for total fabrication} = \begin{cases} 4 \text{ months if } X < 4 \\ X \text{ months if } 4 \leq X \leq 10 \\ (X/2) + 5 \text{ months if } X > 10 \end{cases} \qquad (1)$$

Both procedures were used in computing the fabrication time. The effects on the final fuel cycle cost are discussed along with the results of the cost calculation for batch irradiation.

Transportation of Fresh Fuel

Shipping charges for fresh fuel usually include the freight and insurance charges from the AEC site through conversion and fabrication steps to the reactor site. It is pointed out in Reference 14 that the various industrial converters usually include the shipping charge from the AEC

to the conversion site in the conversion charge. The present AEC suggestion for the computation of this charge is to assume a value of $3.00 per kg of uranium shipped. The breakdown gives a value of $1.50 per kg as shipping charge from the AEC to fabricator, and the same charge for transportation from fabricator to reactor site.

In this study, it has been assumed that the transportation cost from the AEC to converter and from converter to fabricator are included in the respective conversion and fabrication costs. The value of $1.50 per kg uranium was used for the calculation of the pre-reactor transportation charges. This value is somewhat arbitrary, but any specific charge is difficult to obtain unless the shipping distance is known and some of the factors which are subject to negotiation can be determined.

Reactor

The cost incurred at the reactor site can be directly related to: (1) burnup of fissionable material, (2) production of plutonium isotopes, (3) fuel management, (4) load factor and plant availability, and (5) use charge and/or interest rates. Each of these factors will be discussed briefly in this section and their relation to the final fuel cycle cost pointed out.

Burnup of fissionable material

The fission process which provides energy in the form of heat in a nuclear reactor also causes the U-235 content of the fuel to become depleted. The depletion can be viewed as a burnup of the fuel and hence an expense incurred during the time when the fuel is being irradiated. The burnup cost is computed by taking the difference in the value of the fuel charged to the reactor and the value of fuel at discharge. For enriched reactors the depletion of U-235 is dependent upon the integrated product of flux and time. A more common measure of the irradiation of the fuel is the burnup expressed in Megawatt-days per metric ton of fuel. The burnup expressed in this manner takes into account the contribution of the fission of any plutonium isotopes that have been built up in the reactor to the total heat rate. The relationship between the flux-time and the burnup in Mw-days per metric ton for the isotopes found in a nuclear reactor is derived in Benedict and Pigford (1).

Plutonium production

Plutonium production during the irradiation of the core is important because it can be reclaimed during the reprocessing and sold. Since Pu-239 and 241 are fissionable, they contribute to the energy output of the reactor. Pu-239 is produced as a result of neutron capture by U-238. The higher isotopes of plutonium (240 and 241) are also produced

during irradiation by neutron capture and can build up to appreciable fractions for long irradiation times. The equations describing the buildup of plutonium in a reactor are derived in Benedict and Pigford (1). These equations are listed in Appendix B. A computer program was written using these equations to determine the plutonium credit in calculating the fuel cycle costs.

Fuel Management

Several fuel management "schemes" have been proposed to create more favorable fuel cycle cost conditions during the irradiation period. Different types of fuel management affect fuel cycle costs through the technical-economic interrelationships which arise from the change in core composition, power density, flux distribution, and excess reactivity. Some of the schemes considered include: batch irradiation, out-in and in-out fuel movement and graded irradiation.

Batch irradiation

The batch fuel management is characterized by the loading, irradiation, and replacement of the whole core as a single unit. This is the simplest form of fuel management, however it is subject to certain economic and technical disadvantages. For a uniformily enriched core the neutron flux will have a significant spatial variation which results in an

unequal burnup across the core. Also large initial values of excess reactivity are required to attain reasonable core lifetimes. However, the advantage of the scheme is in its simplicity which can offset some of the advantages of a more complex type of management.

The batch irradiation schemes can be applied to uniformly enriched and zone enriched cores. For the zone enriched case, the fuel enrichment in each zone is chosen so that a flatter power density is obtained. The average burnup will be more uniform over the core and hence, the reactivity lifetime can be increased. The biggest disadvantage of zoned enrichment is that fuel of different degrees of enrichment must be fabricated and reprocessed separately.

Out-in fuel movement

In this method the fresh fuel is charged near the outer core positions and moved progressively toward the inner positions. This has the effect of flattening the power density across the core. The average burnup attained is greater since the reactivity is not as limited as in the batch case (11, 15). The main disadvantage is the downtime required for the movement of fuel. The downtime could be eliminated by technical advances in in-core fuel movement machinery. This method of fuel management has been indicated as a practical means of obtaining a more uniform power density and a better average burnup.

In-out fuel movement

This method is the reverse of the out-in method, and is the progressive movement of fuel elements from the inner core positions to the outer core positions. The resultant effect is a distorted flux distribution with large values of peak-to-average power ratios (11, 15). This method has the advantage of increasing reactivity lifetime because the fresh fuel is charged to a position of high importance in the core. The method is not presently practical because of the engineering difficulties in the heat removal for this kind of power distribution.

Graded irradiation

Graded irradiation schemes consist of periodic replacement of the most irradiated fuel elements among different local groups of fuel elements. Thus, each local area in the reactor consists of a group of fuel elements each of which has a different degree of burnup. In this way the fission products become uniformily distributed throughout the core and the fuel composition will stay essentially constant over the irradiation period (11). However, the frequent shutdowns required and the complex system of arranging the fuel elements in the core will tend to offset the gains made by using this type of management.

Use Charge and Interest

The use charge or interest accumulated on the fuel inventory over the core life contributes to the costs incurred during the irradiation time. The pre-reactor costs excluding the fuel inventory are usually financed over a time which includes a portion of the irradiation time. If the use charge applies then the charge on the fuel is over a period covering the core lifetime and the other pre-reactor costs can be weighted to a fraction of the core life. This fraction is proportional to the fraction of the pre-reactor costs which in turn contributes to the total fuel cycle cost. This is not strictly true since the assumption is that income from the sale of electricity during this time goes entirely toward the retirement of these costs.

For the case of private ownership the interest on the fuel inventory must also be considered. Since the purchase of fissionable material is very expensive and since the total fuel cycle cost calculation includes the resale value of the irradiated fuel, it is unlikely that the total income over the core life could meet this cost. The question of whether the interest is calculated on the unpaid balance or computed at a fixed rate on the original principle must be answered. In the case considered in this study the latter method is adopted. The former method can be reduced to the latter by an appropriately averaged interest rate.

Load factor and plant availability

The load factor and the plant availability affect the fuel cycle cost through the production of electricity during the core life. The load factor is the fraction of time per year that the plant can be considered to be operating at full power. The load factor varies from plant to plant depending on the local power demands. For this reason the AEC has suggested the value of 80% be taken for estimating fuel cycle costs (16).

The plant availability is the fraction of time per year that the plant can operate due to downtime for repairs and fuel loading or movement. By multiplying the load factor by the plant availability factor one can get a plant factor. In this study the designated load factor and the plant factor are taken to be equivalent.

Cooling Time

After irradiation in the reactor, the fuel is withdrawn and stored or "cooled" for a length of time to allow the activity to decrease to a level so that shipping and reprocessing can be facilitated. Benedict and Pigford indicate that the U-237 activity is the limiting factor in determining cooling time for natural or slightly enriched uranium irradiated to burnup fraction of the order of 1% (1). A common specification of the permissible activity remaining in separated and decontaminated uranium

is that the beta and gamma activity shall not exceed that of natural uranium in equilibrium with its short-lived daughters. The required cooling time can be calculated if the concentration of U-237 at the end of irradiation is known. This concentration depends on the U-236 concentration. Both depend on the flux and the corresponding capture cross sections. The cooling time is generally set at 120 days for computational purposes in most fuel cycle cost estimates and will be the value taken in this study.

Transportation of Irradiated Fuel

The difference in the cost of shipping irradiated fuel as opposed to unirradiated fuel is mainly due to the extensive shielding required and the increased insurance rates. Reference 13 gives an estimate of this cost for two different cask sizes. It is concluded that the main unknowns are the insurance rates and the negotiable carrier rates. For the purposes of this study a unit charge of $12.45 per kg of U was assumed. This is the value listed in Reference 16.

Chemical Reprocessing

Chemical reprocessing is required to recover the uranium and plutonium from the fission products and to restore the fuel to a useable form. This is usually an economic necessity for uranium enriched fuel. The reprocessing step has been divided into three catagories: (1) the dissolution

and chemical separation of the fuel from the fission products, (2) the conversion of the recovered uranium and plutonium to desired forms, and (3) the losses incurred in each of the above steps.

Separation cost

The separation of the fuel material from the fission products is usually performed by aqueous chemical processes. Nonaqueous methods such as extraction with liquid metals, vacuum volitization of molten metals, oxidative slagging, and electrorefining are being considered for future use. In this study, it has been assumed that a Purex, Redox, or other process giving uranyl and plutonyl nitrate products is used.

The separation cost can be calculated using the following equation.

$$\text{Separation cost } (\$) = K\,(W/R + T) \qquad (2)$$

where, K = The daily charge of the separation plant. This charge is not fixed and is subject to periodic escalation.

W = The weight of uranium in a processing batch in metric tons.

R = The processing rate in metric tons per day. This is a function of the enrichment of the fuel and varies as shown in Figure 2.

T = The turnaround time in days. This is the time needed to cleanup from one batch and get ready for the next.

The equation given above is used by the AEC for computational purposes and is based on a hypothetical plant with a maximum throughput of one metric ton per day. The daily charge K to operate the plant is escalated. When the charge was first initiated in March 1957, it was $15,300 per day. This value included $6850 for depreciation and $8450 for the cost of operation, waste storage, and overhead (13). The depreciation portion is escalated on the basis of the Engineering News Record construction cost index using the value of 694.8 for July 1956 as a base. The remaining portion is escalated according to the U.S. Bureau of Labor Statistics wholesale price index for inorganic chemicals by using the value of 135.3 for July 1956 as the base (13).

It should be pointed out again that these costs are based on a hypothetical plant with a capacity of 1000 Kg. U per day for natural or very slightly enriched uranium. This was done by the AEC to make the price charged more compatible with a plant that industry might build, hence, they are greater than the AEC's "actual" costs because the scale of operation is much greater than that assumed for the conceptual plant. In this study, K values of 17,000, 20,000, and 23,000 dollars per day were used to see the resulting effect on the fuel cycle cost. Fuel Services, Inc. has built a private plant with a similar price structure to the AEC's (6).

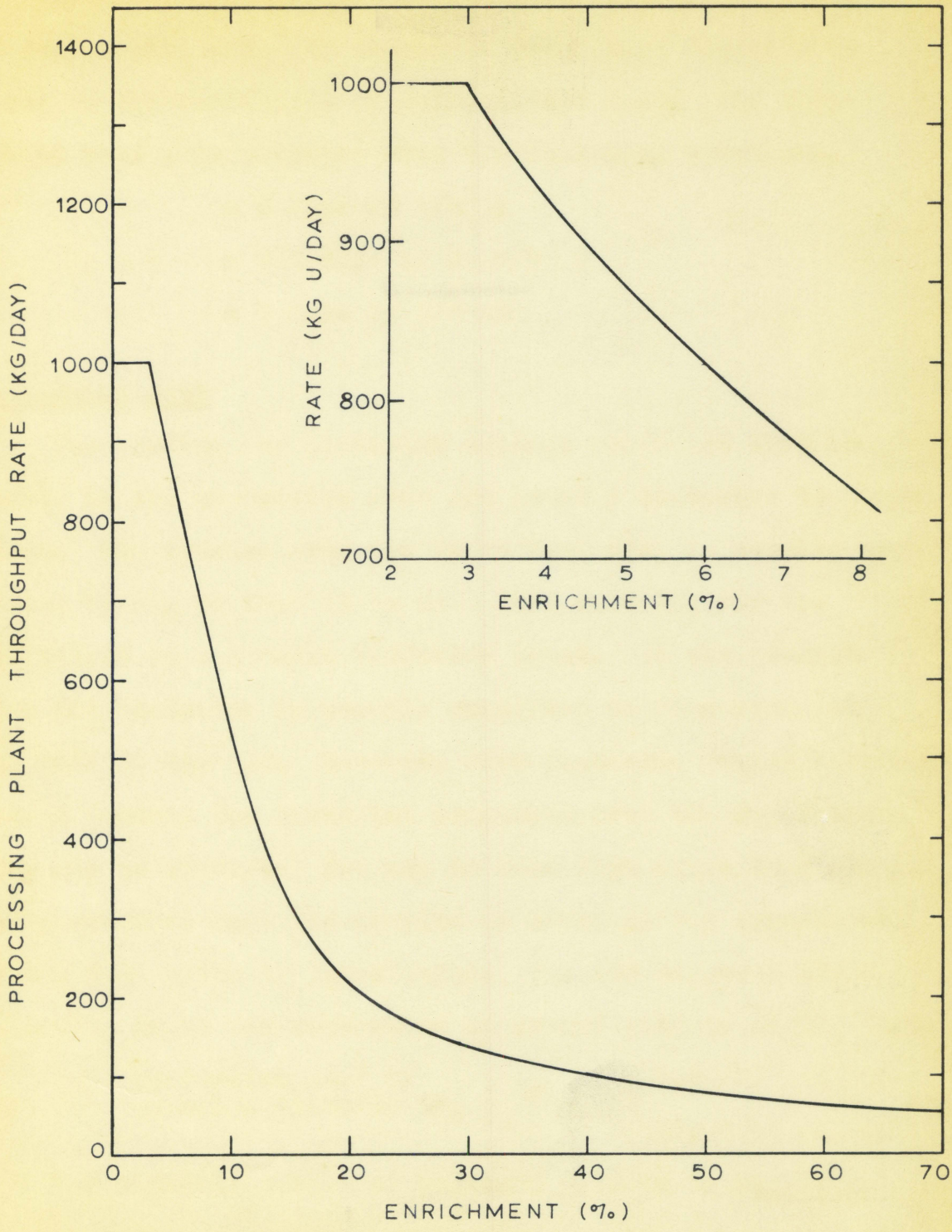

FIGURE 2. PROCESSING PLANT THROUGHPUT RATE AS A FUNCTION OF ENRICHMENT

The processing rate R is shown in Figure 2 as a function of fuel enrichment. It should be noted that Figure 2 is based on the enrichment of unirradiated fuel. The turn-around time T is computed from the following equations.

$$T \begin{cases} = 2 \text{ days if } W/R < 2 \\ = W/R \text{ days if } 2 \leq W/R \leq 8 \\ = 8 \text{ days if } W/R > 8 \end{cases} \qquad (3)$$

Conversion cost

The uranium and plutonium product compounds that are formed in the separation step are usually converted to other forms. The uranium from the separation step is usually converted to UF_6 so that it is in a form suitable for re-enrichment in a gaseous diffusion plant. At the present time the plutonium is usually converted to plutonium metal and sold to the AEC. However, when plutonium fueled reactors become common, the plutonium compounds from the separation step may be converted for use in some form other than metal. The conversion cost for uranium is based on the enrichment of the fuel prior to irradiation. The AEC suggests the following costs for conversion of uranyl nitrate of UF_6 (16).

$$\text{conversion cost of uranyl nitrate to } UF_6 = \begin{cases} \$5.60/\text{kg} & E \leq 5\% \\ \$32.00/\text{kg} & E > 5\% \end{cases} \qquad (4)$$

The conversion cost of plutonyl nitrate to plutonium metal is taken as \$1.50 per gram of contained plutonium (16). In this study it has been assumed that the products from the

separation step are plutonyl and uranyl nitrates although other compounds with similar conversion costs could also be assumed.

Losses

The irrecoverable losses associated with the separation and conversion steps are specified separately for uranium and plutonium. The AEC recommends the following values to be used as standards in calculating the cost in fuel cycle estimates (16).

Uranium losses:	1% of material passing through chemical separation step
	0.3% of material passing through conversion step
Plutonium losses:	1% of total plutonium passing through chemical separation
	1% of remaining material passing through the conversion step

It is assumed that the losses occur at the completion of the process under consideration and are charged on the basis of the value of the ultimate product.

Plutonium Credit

Presently the plutonium that is produced in power reactors is sold to the government on a guaranteed market agreement. The price of plutonium produced in this manner has varied greatly from its inception. For instance prior to June 1962, the buy-back price varied from $30 to $45 per

gram of plutonium metal depending on the concentration of Pu-240. From July 1, 1962 to June 30, 1963 the price was $30 per gram regardless of isotopic composition (13). These prices are based on the sale of classified or weapons grade material. Unclassified plutonium price was set at $12 per gram of metal from 1957 to June 30,1963. Presently the price is $9.50 per gram of metal which terminates January 1, 1971 when the AEC will cut off its guaranteed buy-back policy (6).

In this study plutonium prices of $8, $12, and $16 per gram of metal were used. This is a reasonable range of values that should cover the anticipated fluctuation of plutonium prices in the near future. Many experts believe that when the government ceases to buy back plutonium on a guaranteed basis that the price will decrease to some minimum before the breeder-converter economy becomes prominent in determining plutonium prices. The breeder-converter economy is still at least 20 years away by most estimates.

Another approach is to base the plutonium price on the "fuel value" of plutonium. The fuel value is determined by comparing its value as a fuel to U-235. By this criterion Equation 5 gives the price of Pu-239 based on the cost of energy relative to the energy released by U-235.

$$\text{Price Pu-239} = \frac{\text{Price U-235}(1+\alpha_{25})}{(1+\alpha_{49})} \cdot \frac{A^{25}}{A^{49}} \qquad (5)$$

For example if the price of U-235 is taken as$12.00/gram, the price of plutonium based on its fuel value is $8.88/gram.

The price of plutonium will be determined more by economic factors and technological advances in the near future than by its fuel value. The governmental support of plutonium has inflated its value so that when the AEC terminates its guaranteed buy-back policy the price will be due largely to forces of supply and demand. The government will still be indirectly involved by its development program of plutonium fuels and reactor concepts, and probably the limited purchase of weapons material.

Reenrichment of Uranium

Soon after the fuel has been reprocessed and converted it is returned to the AEC for reenrichment in the gaseous diffusion plants. Because the AEC owns the fissionable material, they request it back in the form that it was initially released, i. e. UF_6. The cost of enriching uranium is based on the ideal cascade equation for isotope separation in a gaseous diffusion plant. This equation is presented in Appendix C along with some studies on the effect of changing the optimum waste concentration and the unit separative charge on the cost of enriched uranium. The present costs for enriched uranium are shown in Figure 3. This curve

illustrates the cost per kg of uranium as UF_6 for the total range of enrichments as based on the 1962 price schedule of the AEC (20). The inset shows the enriched uranium prices over the range of enrichments considered in this study, i. e. from natural to 8%. Note the almost linear portion from 2 to 8% enrichment.

Use Charge

Under the Atomic Energy Act of 1946 and its amendment in 1954, only the United States government could own any special nuclear material under the jurisdiction of the U.S. In 1965 the act was further amended to allow private ownership of nuclear materials starting in 1969 and becoming mandatory after 1973. However, the present situation is still to lease the fuel from the AEC at a rate of 4.75% per year of its average value. This charge applies to all special nuclear materials which include enriched uranium, plutonium and U-233.

The fuel inventory upon which this charge applies includes all materials within the possession of the leasee. However, any plutonium produced by the reactor is not subject to this charge. During irradiation, the U-235 concentration of the fuel changes, and hence the value of the fuel inventory changes. It is usually assumed that the change in U-235 concentration is linear with time. The use charge is computed using the average value of the fuel during the irradi-

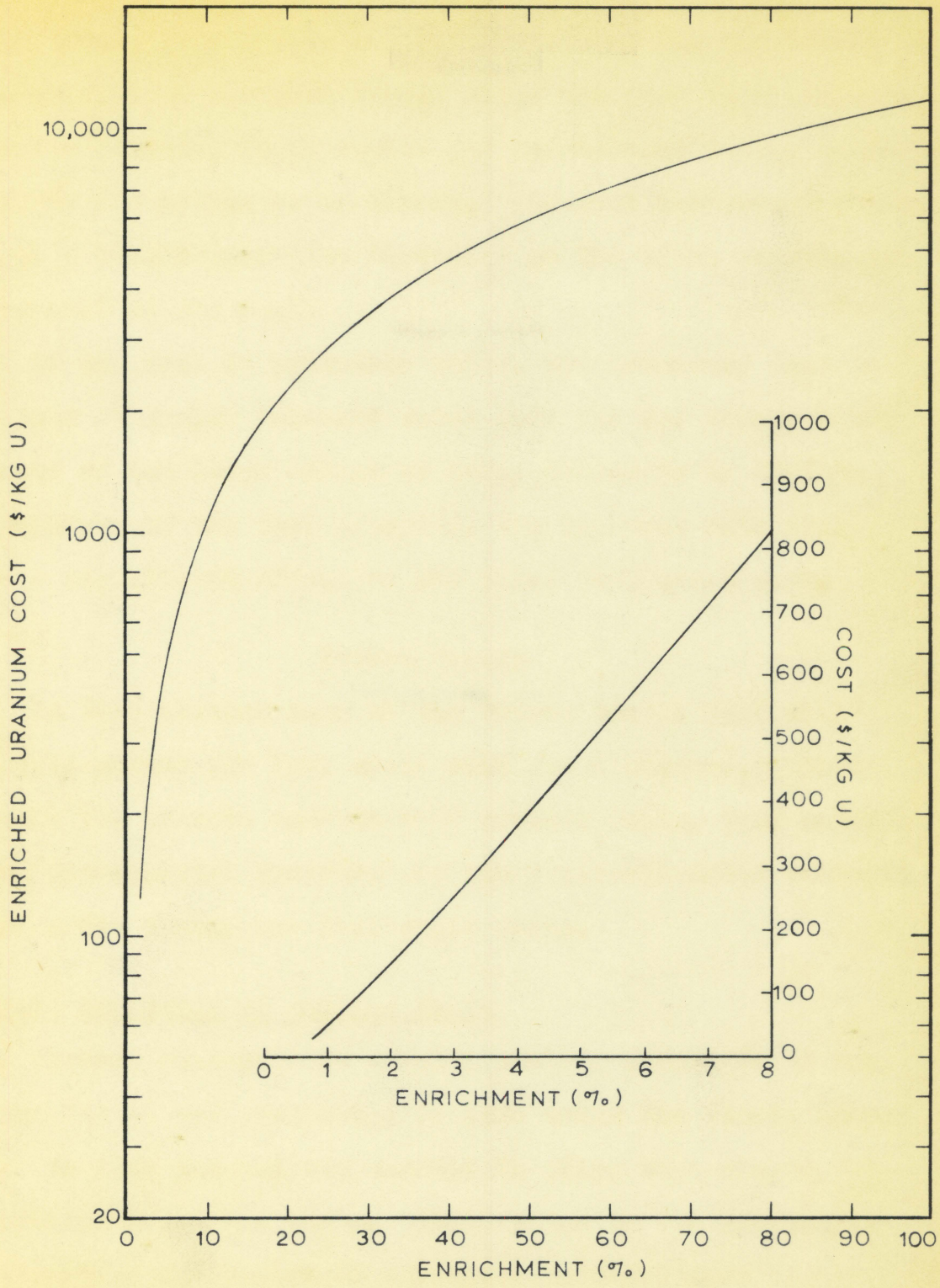

FIGURE 3. ENRICHED URANIUM COST AS A FUNCTION OF ENRICHMENT FOR UF_6

ation time. This charge can be significant for relatively high burnups on enriched fuel. After the fuel is discharged from the reactor, it is cooled and reprocessed during which time the use charge is in effect. Chemical reprocessing also can be a costly operation depending on the type, amount, and enrichment of the fuel.

If the fuel is privately owned, the inventory must be financed at higher interest rates than the use charge rate. Because of the large amount of money needed to be financed in purchase of the fuel material, the interest rate will have a significant effect on the final fuel cycle cost.

Future Trends

In this section some of the future trends that will possibly affect the fuel cycle cost are discussed. These include the private ownership of nuclear fuels, toll enrichment, governmental controls and other miscellaneous concepts which could change the fuel cycle costs.

Private ownership of nuclear fuels

Private ownership of special nuclear materials in the United States was prohibited in 1946 under the Atomic Energy Act. In 1965 the act was amended to allow the private ownership of nuclear fuels. This action by the government is a part of the desire to stimulate peaceful uses of the atom, as well as the encouragement of private industry to

take over operations in which the government has been the sole provider.

Private ownership of nuclear fuels has its advantages and disadvantages. First, the present use charge rate of 4.75% is relatively cheap compared to the 6% or more that would probably have to be paid for the financing of fuel purchase. However, the fuel purchase price could be partially paid during the irradiation time which could give rise to a lower effective interest rate. Another influence on the fuel cycle cost due to private ownership will be the loss of guaranteed buy-back for plutonium. Because the present demand for plutonium is largely military and because of the large stockpiling by the government of fissionable materials, the plutonium price at present is higher than if it were supported on a strictly competitive market. The advent of the converter-breeder reactor systems should increase the value of plutonium again.

Because private ownership has forced toll enrichment, it is expected that the price of enriched uranium will decrease in the near future. Private ownership will allow the true cost of nuclear power to be evaluated without the aid of artificial governmental prices and reduced costs.

Toll enrichment

The AEC has announced that toll enrichment will be available after January 1, 1969. Toll enrichment is the

contracting of the enriching of uranium supplied by the customer to a desired degree. Herron (3) has proposed two methods of toll enrichment for reducing the cost of the fuel cycle. He based his methods on the present AEC diffusion plants and the assumption that a constant output of weapons grade U-235 was the primary goal of these plants. The savings comes primarily from the ability to supply natural uranium by buying it on the world's market at a cost below the price of the AEC.

In the first method, the customer supplies the feed material to give the desired amount of enriched U-235 plus any additional feed needed to maintain the output of weapons grade material. The customer also pays for the incremental separative work required to keep the tailing concentration from increasing.

In the second method, the separative work is held constant and the tailing concentration is allowed to rise. However, more feed material must be supplied in this case to maintain a constant output of weapons grade material.

The above schemes are adaptations of the present system of enrichment. In the future when there are enough power reactors to support private enrichment plants, the need to maintain the highly enriched output will not be a requirement. Since most of the present day power reactors use slightly enriched fuel, it is probable that enrichment needs only to

be carried to a few per cent in these private plants. This should cause a reduction in costs due to the smaller number of stages needed.

Governmental controls

Because of the circumstances in which atomic energy came into being, the governmental control of nuclear fuels and nuclear devices was a necessity in the interest of national security. Recently, however, the need for such stringent governmental controls has been questioned. Mullenbach (5) states that "history reveals no link between national security and government ownership was ever explicitly established on the public record; instead the link was accepted, largely as an article of faith and doctrine". As it turned out, government ownership of fissionable materials necessitated administrative devices for getting enriched uranium into private hands at a reasonable use charge. Industry has found government ownership profitable with the low use charge rates that have prevailed. The Atomic Energy Act also requires the AEC to pay a fair share to any person lawfully producing fissionable material. This policy tends to make the present form of government ownership more attractive than private ownership because the AEC has temporarily set plutonium prices well above the fuel value of the material. The main indirect effect of private ownership would be the

termination of the guaranteed market for by-product plutonium from privately owned power plants. Because of the present low demand for plutonium, it is presumed that the price will fall until the recycling of plutonium in reactors can be proven economically competitive. In general, industry will not find the transition to private ownership profitable because of the present low use charge and the relatively high price of plutonium.

Another effect of the governmental control is the operation of services such as the diffusion plants, reprocessing plants, and other facilities associated with the preparation of nuclear fuels. However, it is the policy of the Commission to supply the services and materials needed by industry only to the extent that they are unavailable commercially. Whenever practical, the government intends to reduce or eliminate its sales and services as industrial sources become available. Prices and charges are based upon the principle of the recovery of full costs and indirect expenses plus an added factor. This added factor includes overhead, interest on investment, process improvement and expenses not subject to absolute determination. The scale of the government's operation makes many of its services very cheap in comparison to a private industrial effort at the present time. The savings passed on to the customer is usually not easily determined and is one of the reasons that

the "true" competitive nature of nuclear power cannot be readily established.

One of the possibilities that may develop to reduce the fuel cycle cost is the use of blended fuel. This is done by blending the uranium from the reprocessing plant which is depleted in U-235 with higher enriched fuel so that the net final enrichment is that desired for the reactor. Possible reduction in cost should be realized because of the direct conversion of reprocessed uranium to the form of the fuel rather than through the intermediate, UF_6. Since the UF_6 returned to the AEC must satisfy stringent specification, the chemical separation must obtain a high degree of separation, especially between the uranium and plutonium (16, 17). Hence, the relaxation of purity requirements in the reprocessing step could be a cost savings.

PROCEDURE

The method used to study the fuel cycle unit energy cost was the systematic variation of several economic parameters. Such a parametric investigation facilitates the evaluation of a case study and allows additional flexibility for possible future economic conditions. From such a study the relative influence of the fuel cycle cost variables can be obtained and an insight into the economic incentives can be gained.

Computations of the fuel cycle costs followed the costing procedure of the AEC with some modifications. These basic methods were put into equation form and programmed for the IBM-7074 computer. The flow diagrams for the main and subprograms are illustrated in Appendix A. The fuel cycle costs were calculated for batch type management for both private and AEC ownership of fuel material. The results of these studies are presented separately and then compared. Table 2 illustrates the values and ranges of the parameters considered in this study.

The fabrication cost for this study was assumed to be independent of the batch size being processed. This is not generally the case but serves to simplify the procedure.

Several auxiliary functions were used to facilitate the calculation of some intermediate expenses. This was done primarily to limit the number of computer inputs as well as

to increase the flexibility of the program. These auxiliary functions which are discussed in this section are: (1) fuel loading as a function of plant size (Mwth) and enrichment (E), (2) enriched uranium cost as a function of enrichment, (3) production of plutonium as a function of burnup (B) and enrichment, (4) separation plant throughput rate as a function of enrichment, and (5) unit conversion cost of UF_6 to UO_2 as a function of enrichment.

Table 1. Range of variables and value of constants used in this study

Parameter	Variable Range	Constant Value
Reactor size	200-1600 Mwth	-------
Initial enrichment	2.0-8.0%	-------
Fuel loading	-------	Equation 6
Unit cost of enriched uranium	-------	Equation 8
Conversion cost of UF_6 to UO_2	-------	Equation 10
Fabrication cost	50-150 $/kg U	-------
Average burnup	10,000-40,000 Mwd/Mt	-------
Conversion loss	-------	1%
Fabrication loss	-------	1%
Thermal efficiency	26-34%	-------
Transportation unit charge, fresh fuel	-------	$1.50/kg U

Table 1 (Continued)

Parameter	Variable Range	Constant Value
Plant load factor	70-100%	-------
Buildup of plutonium isotopes	-------	Equations 11-14
Transportation unit charge, irradiated fuel	-------	$12.45/kg U
Processing plant daily charge	17,000-23,000 $/day	-------
Processing plant capacity	-------	Equation 9
Conversion of uranium, unit cost	-------	Equation 4
Conversion of uranium, loss	-------	0.3%
Conversion of plutonium, unit cost	-------	$1.50/gram
Conversion of plutonium, loss	-------	1.0%
Uranium loss in chemical separation	-------	1.0%
Plutonium loss in chemical separation	-------	1.0%
Price of plutonium metal	8-16 $/gram	-------

Fuel loading

The fuel loading of several operating reactors and some of the proposed reactors of the BWR and PWR types was com-

piled and plotted as a function of their thermal megawatt rating. Thus the value of the fuel inventory can be calculated. In Table 2 a tabulation is given for operating reactors and their parameters as used in this compilation. Table 3 illustrates the fuel loading from a price list by General Electric and is based on a 30% thermal efficiency (7). Table 4 gives fuel loading data taken from "reference reactors" used in other economic studies. Figure 4 is a plot of the fuel loading versus the plant size for the data presented in Tables 2, 3, and 4.

Table 2. Parameters for some actual reactors

Reactor	Type	Mwth	Kg U	(%)	Fuel	Reference
Yankee	PWR	540	20,880	3.4	UO_2	8, 13
Conn. Yankee	PWR	1473	70,100	3.6	UO_2	8
Dresden	BWR	700	51,500	1.5	UO_2	8, 13
Big Rock Point	BWR	240	11,700	3.2	UO_2	8
Humbolt Bay	BWR	165	13,700	2.6	UO_2	8, 13
Bodega Bay	BWR	1008	67,700	2.7	UO_2	8
Dairyland	BWR	165	8,600	3.4	UO_2	8
Malibu	PWR	1473	67,600	3.8	UO_2	8
San Onofre	PWR	1347	58,000	3.6	UO_2	8
Nine Mile Point	BWR	1538	95,000	---	UO_2	8
Oyster Creek	BWR	1600	95,000	---	UO_2	4, 8
SENN (Italy)	BWR	507.8	46,400	2.0	UO_2	8, 13
SENA (France)	PWR	825	39,300	3.25	UO_2	8

Table 3. Fuel loading of G.E. reactors from G.E. price list

Mwe	Mwth at 30% Eff.	Fuel loading, Kg U
50	167	10,730
100	333	20,600
200	667	41,100
250	834	51,300
300	1000	61,500
350	1168	72,500
400	1331	83,800
500	1670	107,300
600	2000	129,000
700	2336	153,800

Table 4. Reference reactors used in some economic studies and the parameters assumed for these reactors

Type	Mwth	Kg U	Enrichment	Fuel	Reference
PWR	810	41,700	3.34%	UO_2	12
BWR	690	52,300	1.50%	UO_2	12
PWR	85	6,680	3.30%	UO_2	19
PWR	555	32,760	3.10%	UO_2	19
PWR	925	55,380	3.20%	UO_2	19
BWR	65	5,326	2.20%	UO_2	19
BWR	508	41,400	1.90%	UO_2	19
BWR	980	56,377	1.70%	UO_2	19

An equation was fitted to the points in Figure 4 by assuming that a straight line would represent the reactors of the same enrichment. This gives a generating equation which is linear in enrichment and sweeps out a family of curves of the form:

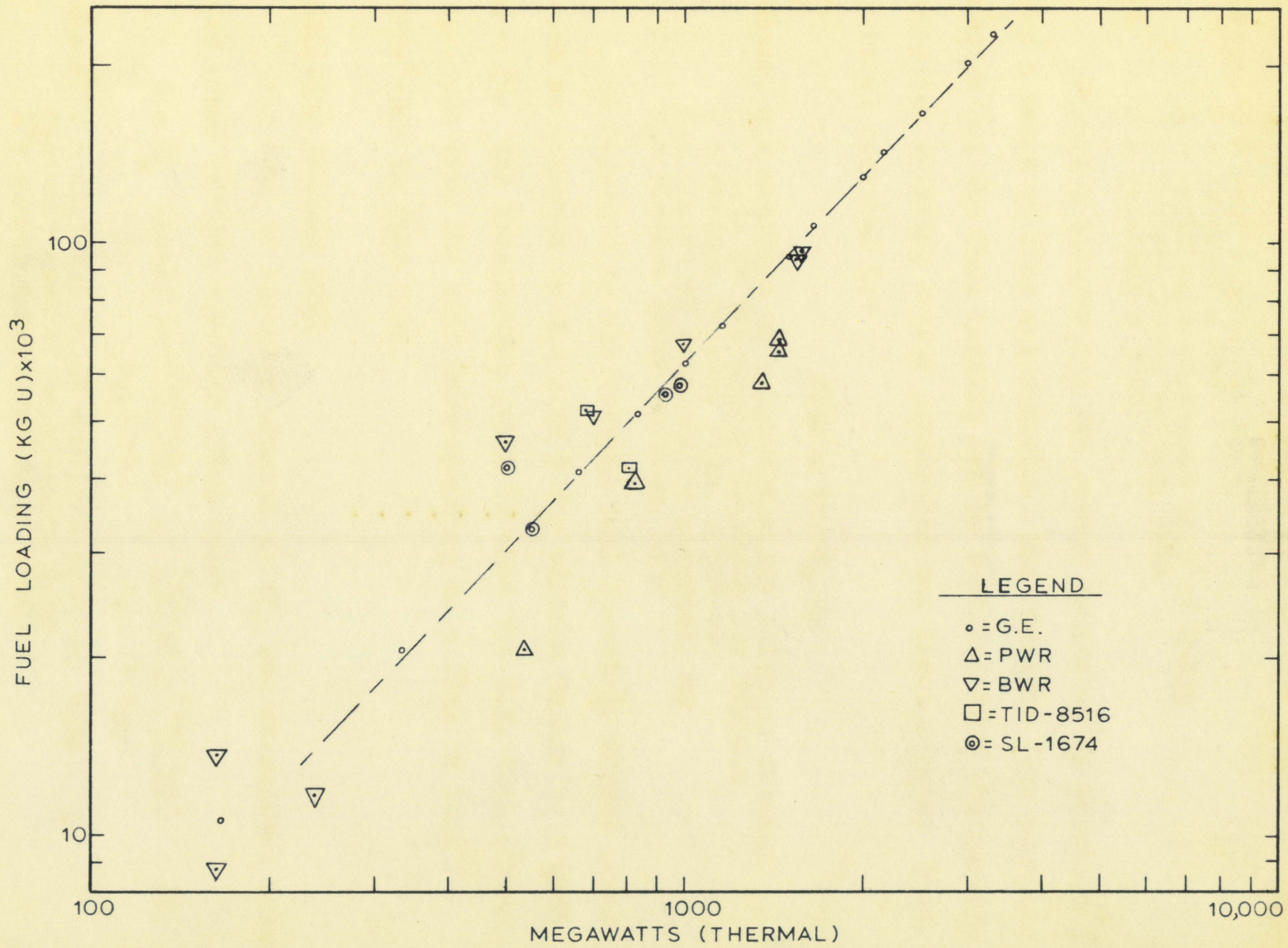

FIGURE 4. FUEL LOADING FOR SOME ACTUAL AND HYPOTHETICAL REACTORS

$$y = (K/E)X + C \qquad (6)$$

where, y = fuel loading in kg U
K = constant = 148
E = enrichment expressed in % of U-235
X = thermal power rating, Mwth
C = constant = 3000

Figure 5 illustrates the curves generated by Equation 6 for a range of fuel enrichments. The straight line approximation for the fuel loading can be verified from the general equation relating energy production and fission rate. This general equation is:

$$Mwth = A \cdot \phi \cdot W_e \cdot \sigma_f \qquad (7)$$

where, A = constant of proportionality relating fission rate to the energy released per fission
ϕ = average thermal flux, n/cm^2-sec
W_e = weight of fissionable material, kg
σ_f = fission cross section, cm^{-2}

In Figure 6 is illustrated fuel inventory versus plant size as computed by Equation 7 for various values of ϕ with E = 3%. One interesting point is that the G.E. data points coincide with the line corresponding to a flux of 1×10^{13} n/cm^2-sec on this plot.

Enriched uranium cost

The cost of enriched uranium as UF_6 was calculated using the ideal cascade equation given below.

$$C = C_E \quad (2x-1) \ln \frac{x(1-x_{wo})}{x_{wo}(1-x)} + \frac{(x-x_{wo})\,(1-2x_{wo})}{x_{wo}\,(1-x_{wo})} \qquad (8)$$

where, C = cost per kg of enriched uranium, $/kg
C_E = unit cost of separation, $/kg
x = atomic concentration of product

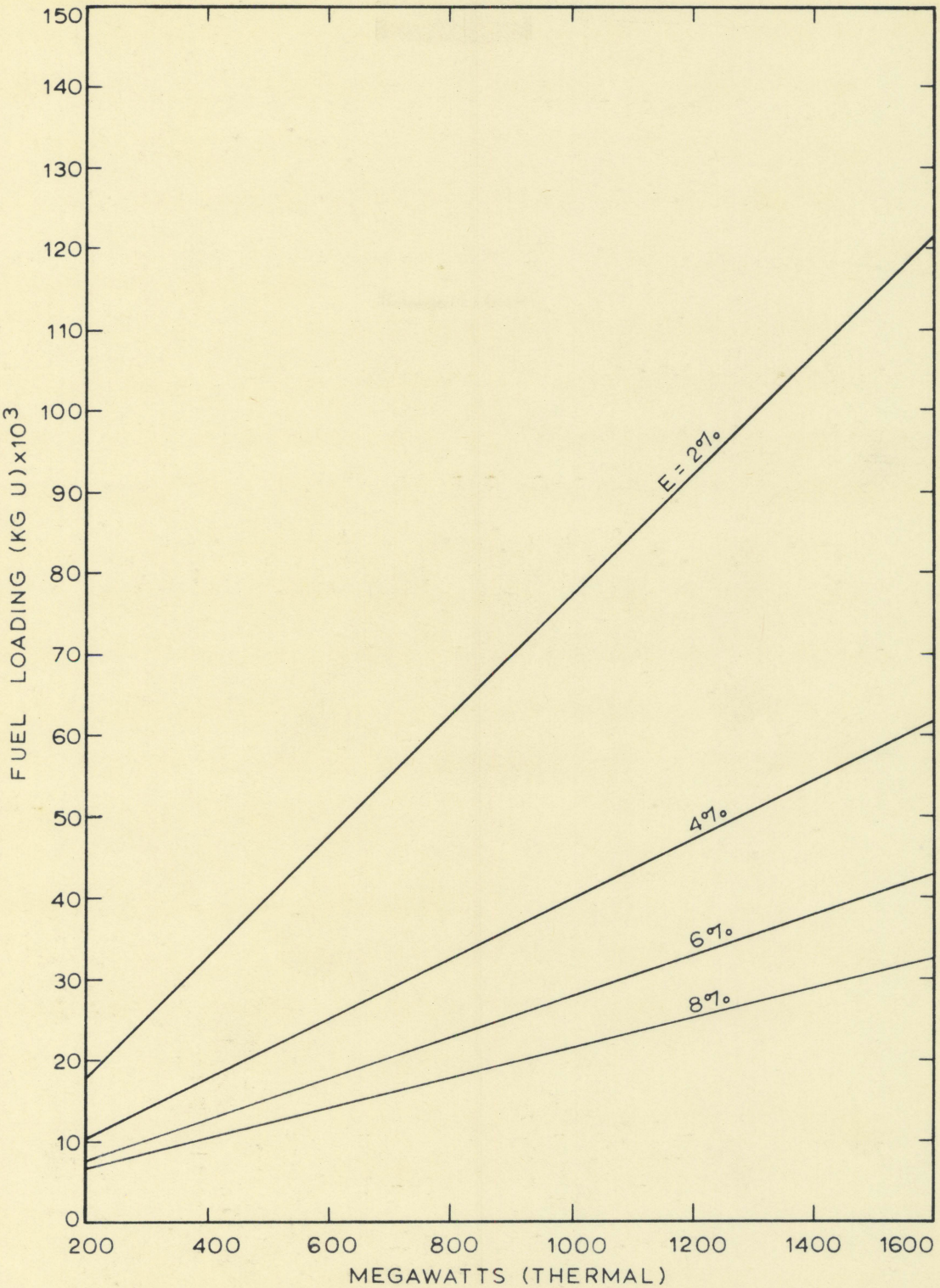

FIGURE 5. REACTOR FUEL LOADING AS A FUNCTION OF PLANT SIZE AND ENRICHMENT

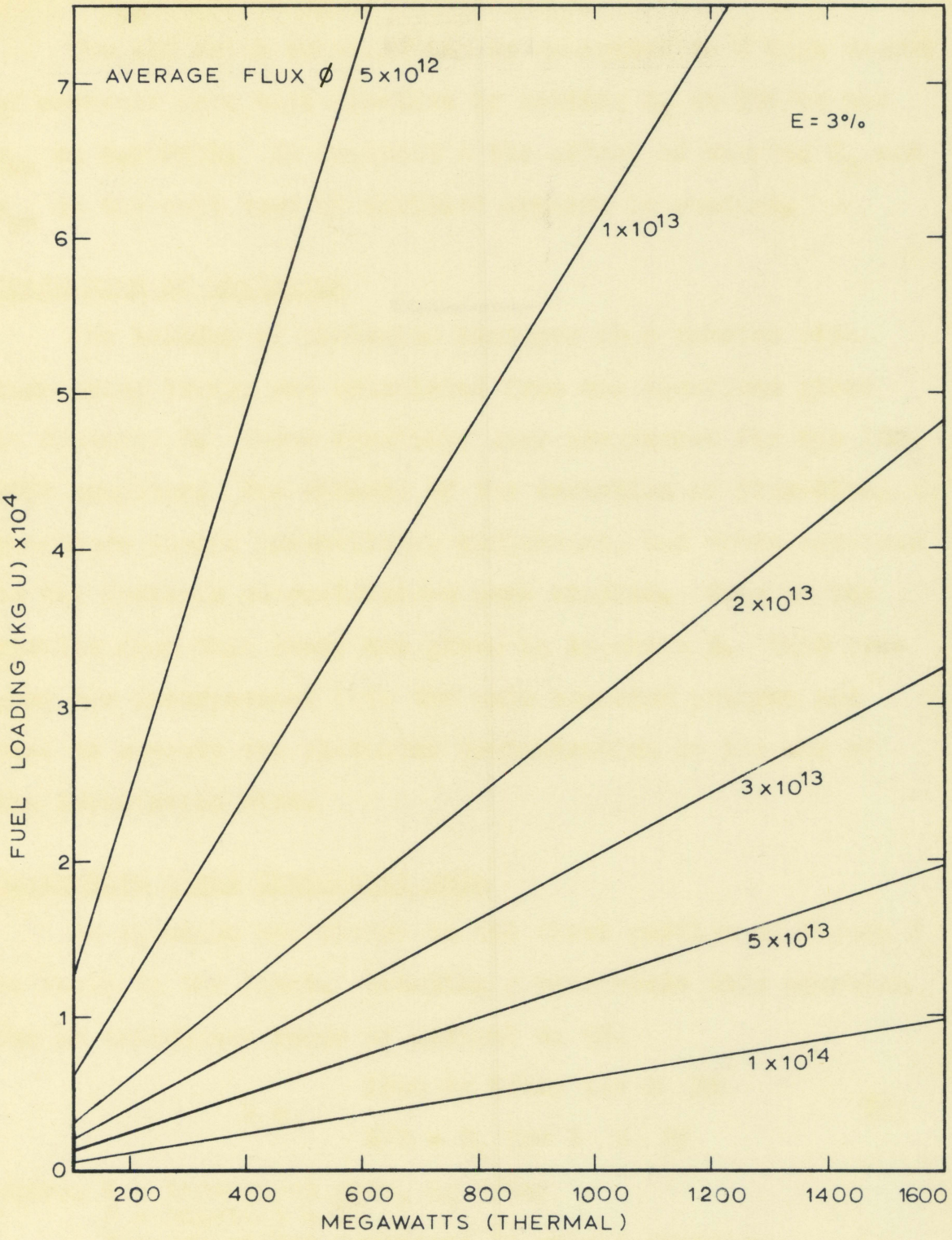

FIGURE 6. FUEL LOADING AS A FUNCTION OF AVERAGE THERMAL FLUX AND PLANT SIZE FOR E=3%

x_{wo} = optimum waste concentration

The AEC price schedule can be generated to a high degree of accuracy from this equation by setting C_E at \$30/kg and x_{wo} at 0.002531. In Appendix C the effect of varying C_E and x_{wo} on the unit cost of enriched uranium is studied.

Production of plutonium

The buildup of plutonium isotopes in a reactor with increasing burnup was calculated from the equations given in Appendix B. These equations were programmed for the IBM-7074 computer. The effects of the variation of flux-time, resonance escape probability, enrichment, and cross sections on the isotopic concentrations were studied. Some of the results from this study are given in Appendix B. This program was incorporated into the main computer program and used to compute the plutonium concentration at the end of the irradiation time.

Separation plant throughput rate

An equation was fitted to the first portion of Figure 2 as shown in the inset. Equation 9 represents this equation for an enrichment range of natural to 8%.

$$R = \begin{cases} 1000 \text{ kg U/day for } E \leq 3\% \\ S/E + B_1 \text{ for } 3 < E < 8\% \end{cases} \qquad (9)$$

where, R = throughput rate, kg U/day
S = constant = 16
E = enrichment expressed in weight fraction
B_1 = constant = -550

Since only integral values of enrichment were used in this study, the maximum relative error is 2.1% at E = 4% over the range that Equation 9 is applicable.

Unit conversion cost of UF_6 to UO_2

This cost varies from vendor to vendor. Therfore, the average prices illustrated in Figure 1 were used. Because of the limited range of batch sizes, the 40 metric ton curve was assumed to be representative of the functional form of the fitted equation. For the same reason the conversion cost was assumed to be independent of the batch size. The following equation was used to generate the unit conversion cost.

$$C_c = ME + B_2 \qquad (10)$$

where, C_c = unit conversion cost, \$/kg U
M^c = constant = 0.25
E = enrichment in % of U-235
B_2 = constant = 4.475

The results of the computer studies are presented in the form of curves. These curves indicate the variation of the fuel cycle cost as the parameters are varied over their ranges. The curves are plotted so that they can be used in combination to calculate the fuel cycle cost for any given set of parameters. Also many of these curves are plotted as correction factors to be used to correct the normalized fuel cycle costs.

DISCUSSION OF RESULTS

The results of the computer runs for batch type fuel management considering private ownership and use charge situations are presented in a series of curves. These curves are arranged so that a rapid calculation can be made of the fuel cycle cost for a particular set of parameters. A comparision is made between the private ownership case and the use charge case to illustrate the difference in fuel cycle costs that might be expected in the transition to private ownership.

Private ownership case

For the private ownership case only the batch type of fuel management was studied in detail. The results are based on the set of reference parameters listed in Table 5. These parameters are arbitrarily choosen although they correspond to a consistent set at present state of technology.

Table 5. Parameters of reference reactor for this study

Parameter	Value
Thermal megawatt rating	600 Mwth
Fabrication cost	$100/kg U
Thermal efficiency	30%
Load factor	80%
Processing plant daily charge	$20,000/day
Price of plutonium	$12/gram

In Figure 7 is illustrated the fuel cycle cost for the reference reactor as a function of average burnup and enrichment. This curve is used as a basis in calculating the fuel cycle costs for other combinations of parameters. Note that the fuel cycle cost increases with increasing enrichment and decreasing burnup. This general trend will be evident in many of the curves in this study. It should also be noted that the values of burnup for a given enrichment are not always compatible, but serve to illustrate the effect of these parameters on the fuel cycle cost.

Figures 8 to 11 are the correction curves used to correct the reference reactor fuel cycle cost for other plant sizes. Each curve is plotted as a function of plant size and burnup for a given enrichment. The correction for a given value of enrichment is largest for low burnups and small reactor sizes. At large plant sizes the lower values of burnup give a greater effect on the fuel cycle cost. This is to be expected since for the reference case the larger values of burnup lie in the flatter portion of the curve. Hence, the correction for large plants will be less for greater values of burnup. In Figure 12 is emphasized the magnitude of this correction by comparing the fuel cycle cost for the 200 and 1600 Mwth plant sizes.

The curve illustrated in Figure 13 is a means of correcting the reference case for other values of thermal effi-

ciency. In using this curve one takes the fuel cycle value from Figure 7, projects it from the proper line and then reads the adjusted value of the fuel cycle cost from the ordinate axis. This gives the fuel cycle cost at the desired thermal efficiency. In Figure 14 is given the correction for the fabrication cost when it is different from the reference plant value of $100/kg. This curve is plotted as a function of burnup and is independent of enrichment. The magnitude of the correction is less than 0.7 mills/kwhr for all cases.

In Figures 15 to 18 are illustrated the correction to the fuel cycle cost for various plutonium prices. These curves are plotted as a function of burnup for each value of enrichment. The correction involved is of the order of 0.2 mills/kwhr for the maximum case. Note that as the enrichment increases the lines become steeper thus indicating a greater sensitivity to the price of plutonium. Figures 19 through 22 show the processing plant correction to the reference plant fuel cycle cost. These curves are plotted as a function of burnup for the various fuel enrichments. The relative correction is small, the maximum being less than 0.08 mills/kwhr. The load factor correction to the fuel cycle cost is shown in Figures 23 through 26. These curves can be used to adjust the reference fuel cycle cost to other values of load factor.

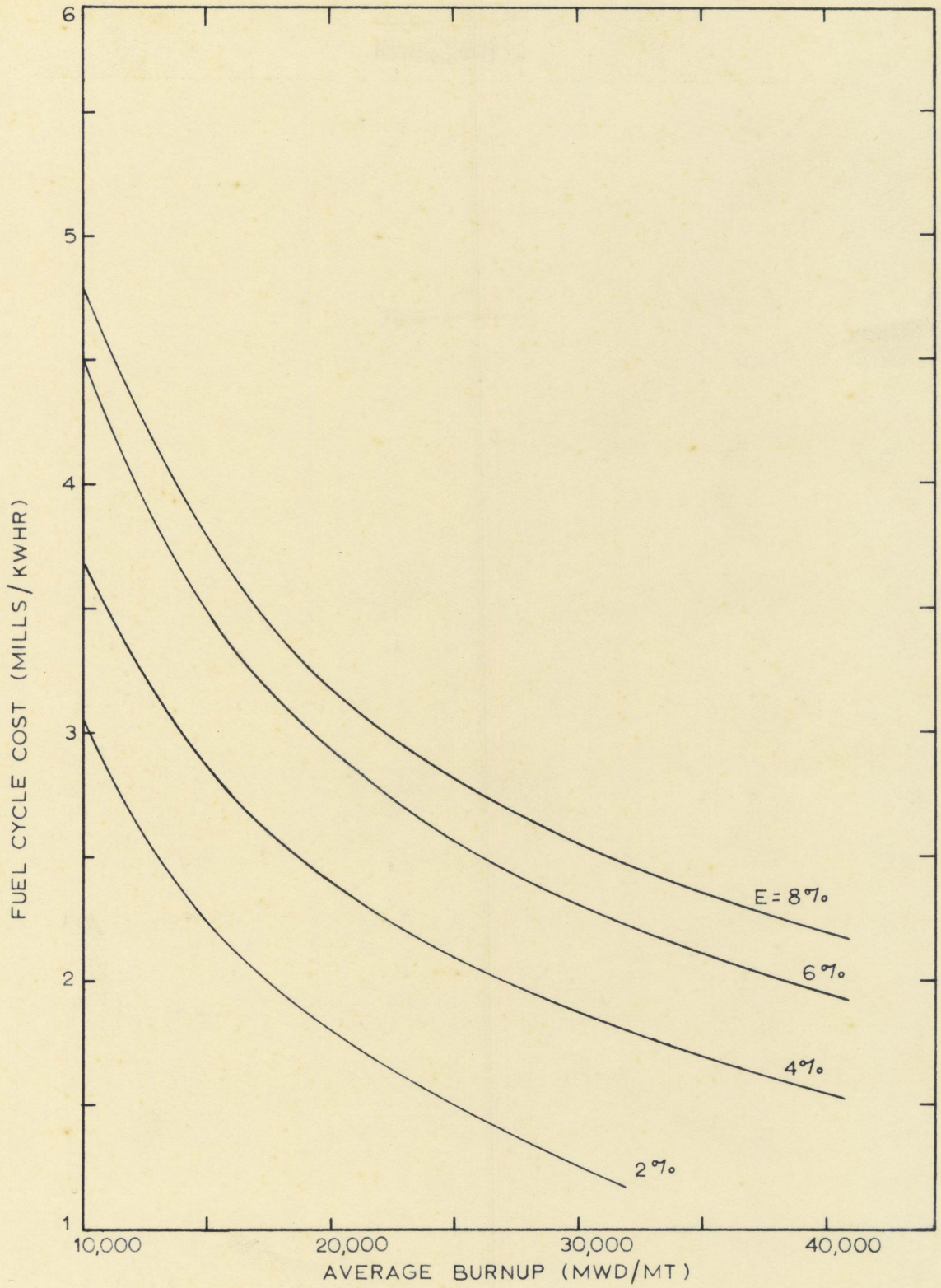

FIGURE 7. FUEL CYCLE COST FOR 600 MWTH PLANT

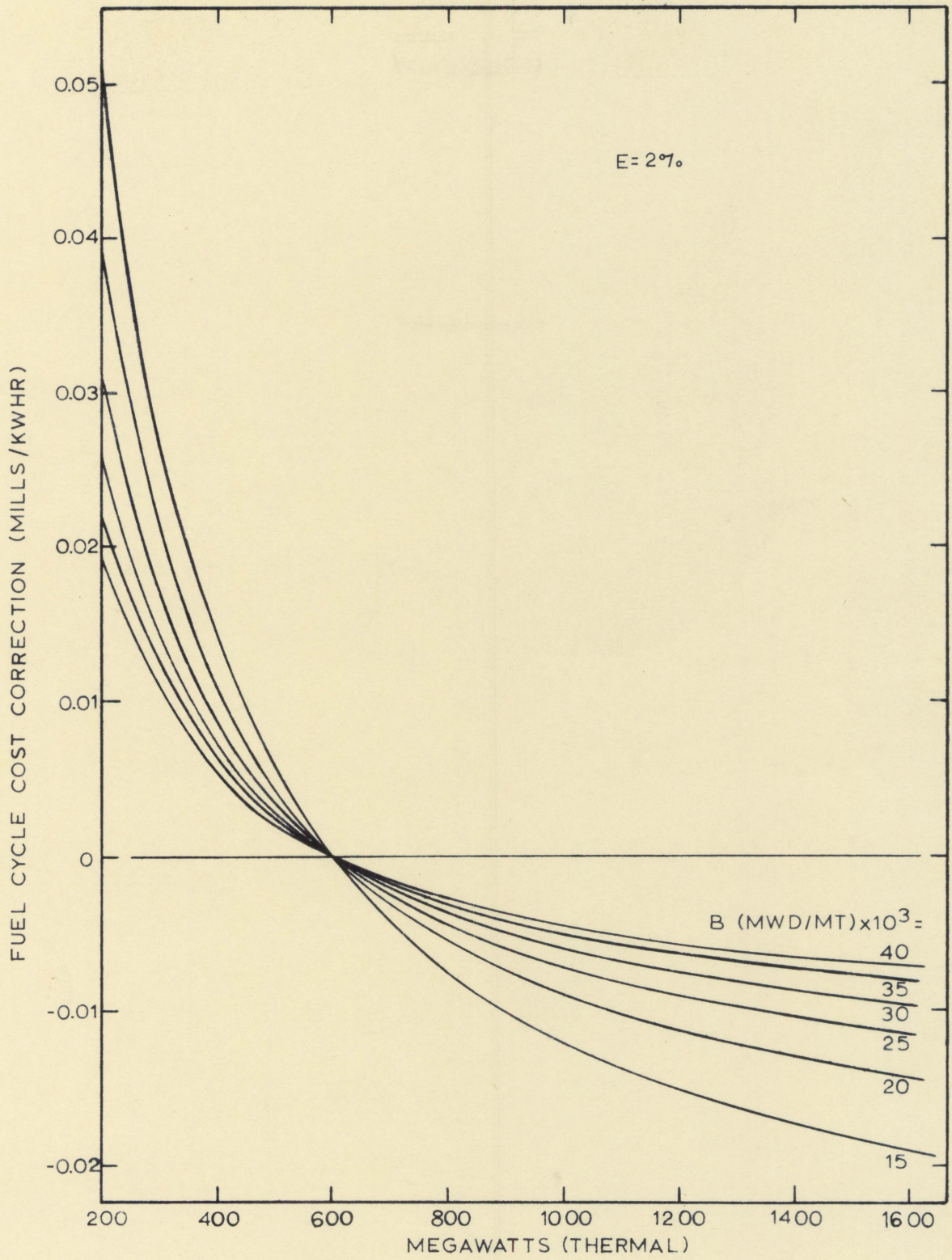

FIGURE 8. PLANT SIZE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF SIZE AND BURNUP FOR E=2%

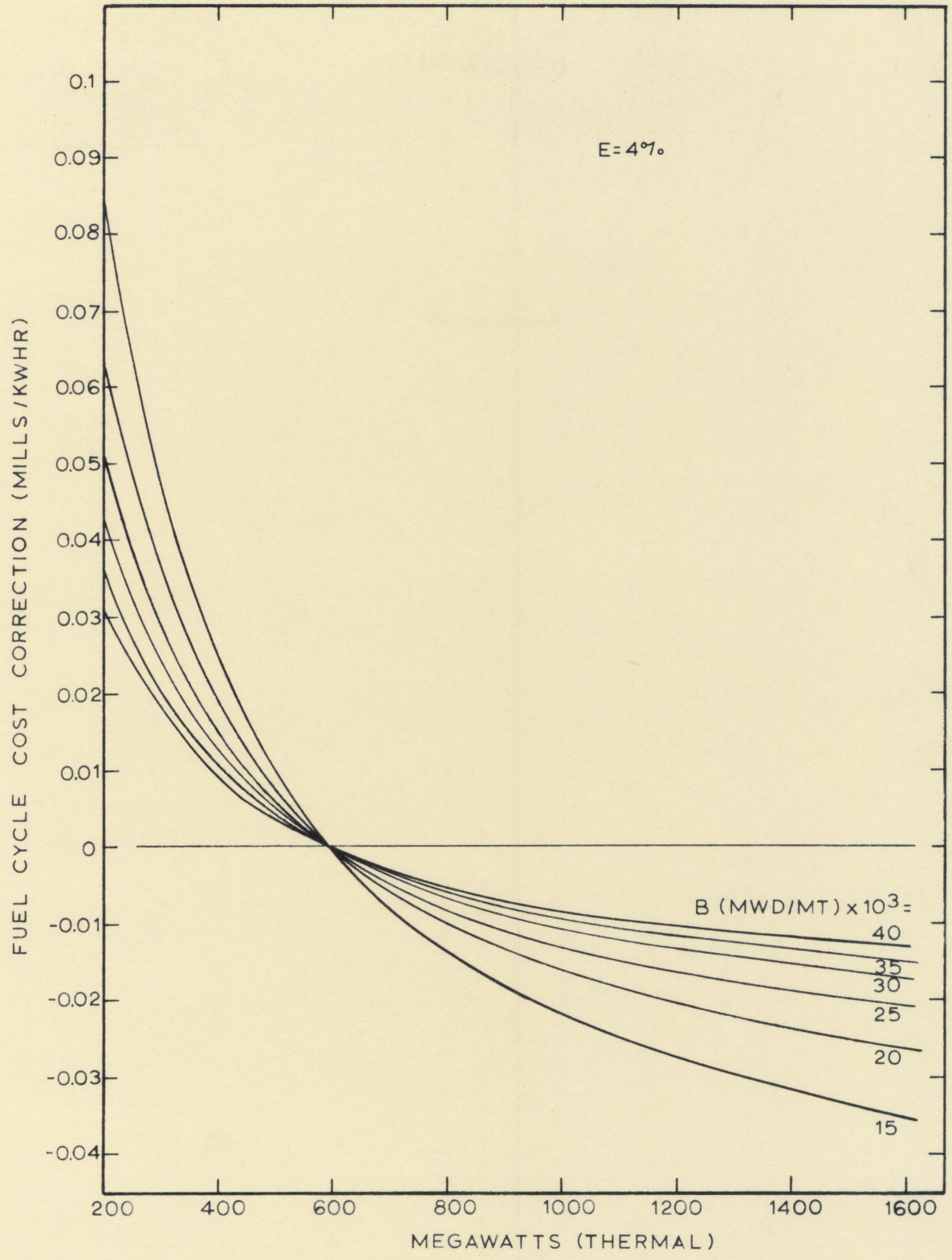

FIGURE 9. PLANT SIZE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF SIZE AND BURNUP FOR E=4%

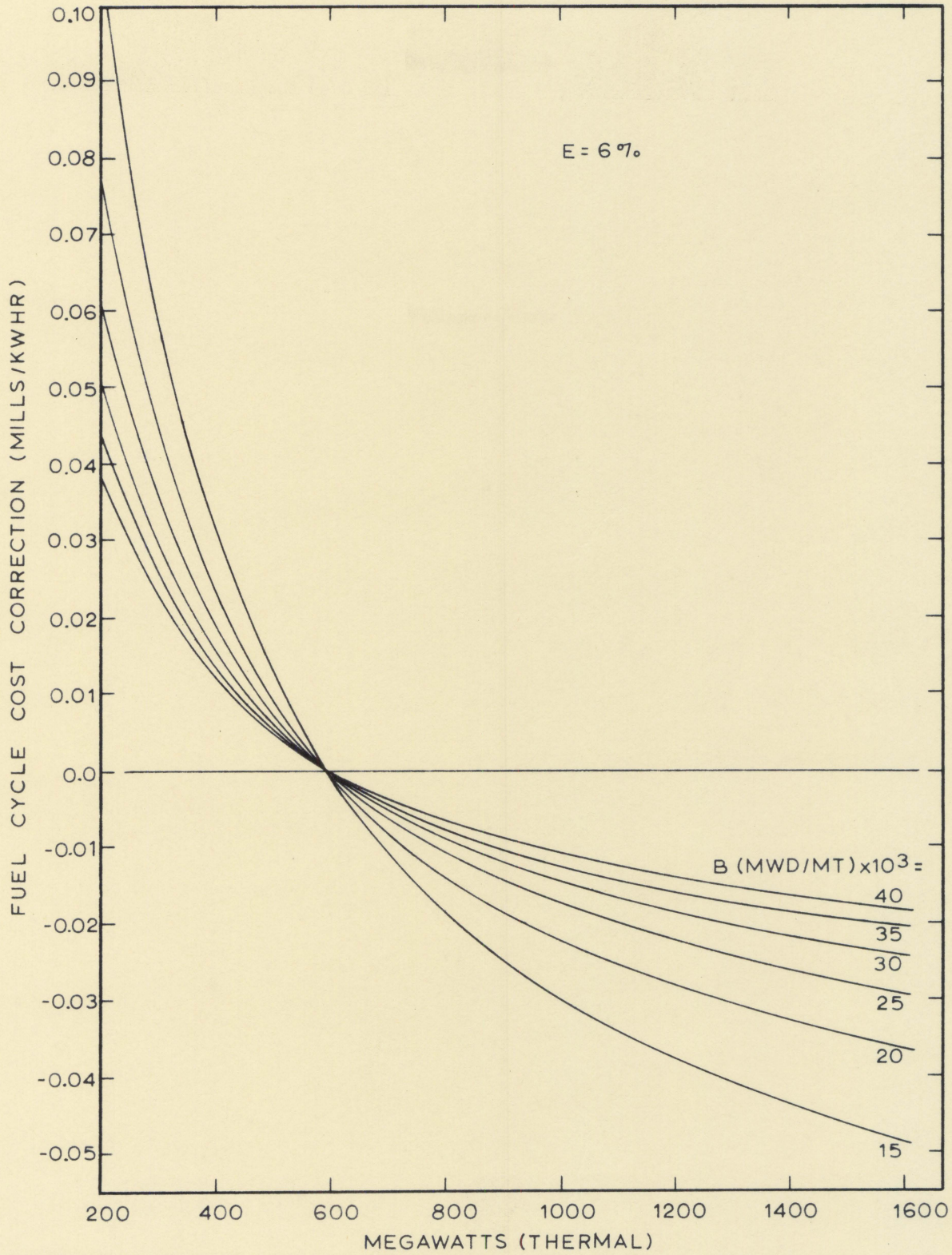

FIGURE 10. PLANT SIZE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF SIZE AND BURNUP FOR E = 6%

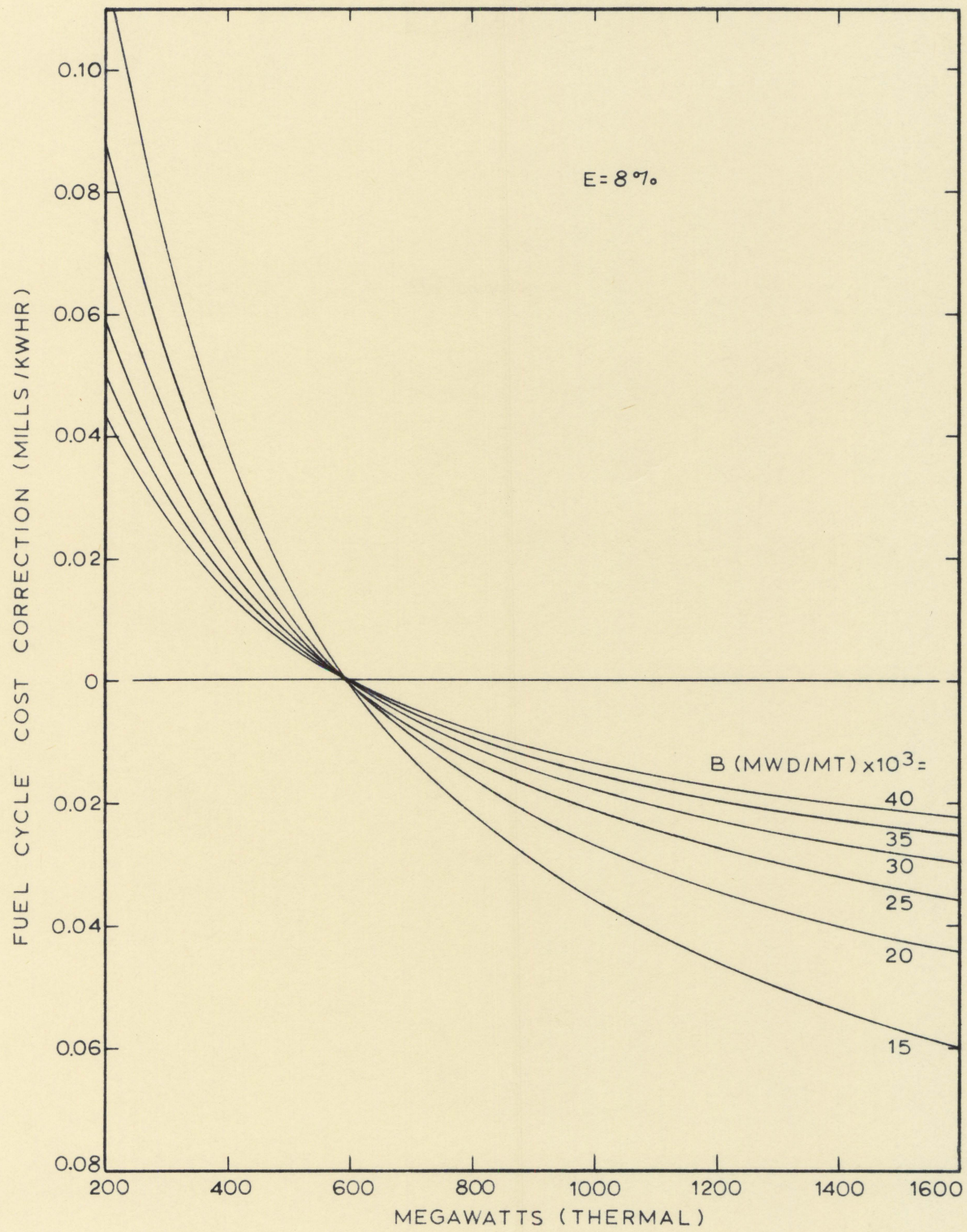

FIGURE 11. PLANT SIZE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF SIZE AND BURNUP FOR E = 8 %

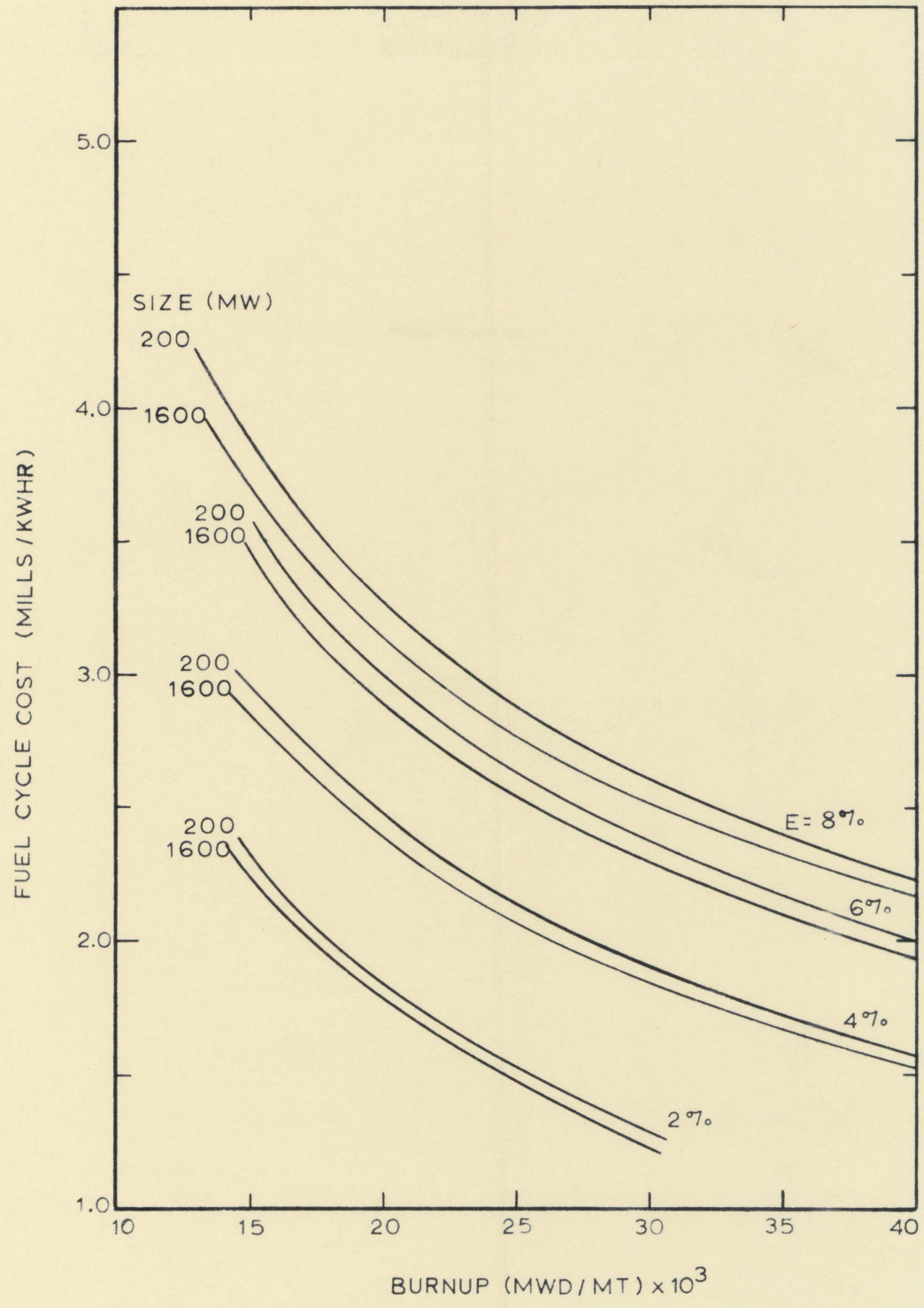

FIGURE 12. COMPARISON OF FUEL CYCLE COSTS FOR THE 200 AND 1600 MW REACTOR SIZES

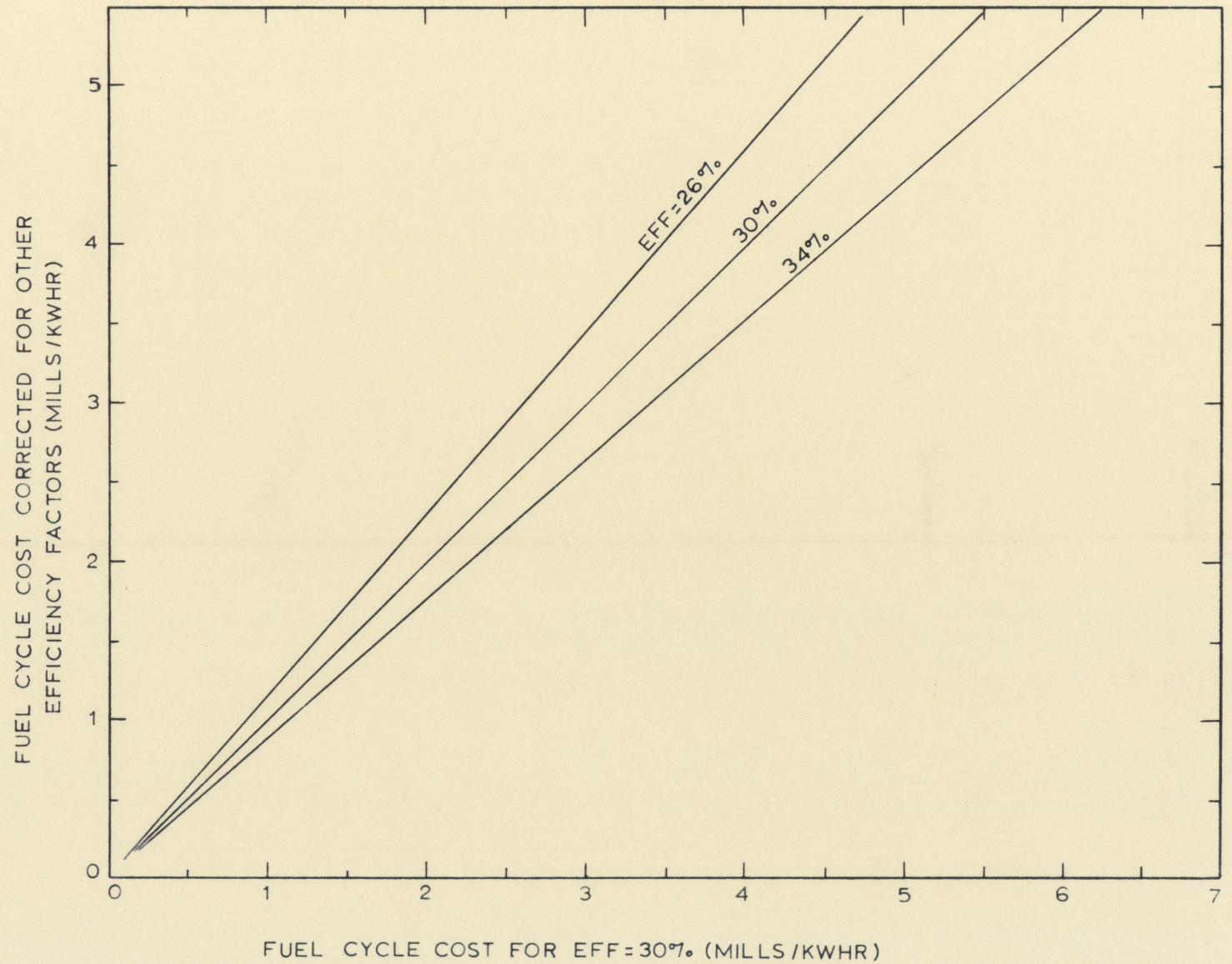

FIGURE 13. FUEL CYCLE COST CORRECTION FOR VARIOUS EFFICIENCY FACTORS

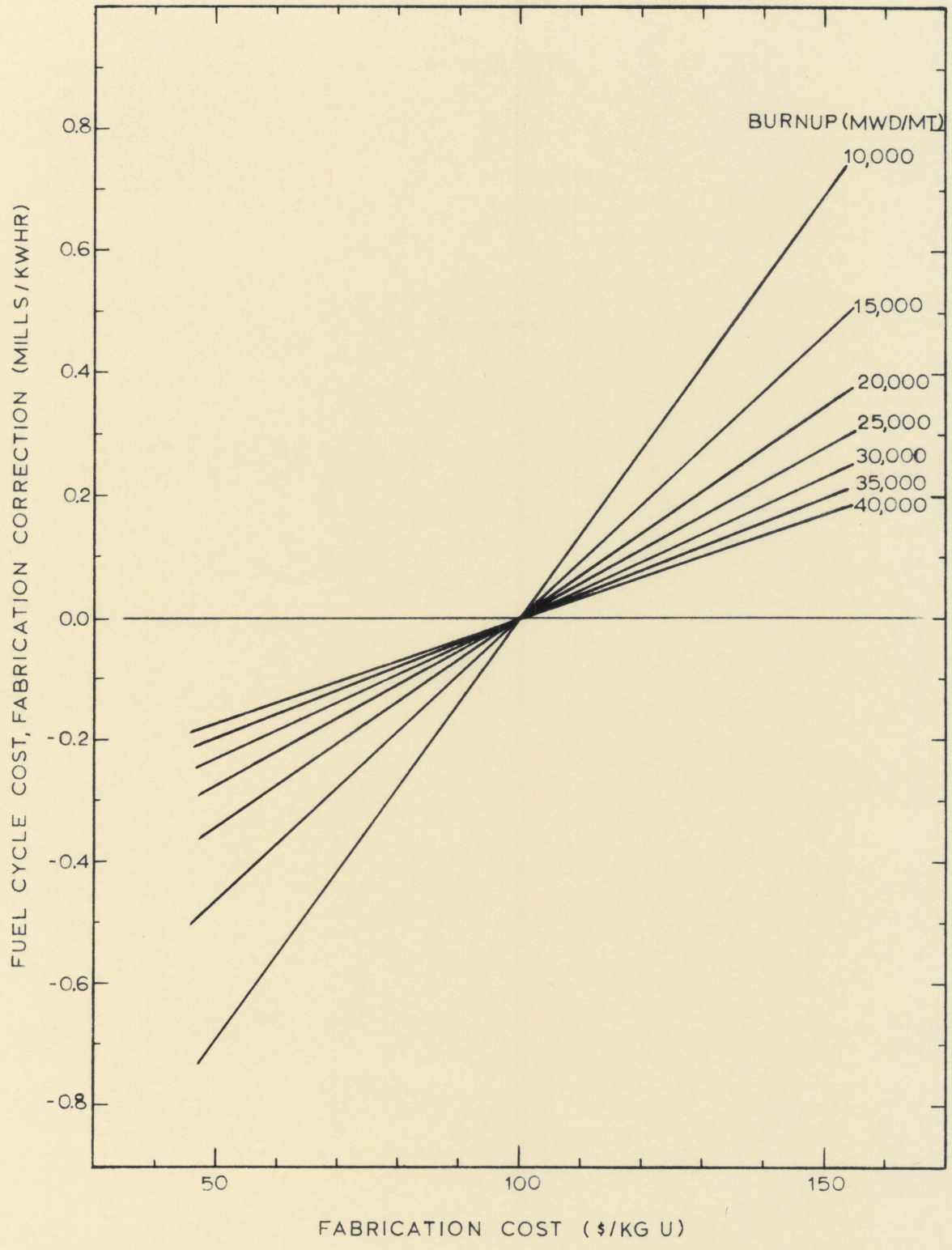

FIGURE 14. FABRICATION CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF FABRICATION COST AND BURNUP

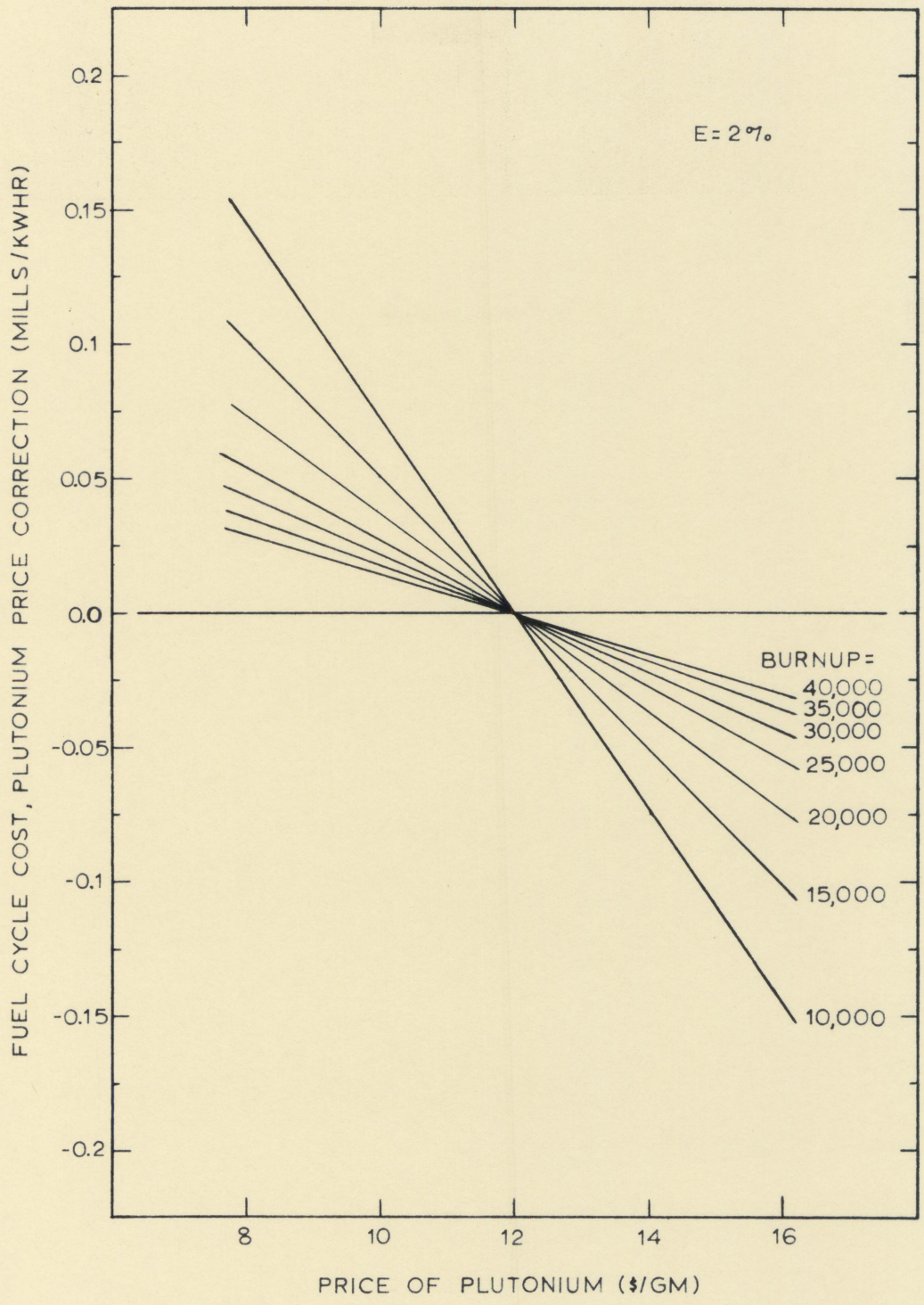

FIGURE 15. PLUTONIUM PRICE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PLUTONIUM PRICE AND BURNUP FOR E = 2%

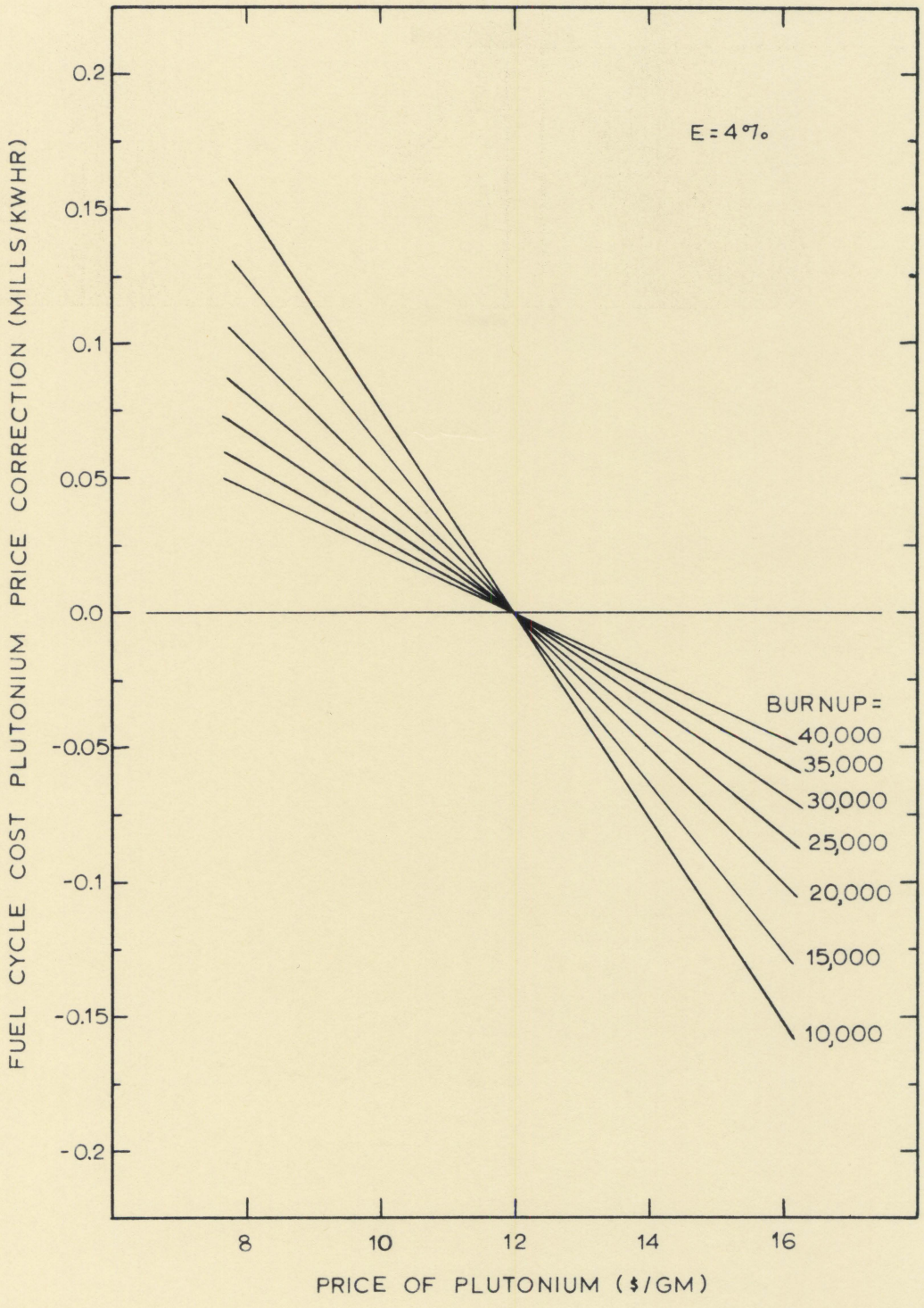

FIGURE 16. PLUTONIUM PRICE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PLUTONIUM PRICE AND BURNUP FOR E=4%

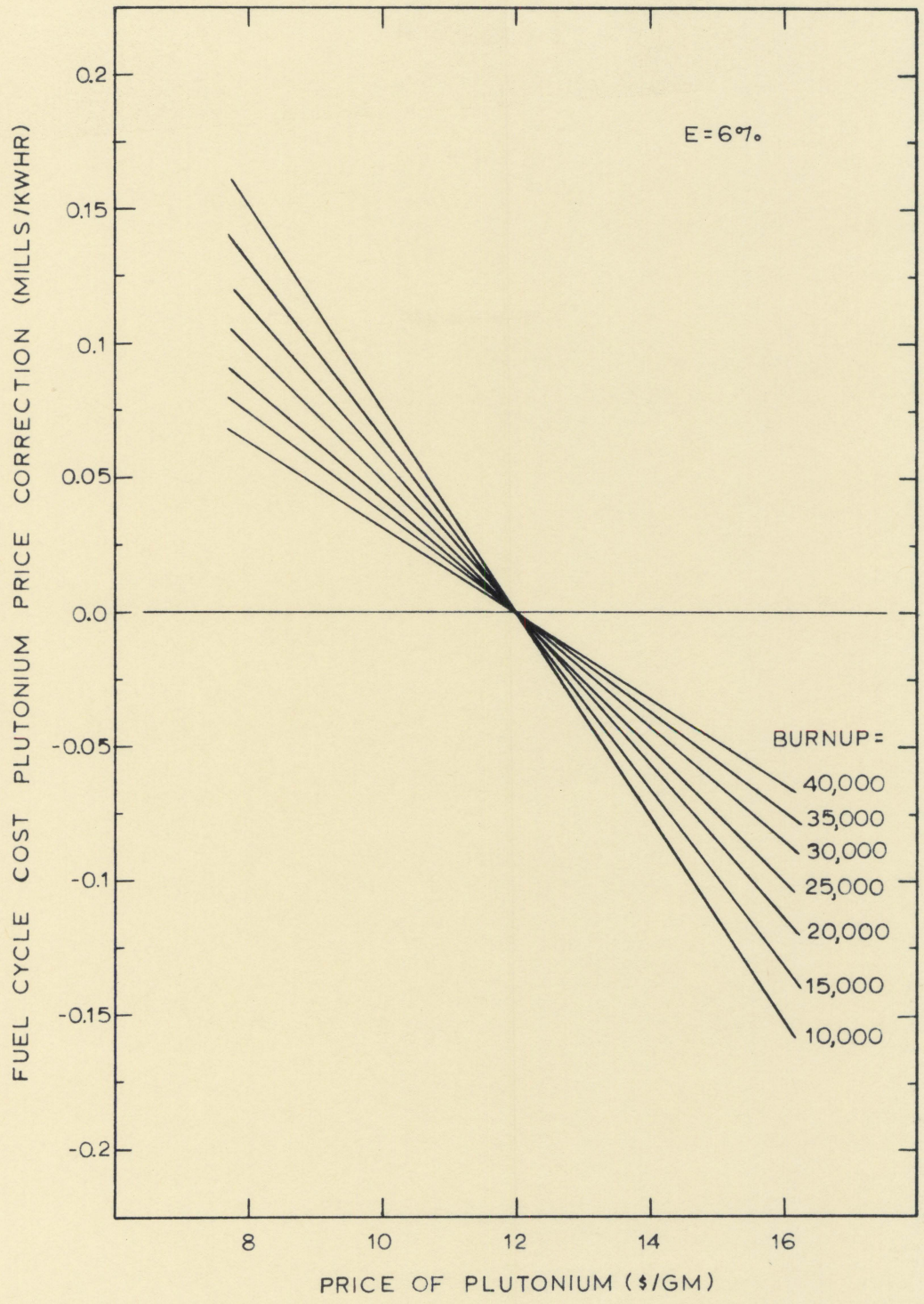

FIGURE 17. PLUTONIUM PRICE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PLUTONIUM PRICE AND BURNUP FOR E=6%

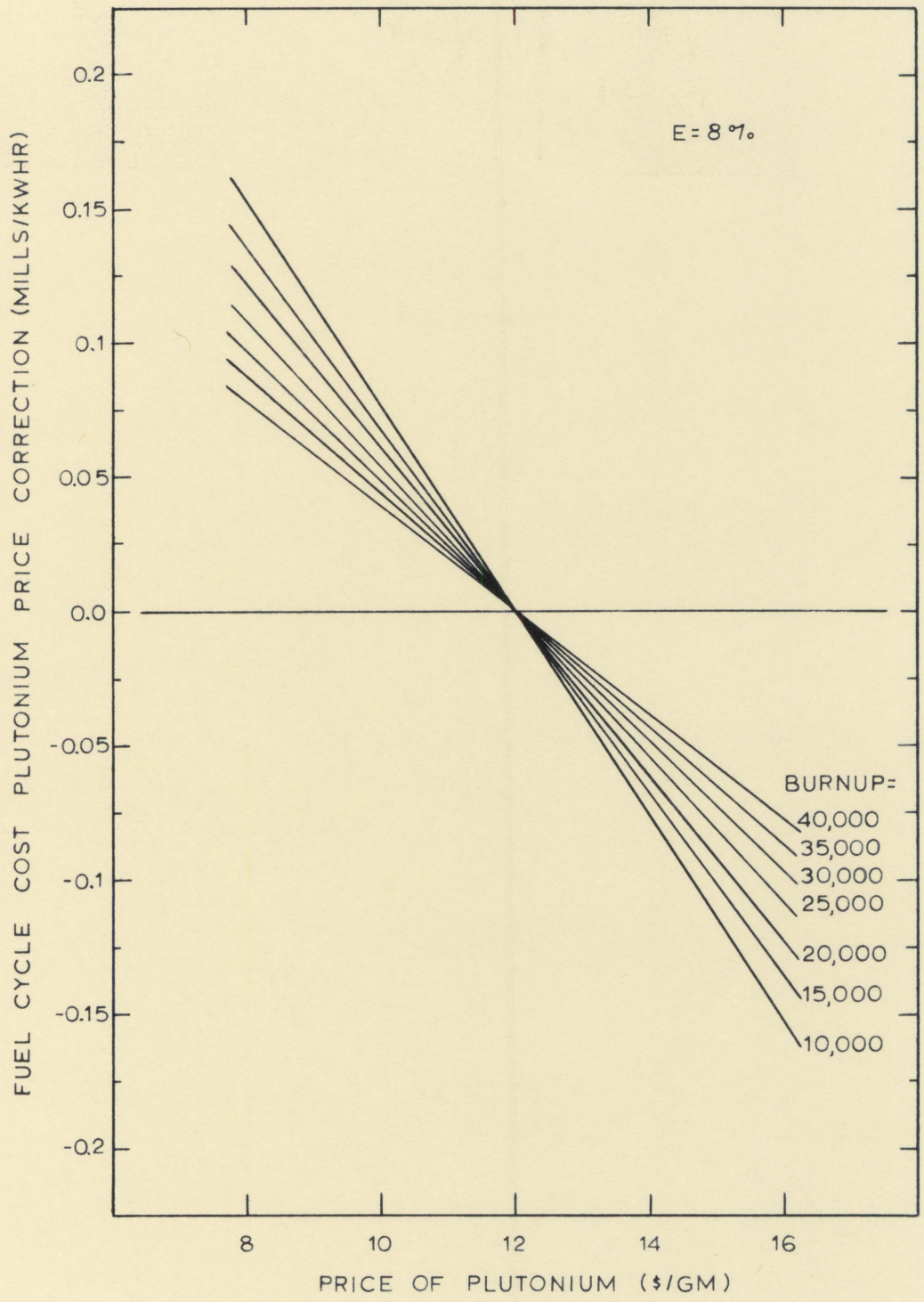

FIGURE 18. PLUTONIUM PRICE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PLUTONIUM PRICE AND BURNUP FOR E=8 %

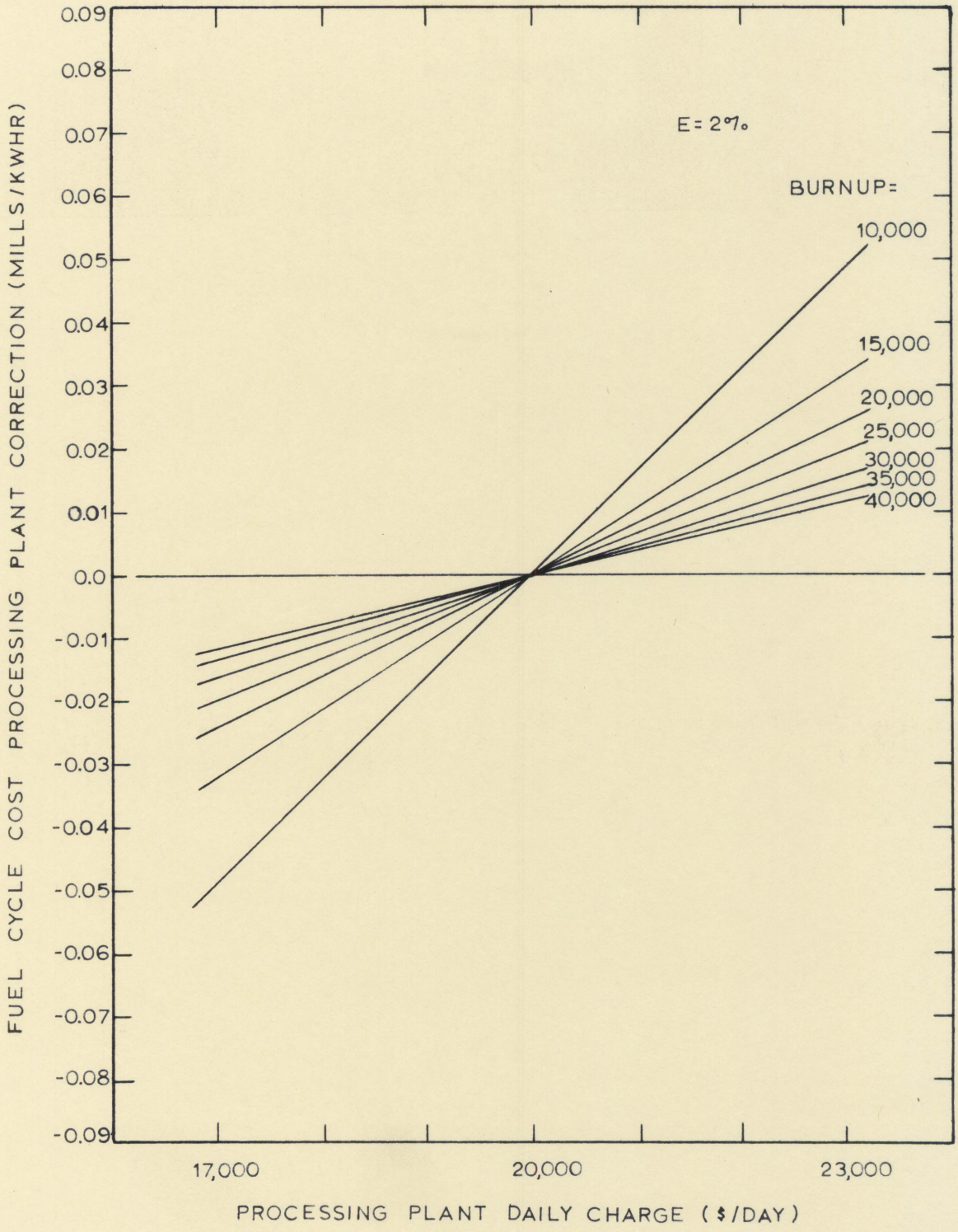

FIGURE 19. PROCESSING PLANT CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PROCESSING PLANT DAILY CHARGE AND BURNUP FOR E = 2%.

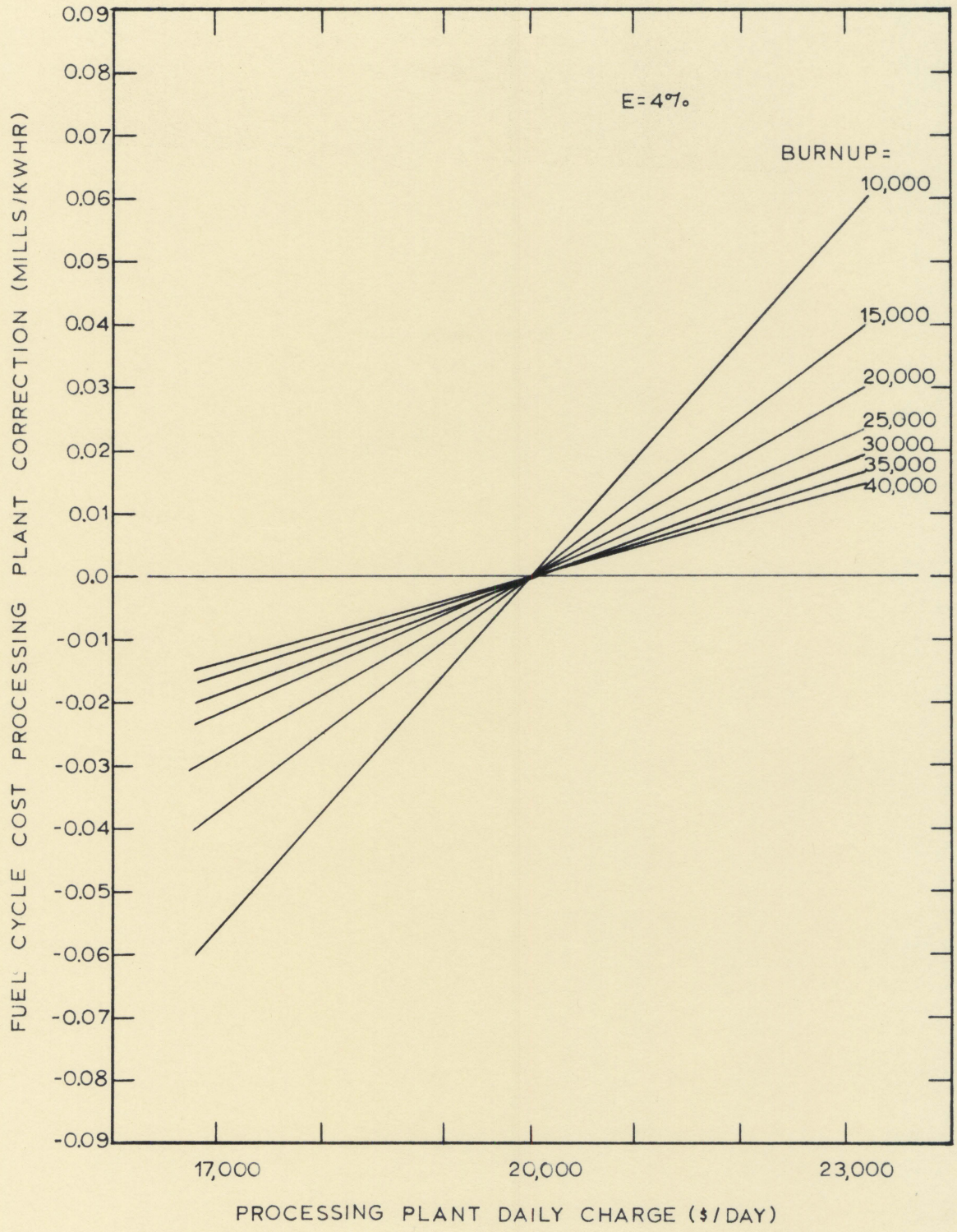

FIGURE 20. PROCESSING PLANT CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PROCESSING PLANT DAILY CHARGE AND BURNUP FOR E=4%

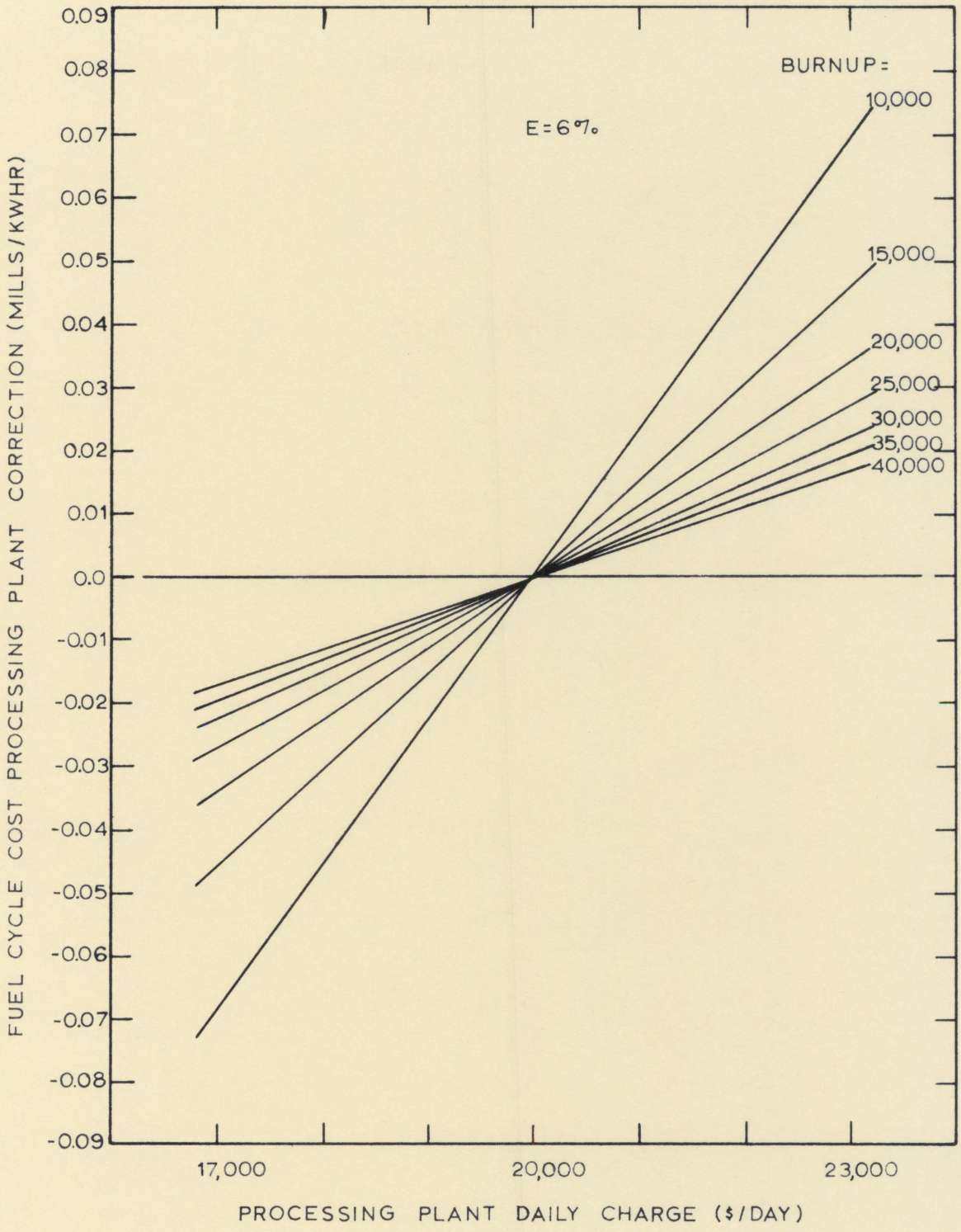

FIGURE 21. PROCESSING PLANT CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PROCESSING PLANT DAILY CHARGE AND BURNUP FOR E=6%

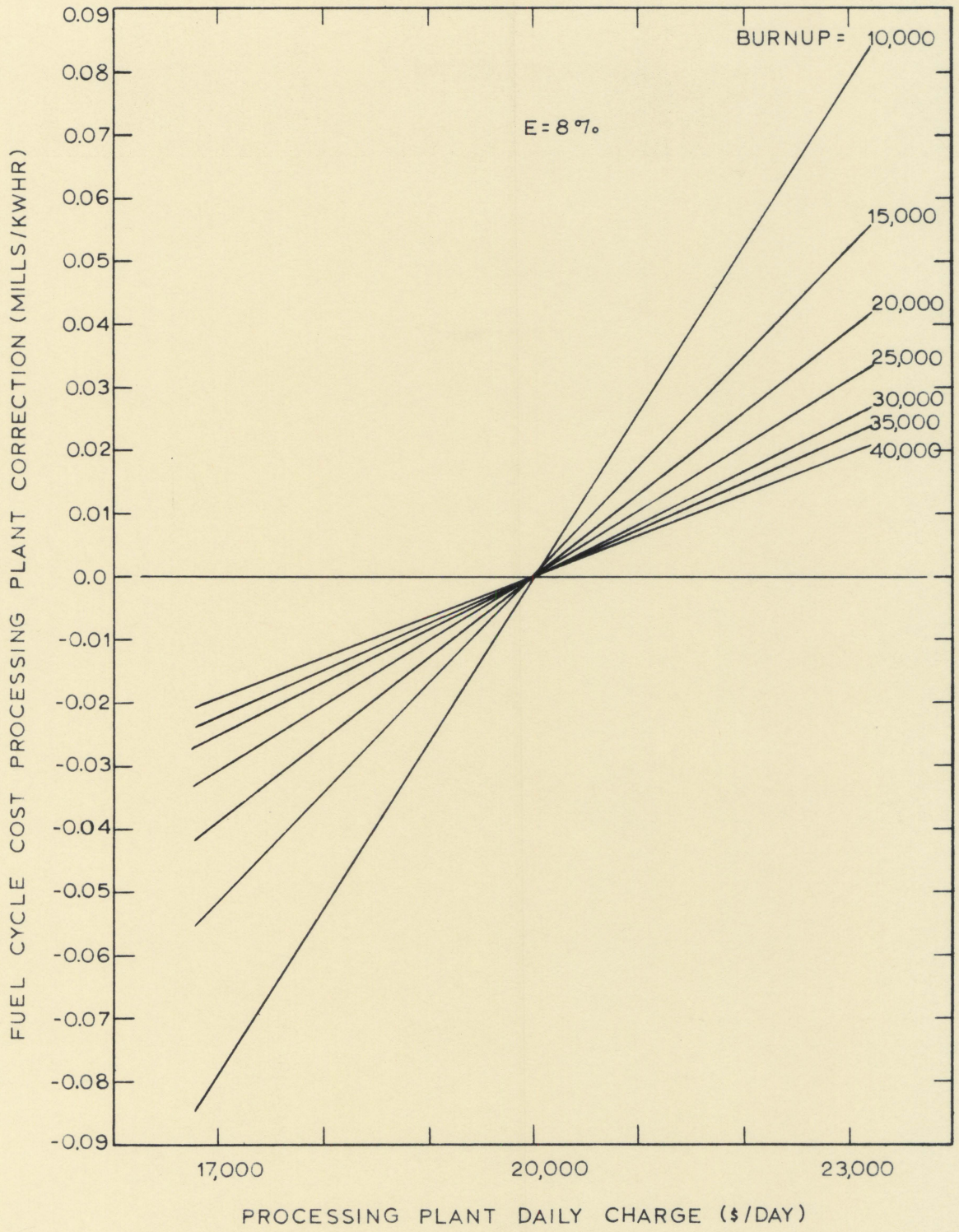

FIGURE 22. PROCESSING PLANT CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF PROCESSING PLANT DAILY CHARGE AND BURNUP FOR E = 8%.

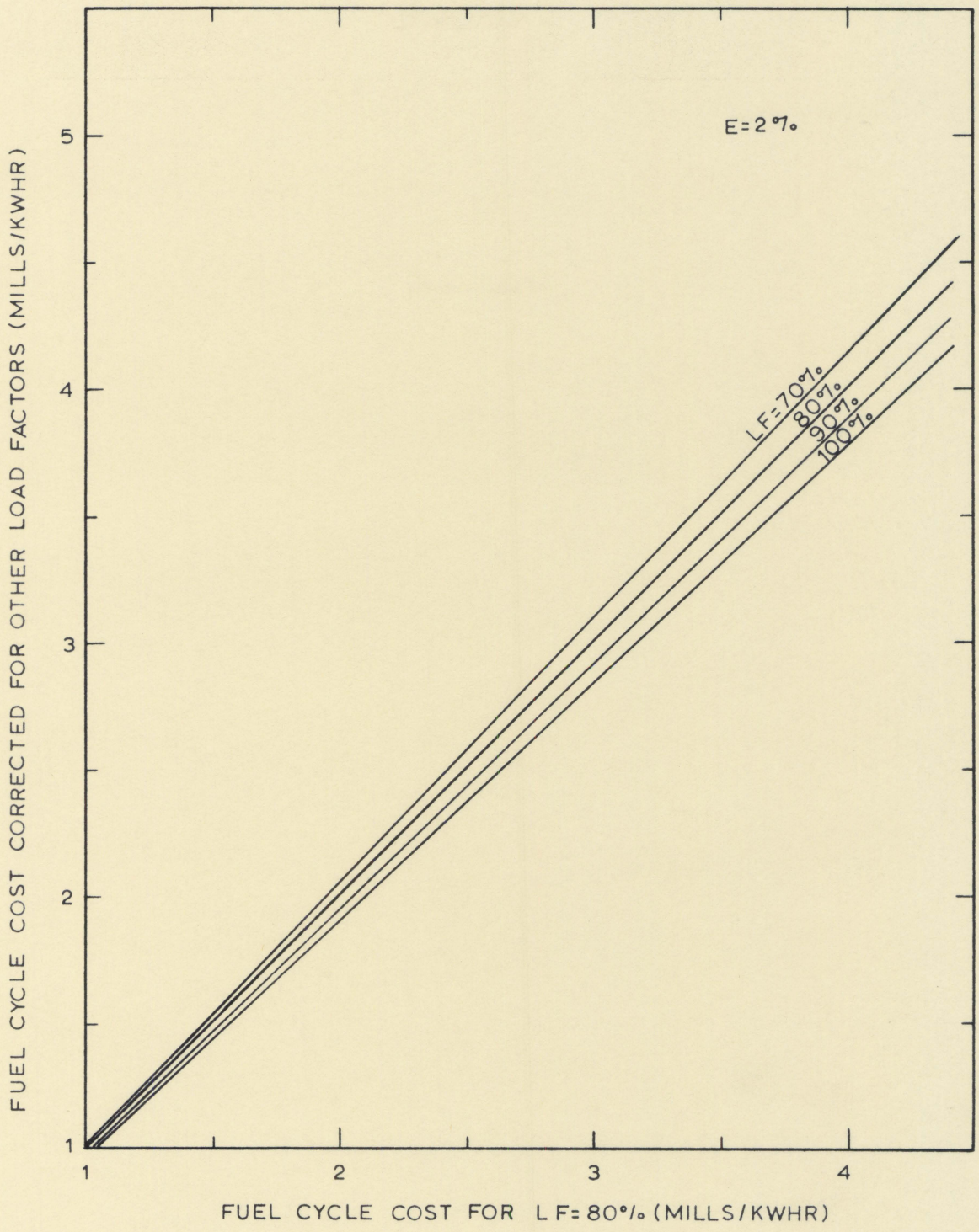

FIGURE 23. FUEL CYCLE COST CORRECTION FOR VARIOUS LOAD FACTORS FOR E=2%

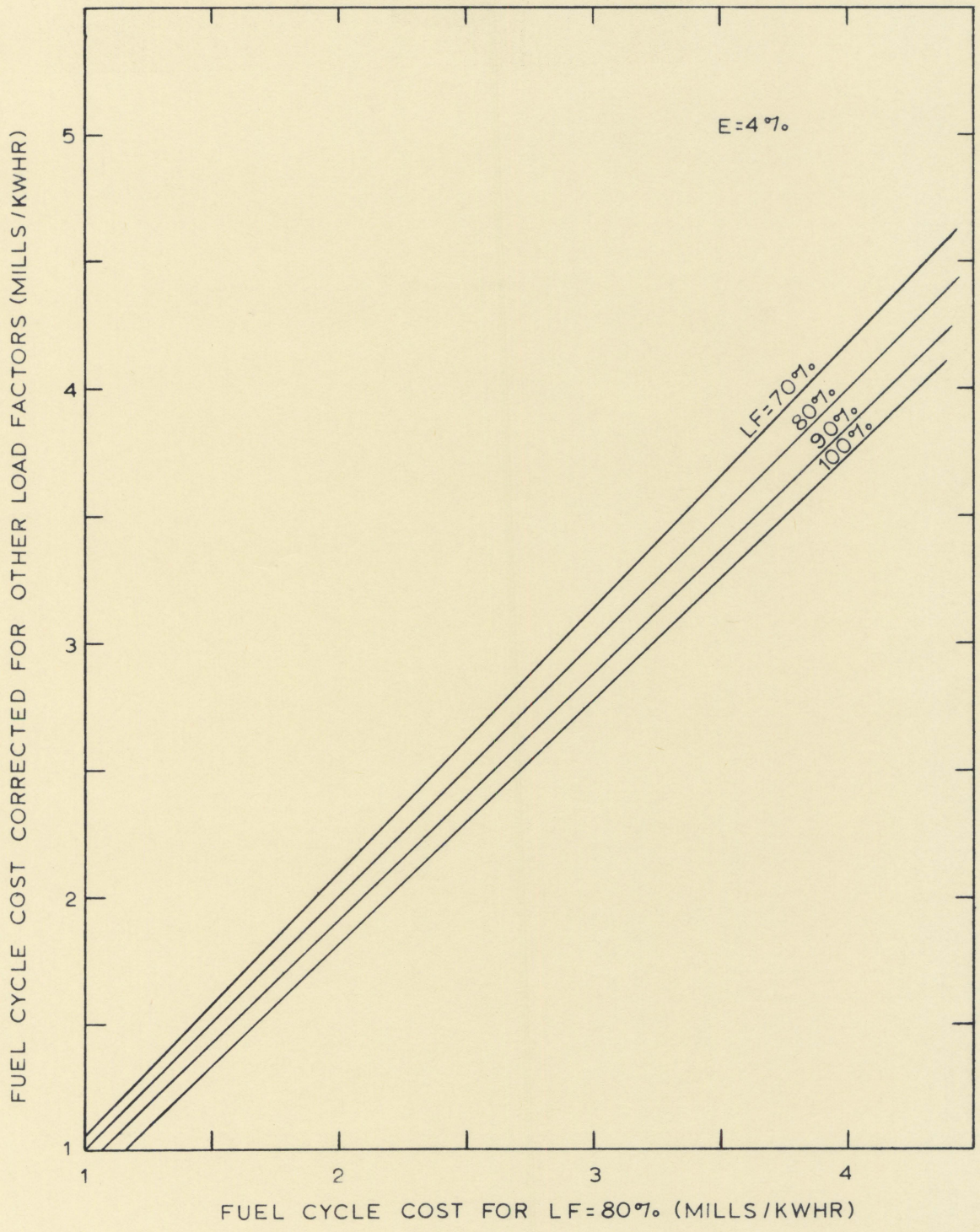

FIGURE 24. FUEL CYCLE COST CORRECTION FOR VARIOUS LOAD FACTORS FOR E=4%

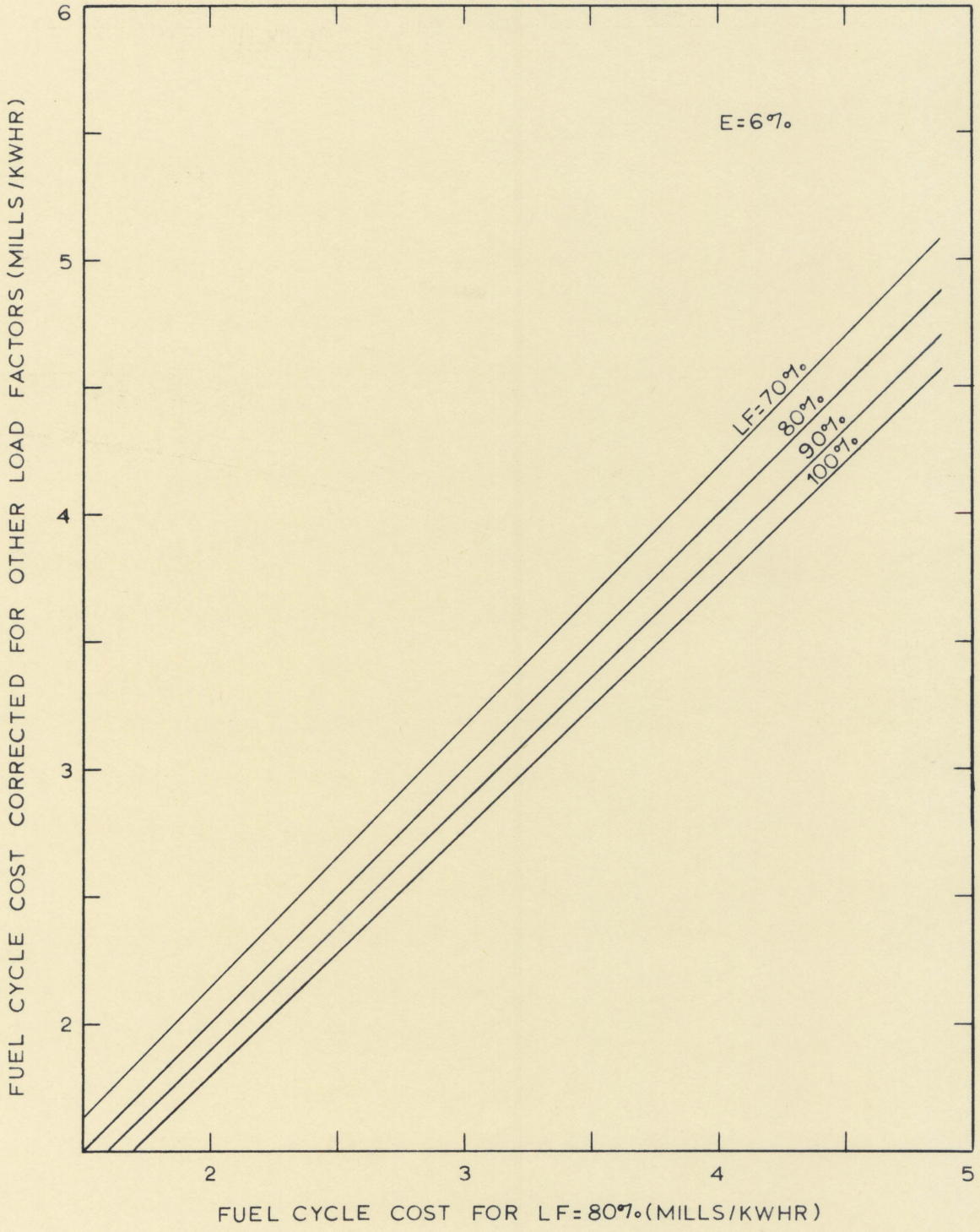

FIGURE 25. FUEL CYCLE COST CORRECTION FOR VARIOUS LOAD FACTORS FOR E=6%

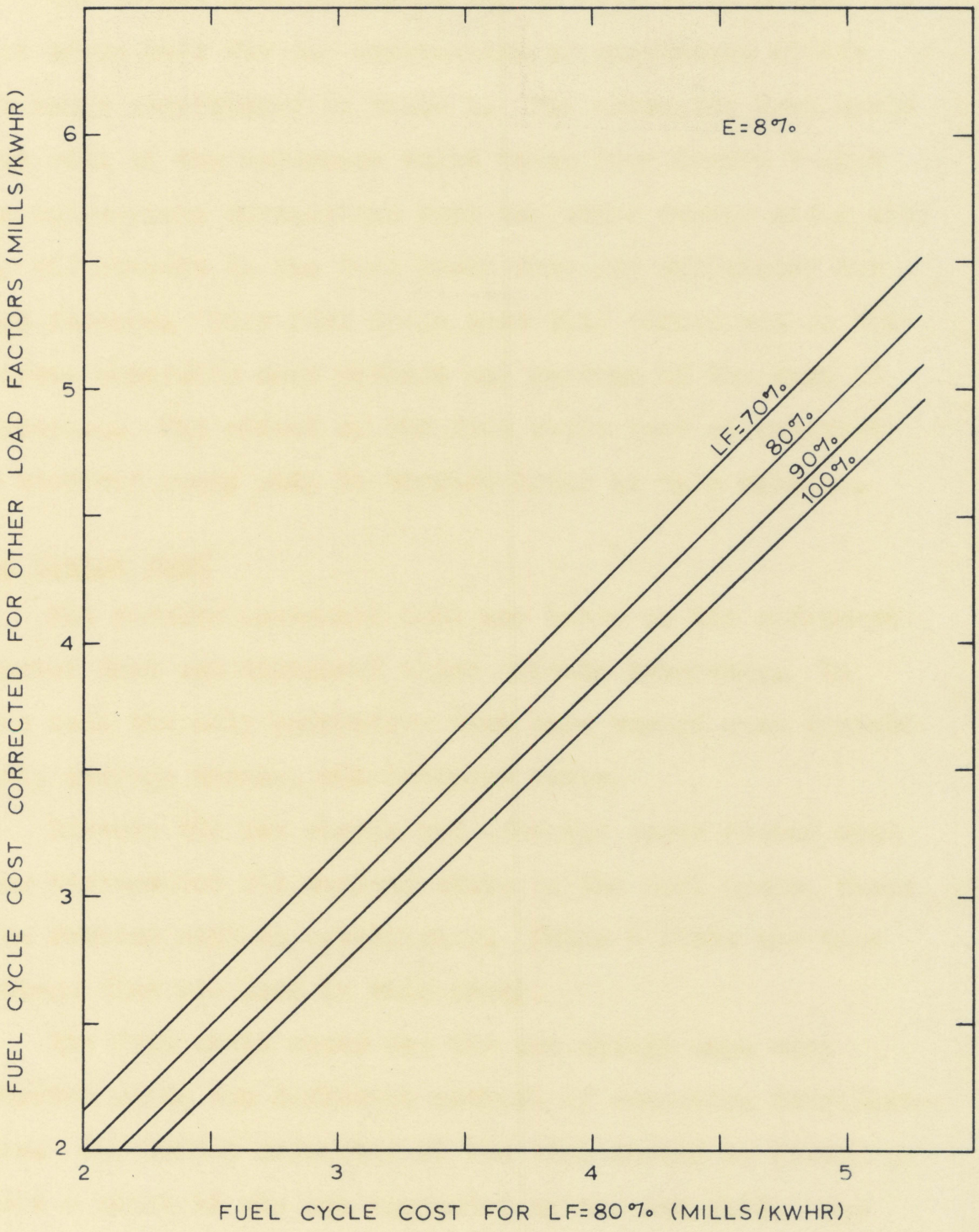

FIGURE 26. FUEL CYCLE COST CORRECTION FOR VARIOUS LOAD FACTORS FOR E=8%

The curves just presented can be used to calculate the fuel cycle cost for any combination of parameters within the range established in Table 1. The corrected fuel cycle cost will be the reference value taken from Figure 7 plus the appropriate corrections from the other curves along with any adjustments to the fuel cycle cost for efficiency and load factors. This fuel cycle cost will correspond to the private ownership case without any mention of the cost of financing. The effect on the fuel cycle cost of interest on borrowed money will be studied later in this section.

Use charge case

The results presented here are based on the reference reactor that was discussed under private ownership. In this case the only parameters that were varied were enrichment, average burnup, and interest rates.

Because the use charge and interest costs depend upon time factors for the various steps in the fuel cycle, these time factors must be established. Table 6 lists the time factors that are used in this study.

The fuel cycle costs for the use charge case were computed using two different methods of computing fabrication time. One method consisted of the time factor as listed in Table 6 which is the one suggested by the AEC (16). The second method of calculating fabrication time is based on a discussion in Reference 14 and is illustrated by Equation 1.

Table 6. Time factors used for use charge case

Parameter	Value
Shipping time, AEC to fabricator	30 days
Shipping time, fabricator to reactor	30 days
Conversion and fabrication time	4 Mt/month
In-core irradiation time	Depends on B and LF
Cooling time	120 days
Shipping time to processor	30 days
Reprocessing time	Equations 2 and 3
Conversion	Equation 4

In Figure 27 is a comparison of the fabrication time as computed by these two methods for the 600 Mwth plant size as a function of enrichment. The difference is considerable and affects the fuel cycle cost to a significant degree. In Figure 28 is illustrated the fuel cycle cost for the use charge rate at 4.75% and the reference plant parameters for fabrication time computed as 4 Mt/month. This curve is similar to the one plotted in Figure 7, and will be utilized in a similar manner. Figure 29 is a difference curve from which can be illustrated the difference between the private ownership case and the use charge case for the 600 Mwth plant size. This is equivalent to the difference between Figure 7 and Figure 28. The difference is given in mills/kwhr and is a measure of the contribution of the use charge to the fuel cycle cost.

In Figures 30 to 33 are given the differences between

the private ownership and use charge cases as a function of reactor size and burnup for the values of enrichment considered. These curves allow the fuel cycle cost calculated for the private ownership case to be adjusted to the use charge case. Note the behavior of these curves at the lower values of plant size. A minimum is clearly indicated for some of the larger values of burnup.

In Figure 34 the difference in the use charge case for the two methods of computing the fabrication time is illustrated. This difference is plotted as a function of burnup and enrichment for the 600 Mwth plant size. In Figures 35 through 38 the differences are given between the fuel cycle cost for the use charge case for both methods of computing fabrication time. This series of curves can be used to compute the fuel cycle cost by adding the difference to the difference obtained from the series 30 to 33 and then adding the total difference to the private ownership value for the appropriate parameters.

Comparison between private ownership and use charge case

Before a valid comparison can be made between the private ownership case and the use charge case, the financing cost for the private ownership case must be taken into account. In computing the interest cost on the fuel inventory and the pre-reactor costs, interest rates of 6 to 10% were used. The time that the interest rate was applied was taken

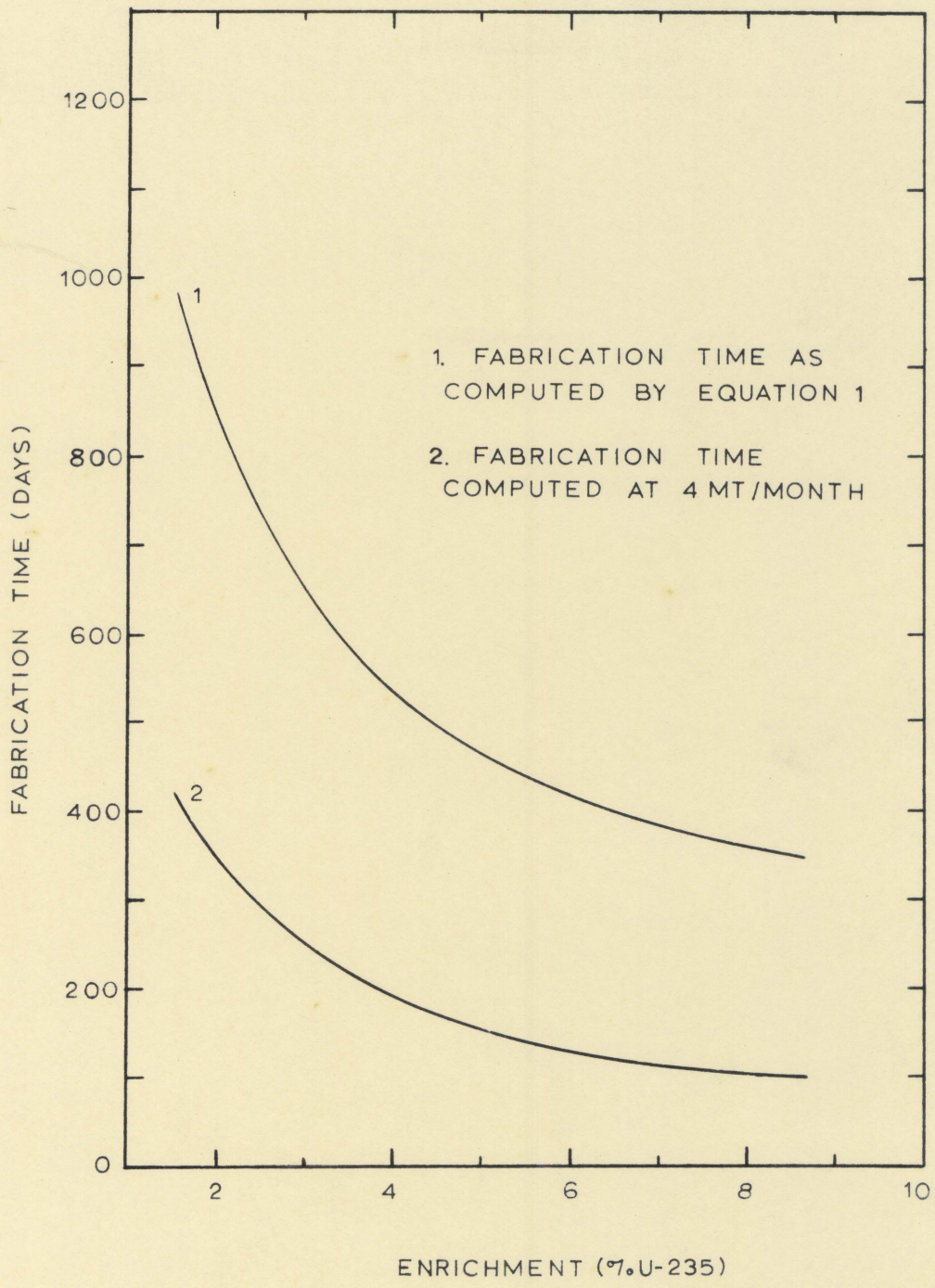

FIGURE 27. COMPARISON OF TWO METHODS OF COMPUTING FABRICATION TIME FOR REFERENCE PLANT

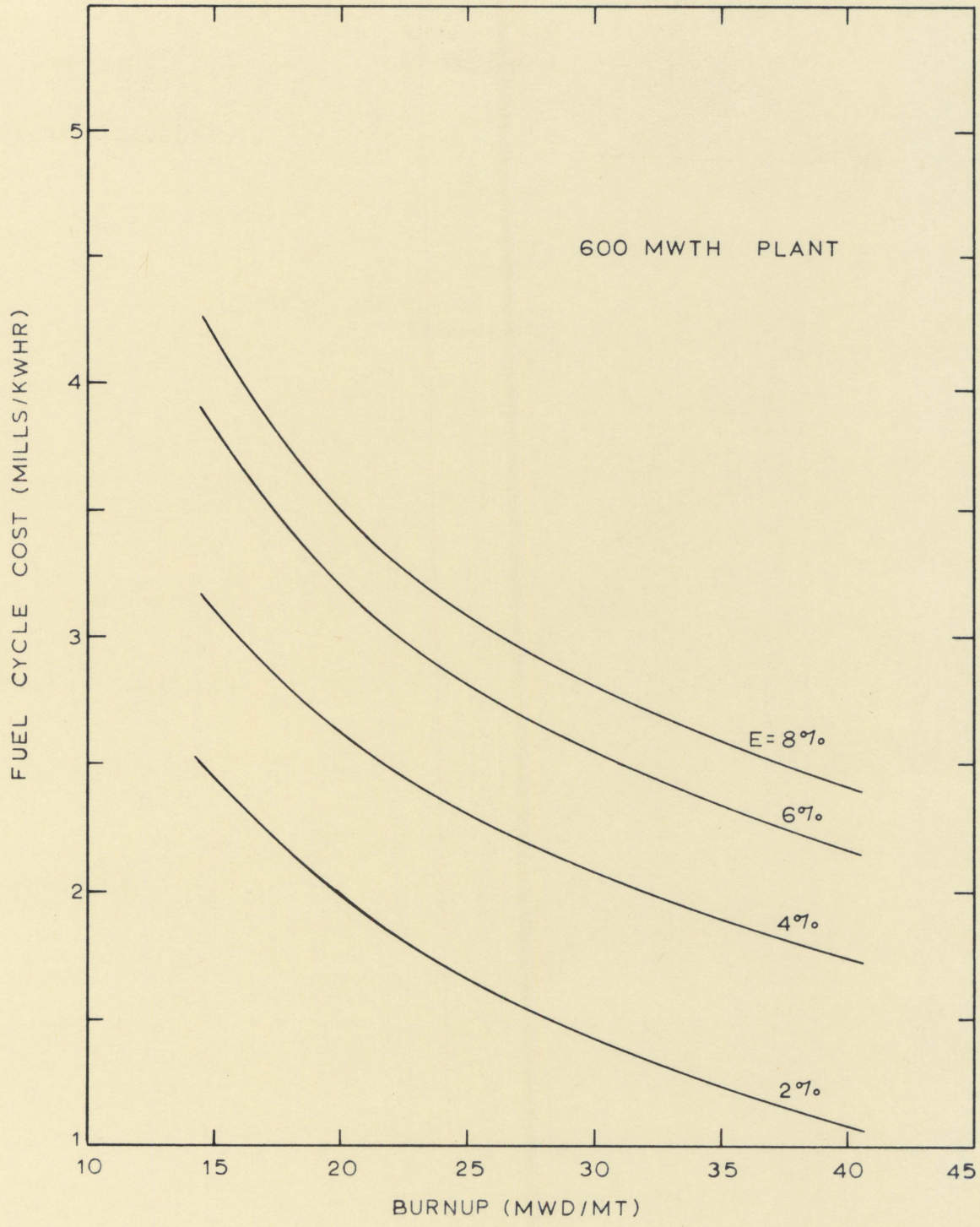

FIGURE 28. FUEL CYCLE COST FOR USE CHARGE CASE AS A FUNCTION OF BURNUP AND ENRICHMENT FOR 600 MWTH PLANT

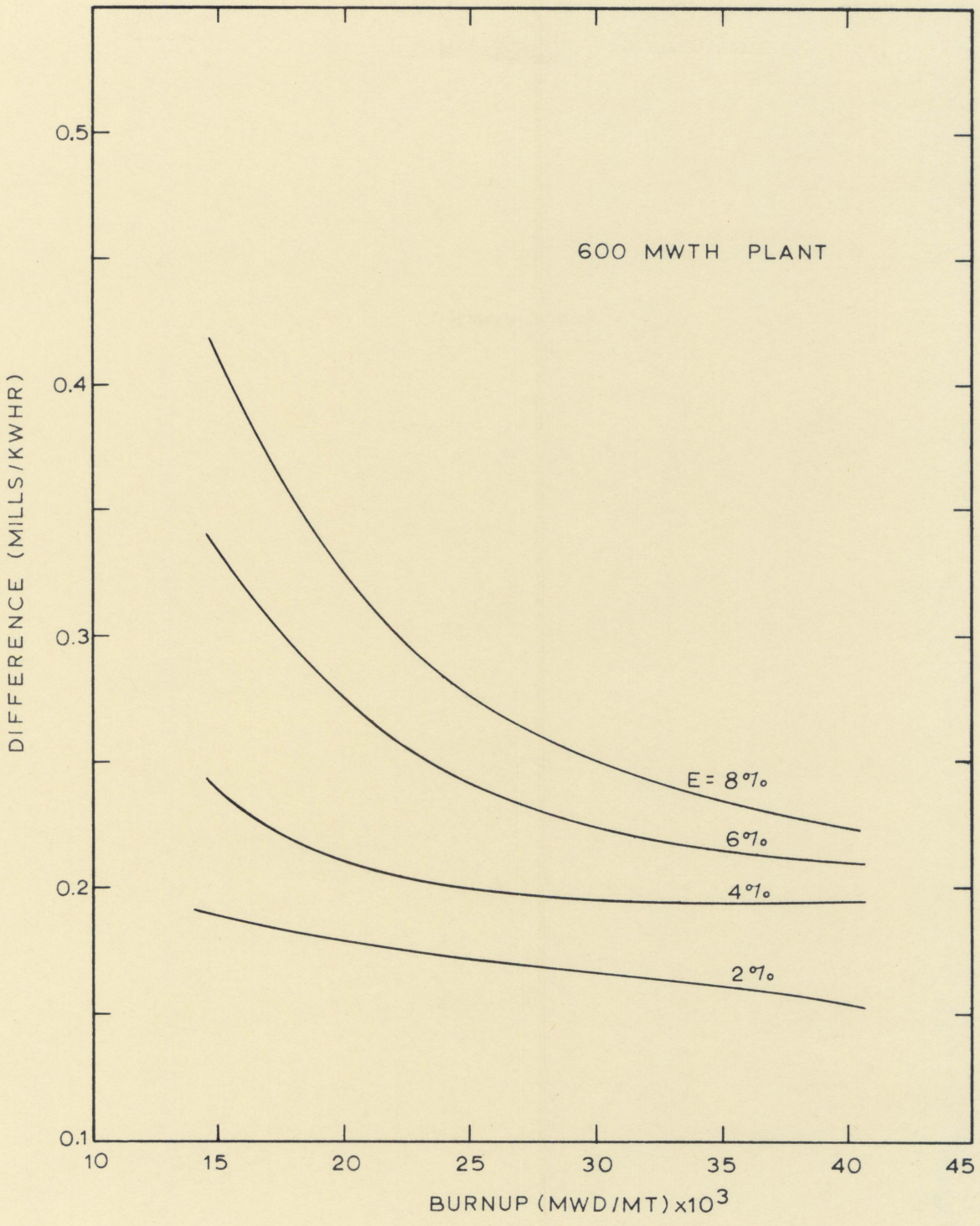

FIGURE 29. DIFFERENCE BETWEEN PRIVATE OWNERSHIP AND USE CHARGE CASE AS A FUNCTION OF BURNUP AND ENRICHMENT FOR 600 MWTH PLANT

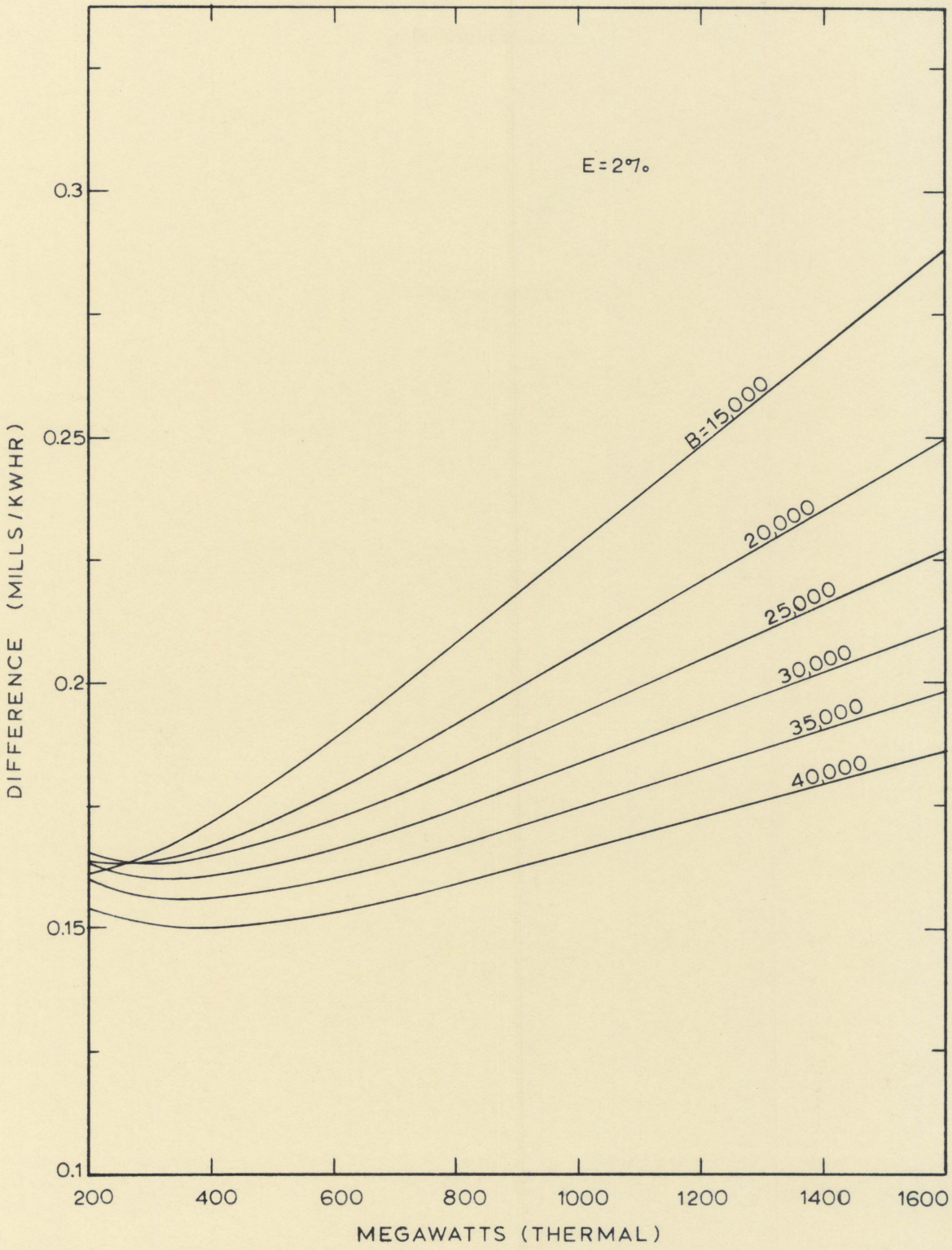

FIGURE 30. DIFFERENCE BETWEEN PRIVATE OWNERSHIP AND USE CHARGE CASE AS A FUNCTION OF SIZE AND BURNUP FOR E = 2%

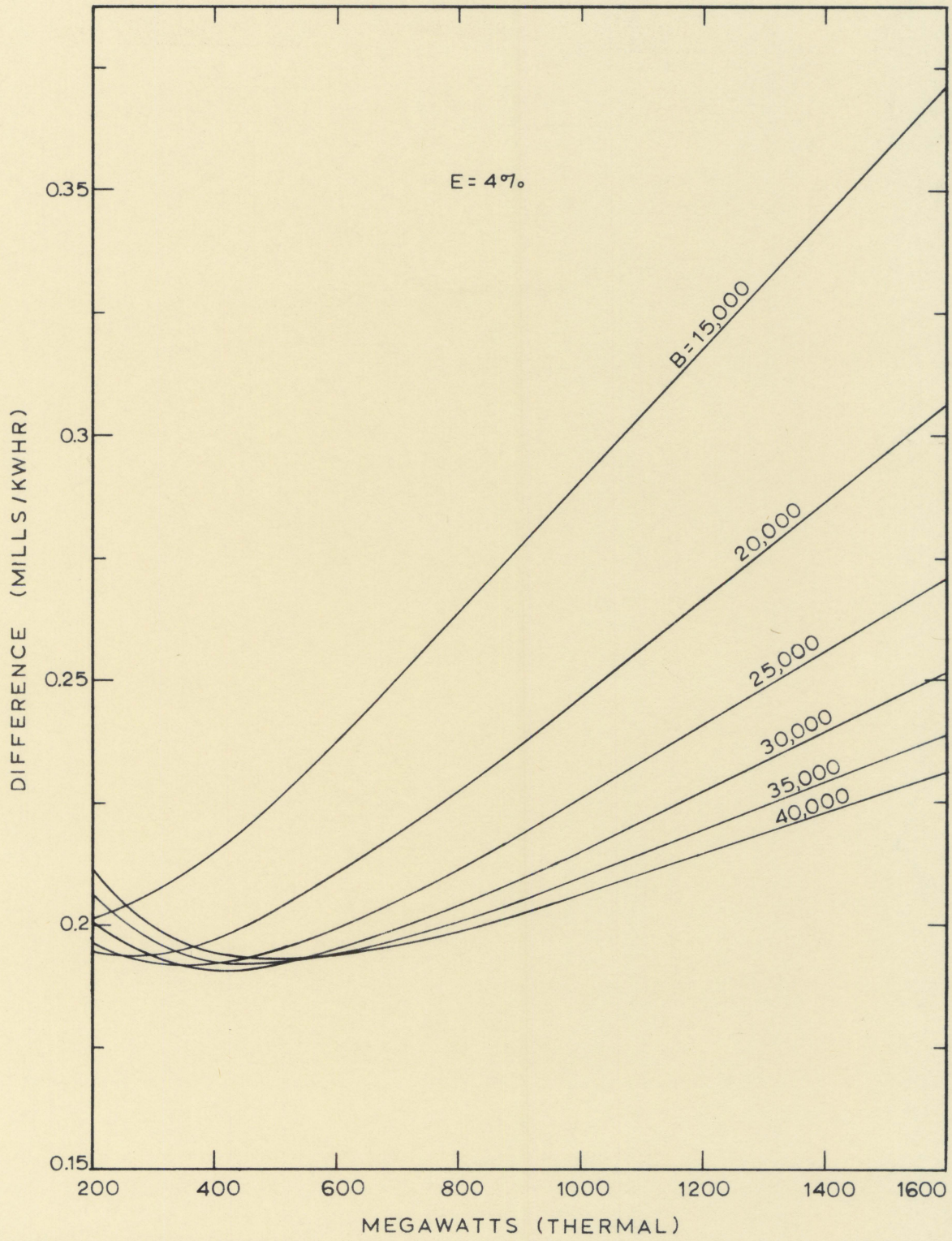

FIGURE 31. DIFFERENCE BETWEEN PRIVATE OWNERSHIP AND USE CHARGE CASE AS A FUNCTION OF SIZE AND BURNUP FOR E=4%

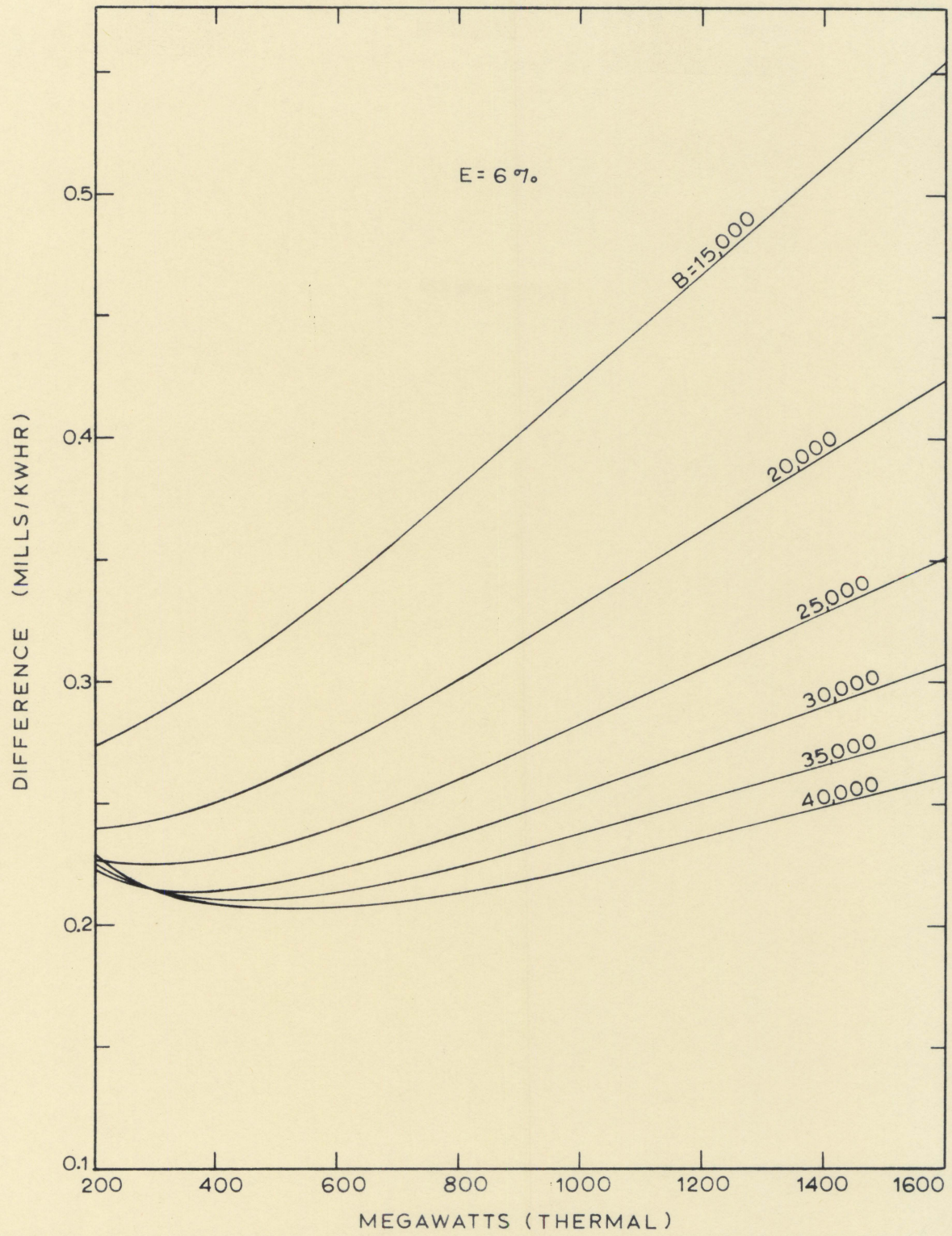

FIGURE 32. DIFFERENCE BETWEEN PRIVATE OWNERSHIP AND USE CHARGE CASE AS A FUNCTION OF SIZE AND BURNUP FOR E=6%.

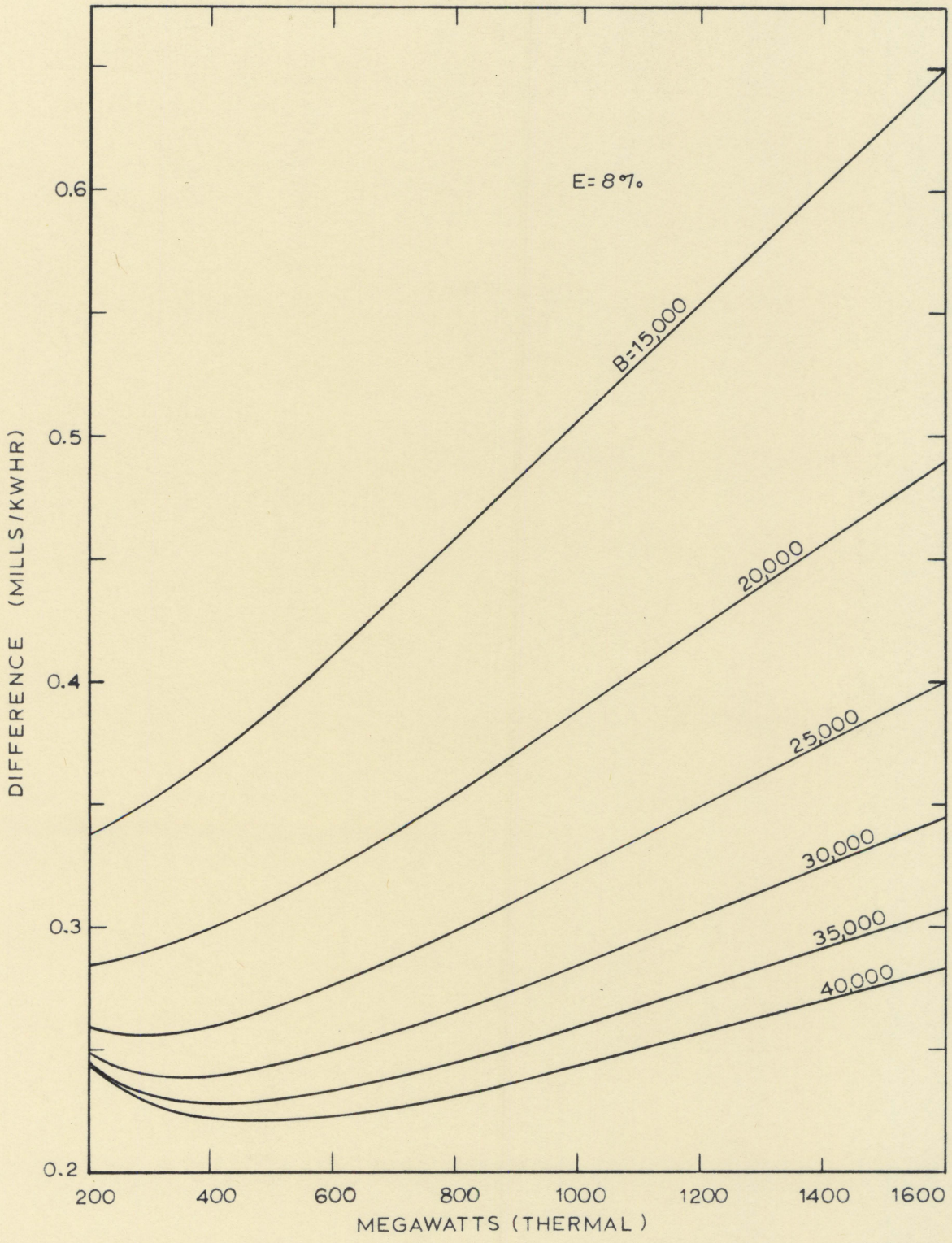

FIGURE 33. DIFFERENCE BETWEEN PRIVATE OWNERSHIP AND USE CHARGE CASE AS A FUNCTION OF SIZE AND BURNUP FOR E=8%.

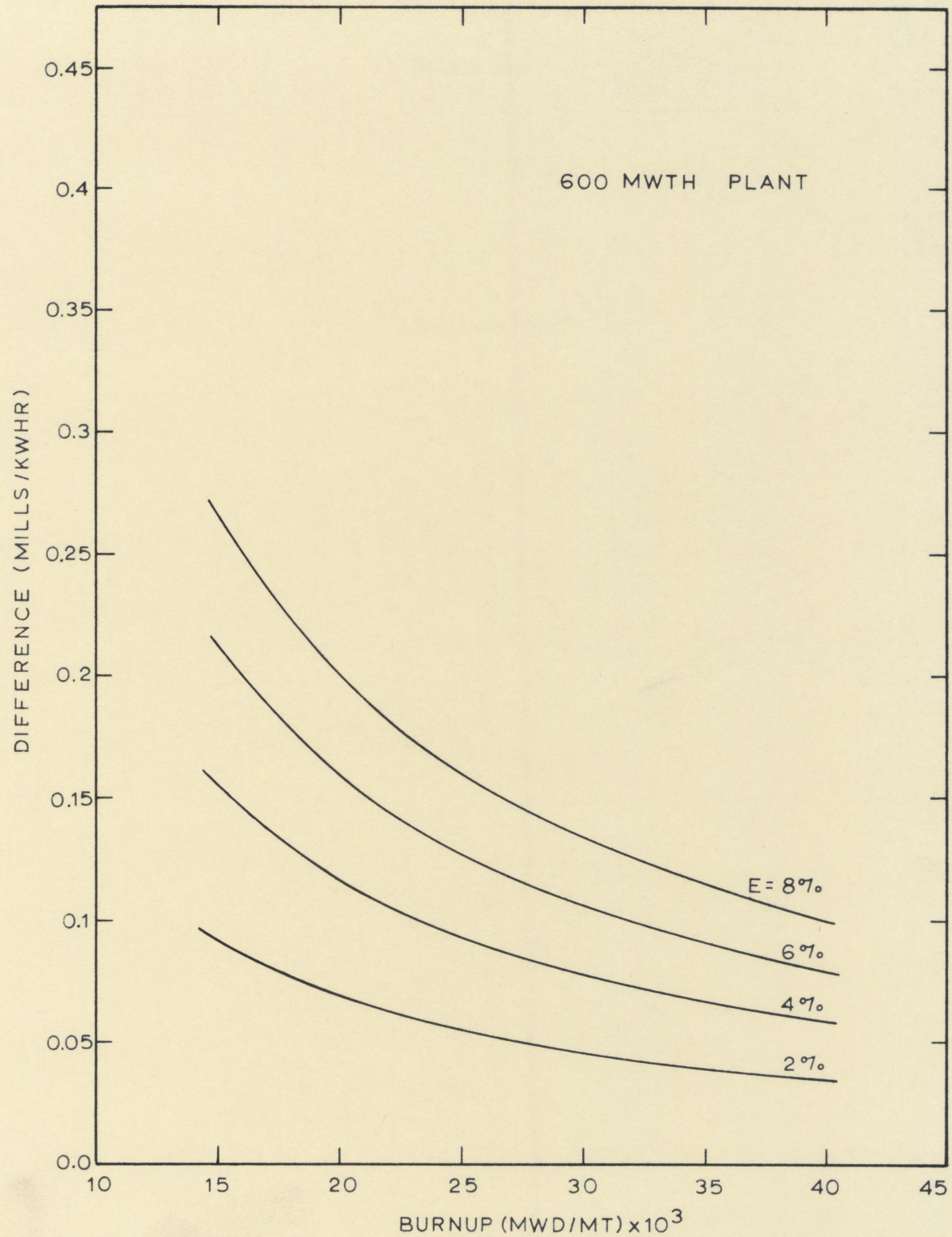

FIGURE 34. FUEL CYCLE COST DIFFERENCE BETWEEN USE CHARGE CASE FOR TWO METHODS OF COMPUTING FABRICATION TIME AS A FUNCTION OF BURNUP AND ENRICHMENT FOR 600MW PLANT

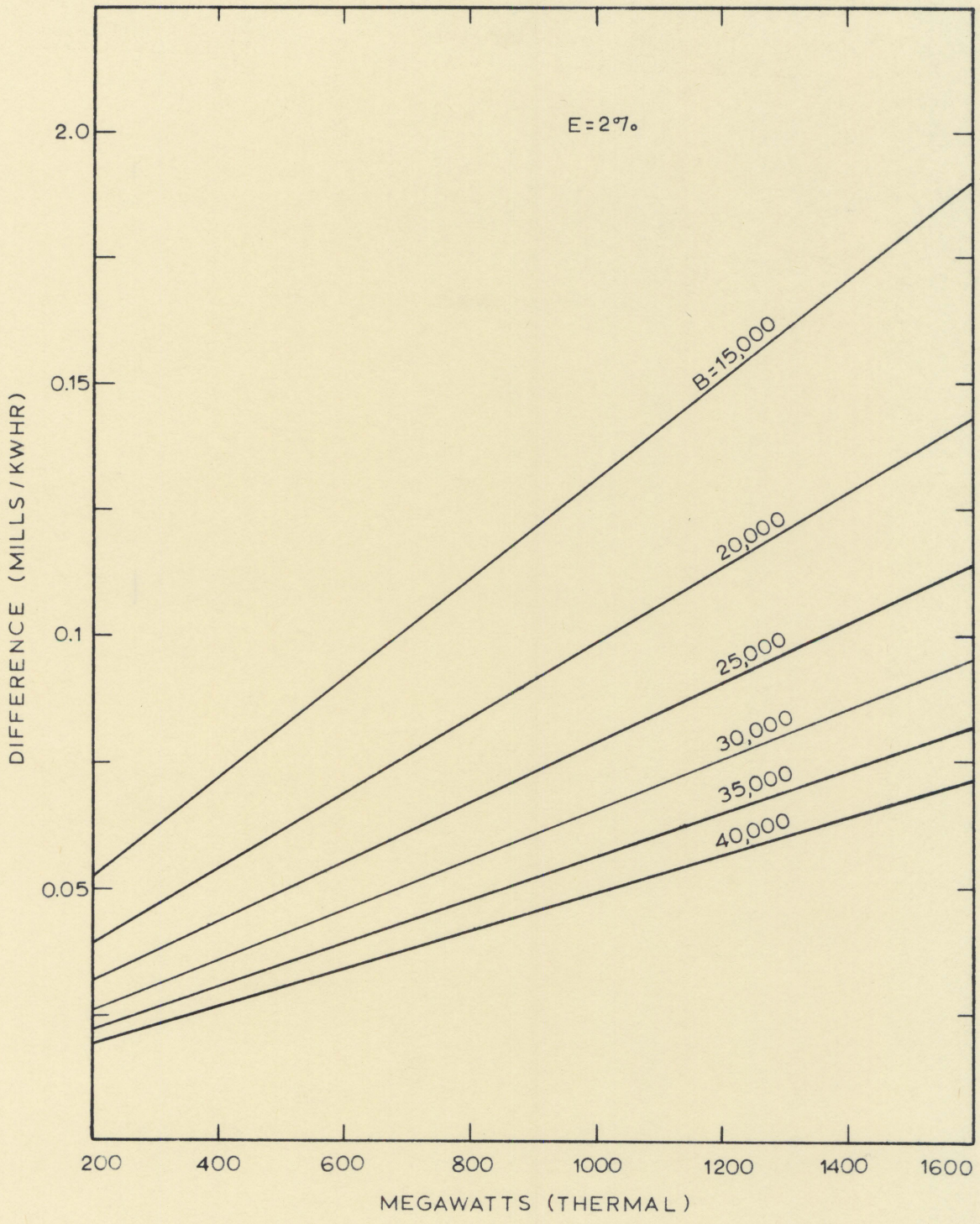

FIGURE 35. FUEL CYCLE COST DIFFERENCE BETWEEN USE CHARGE CASE FOR TWO METHODS OF COMPUTING FABRICATION TIME AS A FUNCTION OF SIZE AND BURNUP FOR E = 2%.

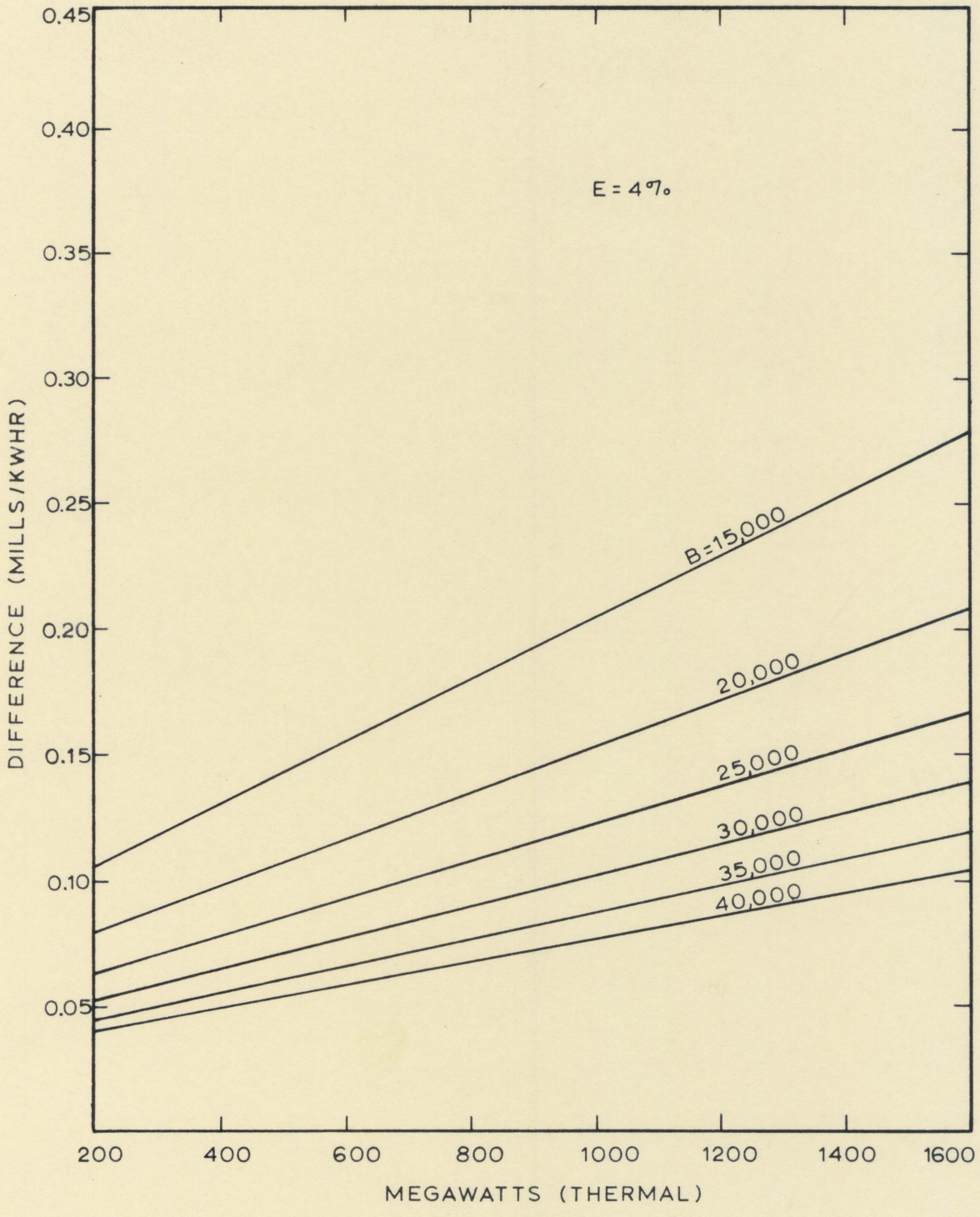

FIGURE 36. FUEL CYCLE COST DIFFERENCE BETWEEN USE CHARGE CASE FOR TWO METHODS OF COMPUTING FABRICATION TIME AS A FUNCTION OF SIZE AND BURNUP FOR E=4%

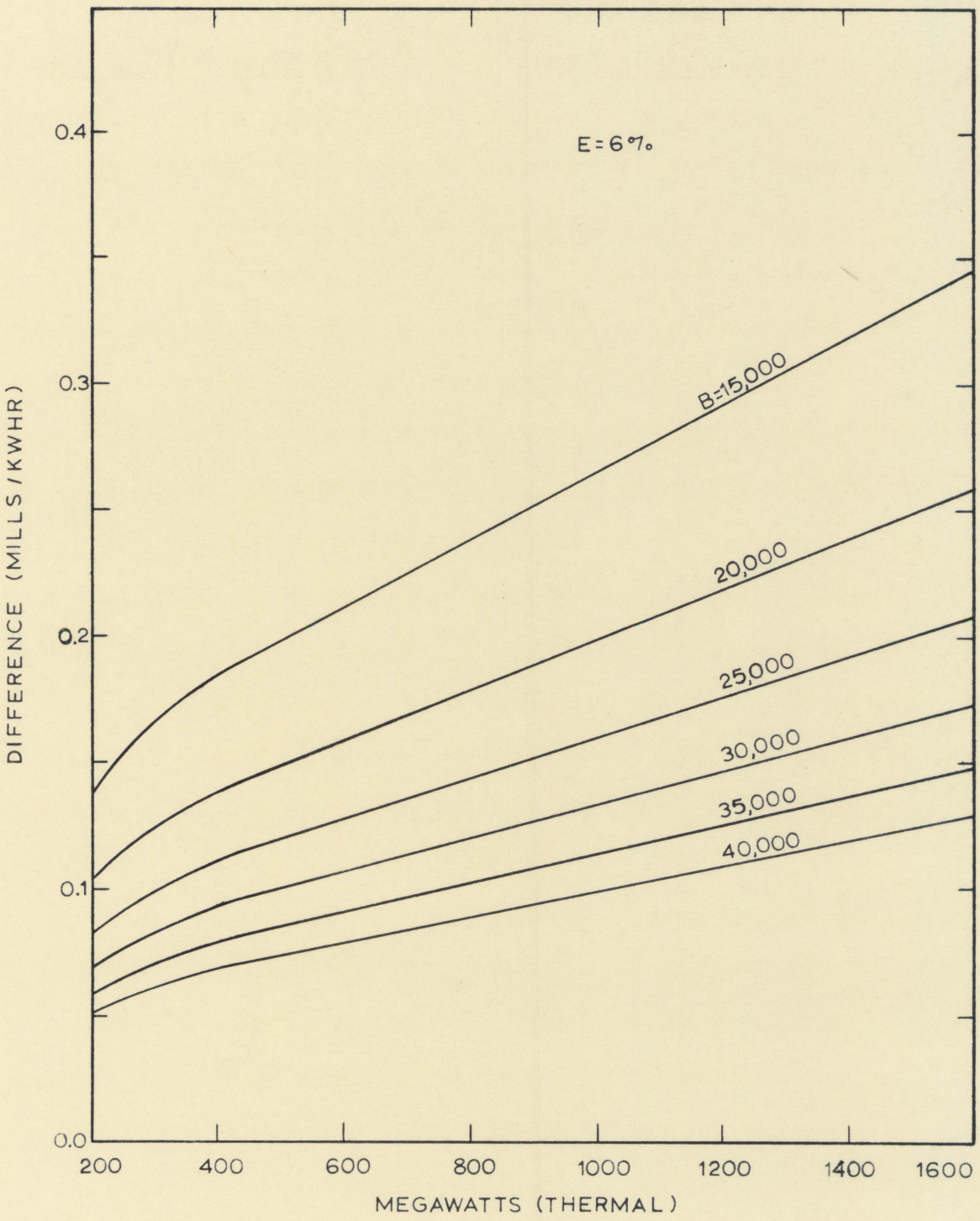

FIGURE 37. FUEL CYCLE COST DIFFERENCE BETWEEN USE CHARGE CASE FOR TWO METHODS OF COMPUTING FABRICATION TIME AS A FUNCTION OF SIZE AND BURNUP FOR E=6%

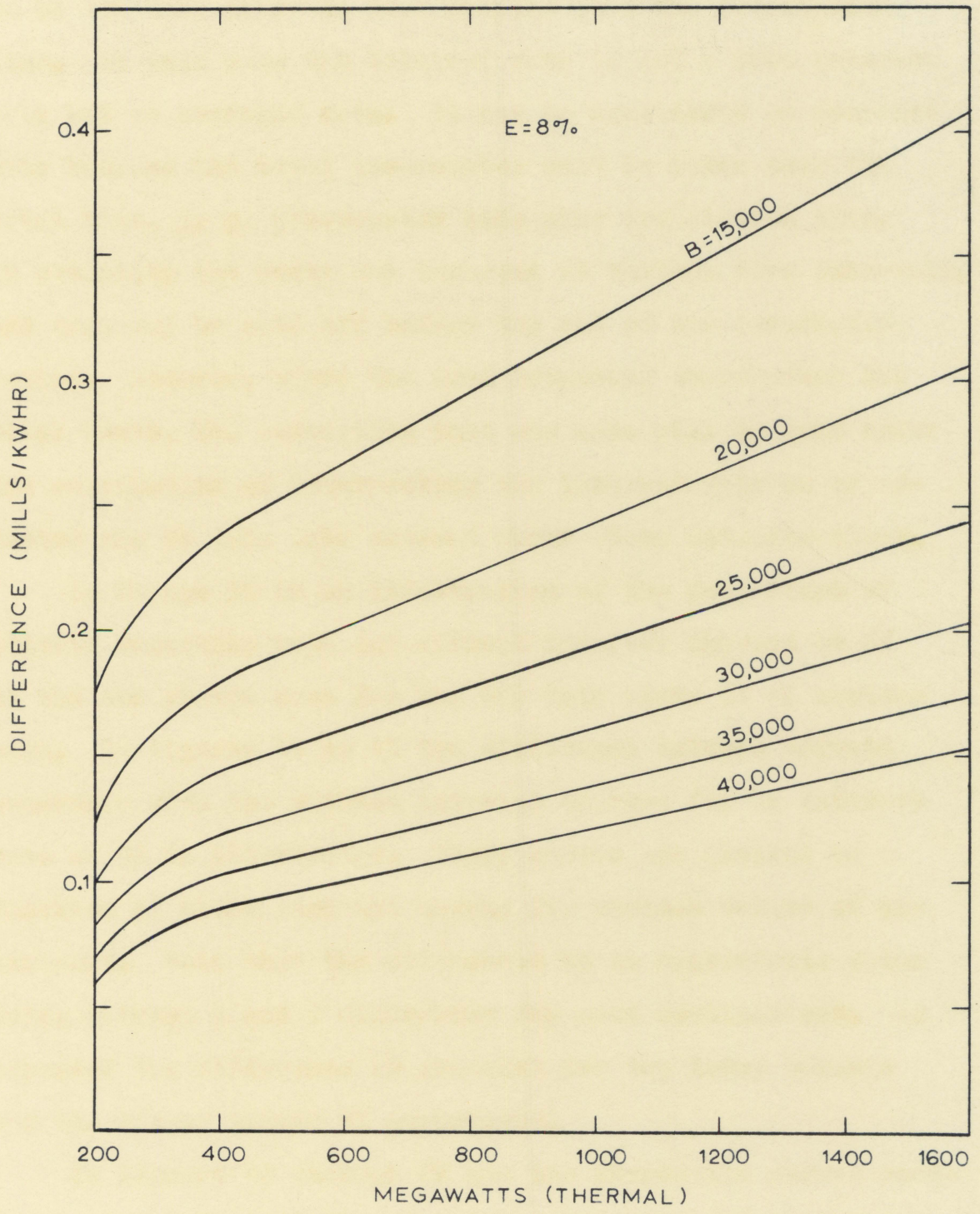

FIGURE 38. FUEL CYCLE COST DIFFERENCE BETWEEN USE CHARGE CASE FOR TWO METHODS OF COMPUTING FABRICATION TIME AS A FUNCTION OF SIZE AND BURNUP FOR E=8%

to be the time prior to fuel loading plus the irradiation time. In this case the interest rate is not a true interest rate but an averaged rate. It can be considered an averaged rate because the total pre-reactor cost is taken over the total time, i. e. pre-reactor time plus irradiation time. In actuality the costs are incurred at various time intervals, and some may be paid off before the end of the irradiation period. However, since the fuel inventory overshadows the other costs, the assumption that was made will be good under the restriction of interpreting the interest rate as an adjusted one to take into account these other considerations.

In Figure 39 is an illustration of the comparison of private ownership with and without interest charged at 8% to the use charge case for the 600 Mwth plant at 4% enrichment. In Figures 40 to 43 the difference between private ownership with and without interest charged for an interest rate of 8% is illustrated. These curves are plotted as a function of plant size and burnup for various values of enrichment. Note that the difference is an appreciable value being between 1 and 2 mills/kwhr for most combinations. As expected the difference is greatest for the lower burnups and the larger values of enrichment.

In Figures 44 through 47 are the correction curves needed to adjust the private ownership case with interest for values of interest rates other than 8%. These curves are

plotted as functions of interest rate and burnup for a given enrichment.

It can be seen from the curves just presented that the interest on the costs incurred during the fuel cycle can cause a substantial increase over the fuel cycle cost computed without the interest included. This difference may not be as great as indicated in this study since many factors enter into the financing of the costs of this magnitude. The government can be expected to give some assistance in the transition to private ownership. The area of financing is expected to be the pivot point on which the true competitiveness of nuclear power will be tested.

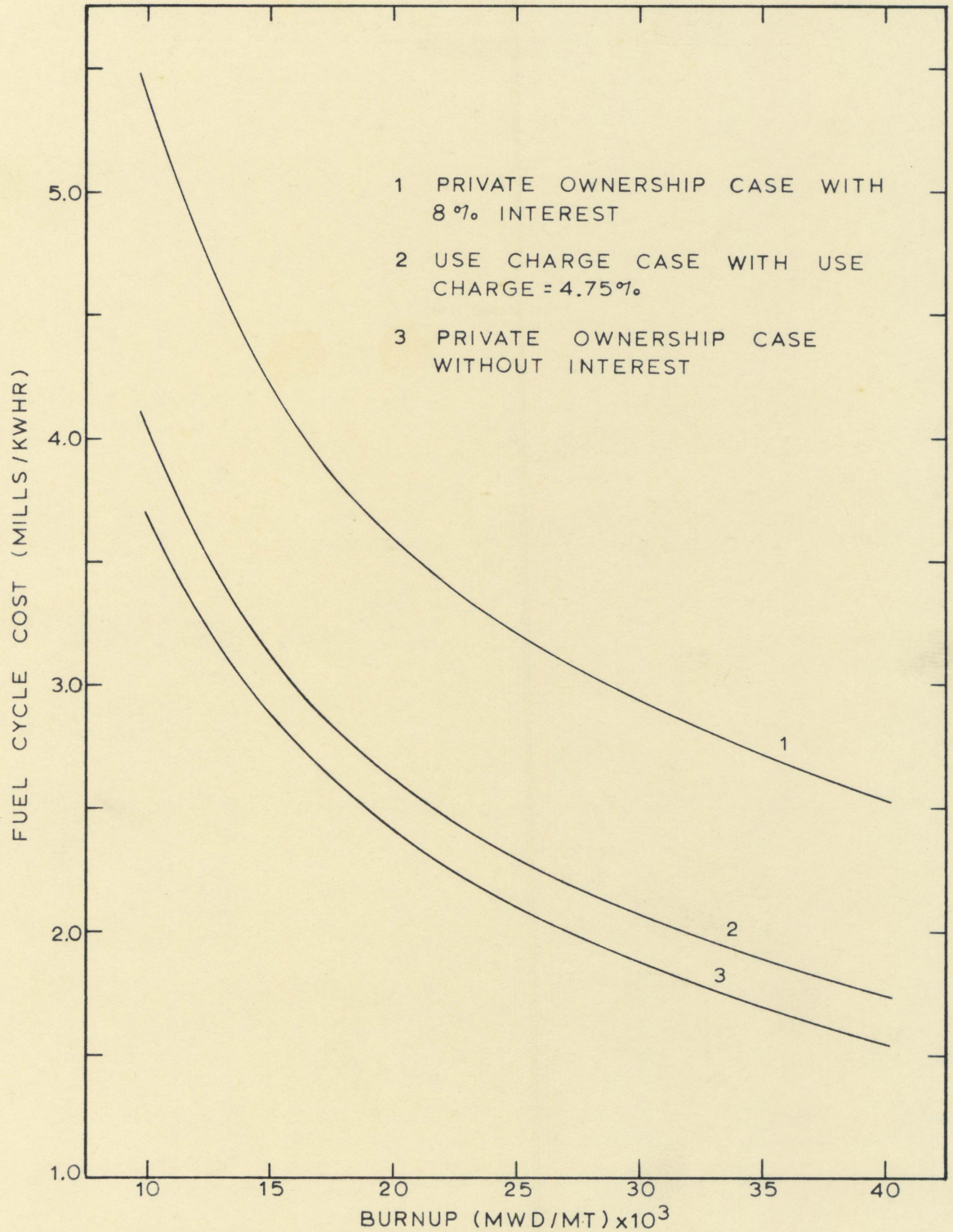

FIGURE 39. COMPARISON OF PRIVATE OWNERSHIP CASE WITH AND WITHOUT INTEREST CHARGED TO USE CHARGE CASE FOR 600 MWTH PLANT AND E=4%

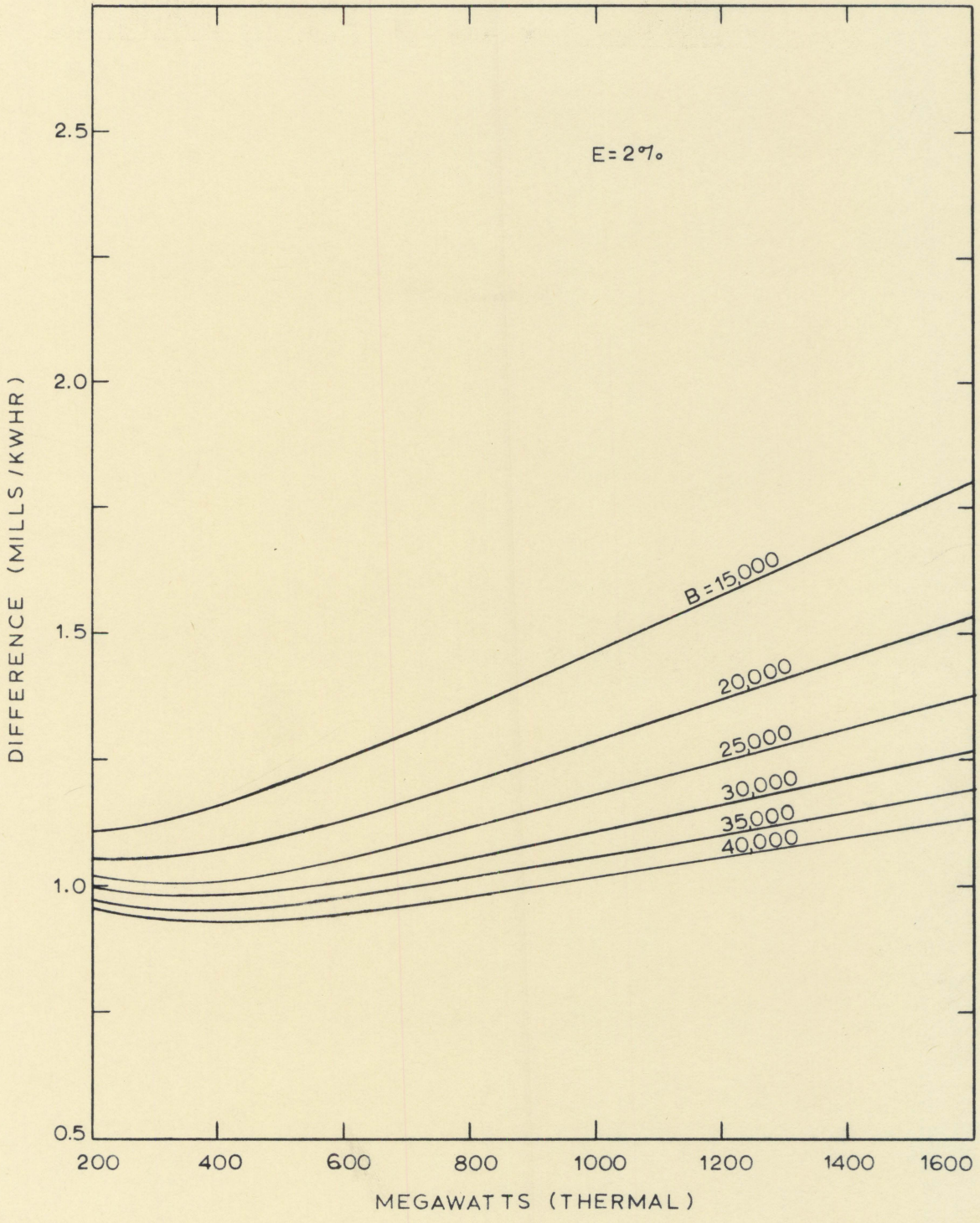

FIGURE 40. DIFFERENCE BETWEEN PRIVATE OWNERSHIP CASE WITH AND WITHOUT INTEREST CHARGED AS A FUNCTION OF SIZE AND BURNUP FOR E = 2%.

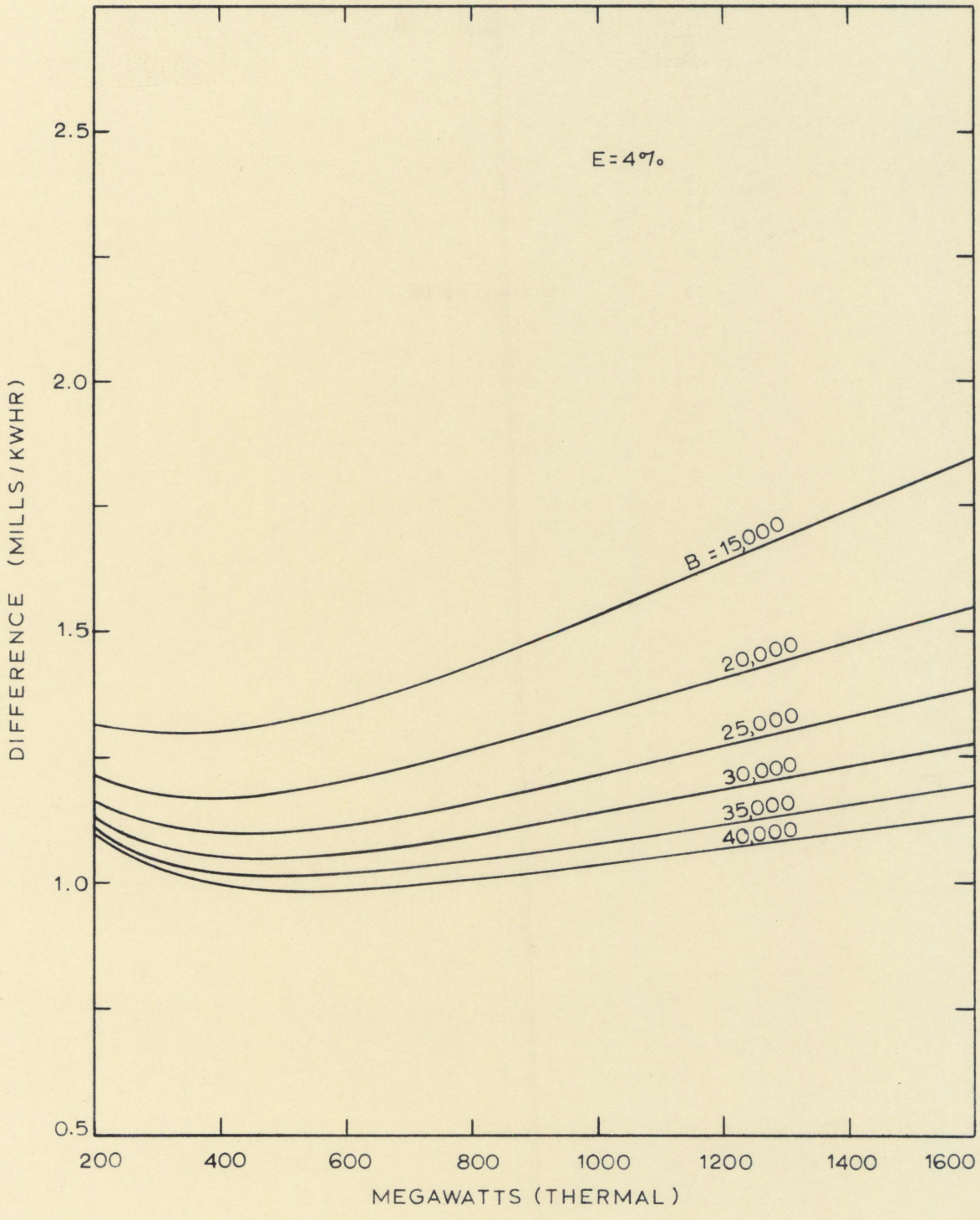

FIGURE 41. DIFFERENCE BETWEEN PRIVATE OWNERSHIP CASE WITH AND WITHOUT INTEREST CHARGED AS A FUNCTION OF SIZE AND BURNUP FOR E=4%

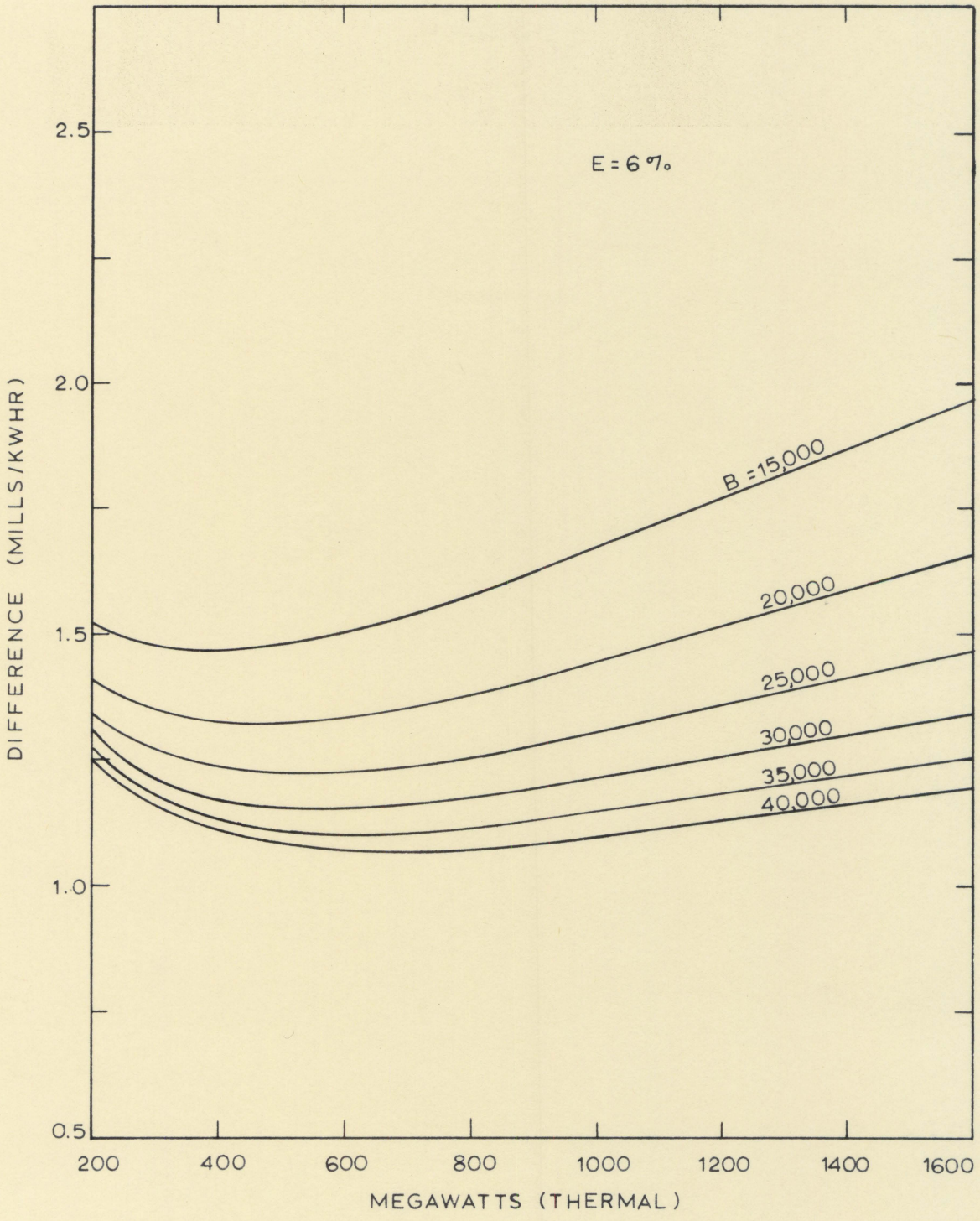

FIGURE 42. DIFFERENCE BETWEEN PRIVATE OWNERSHIP CASE WITH AND WITHOUT INTEREST CHARGED AS A FUNCTION OF SIZE AND BURNUP FOR E = 6 %

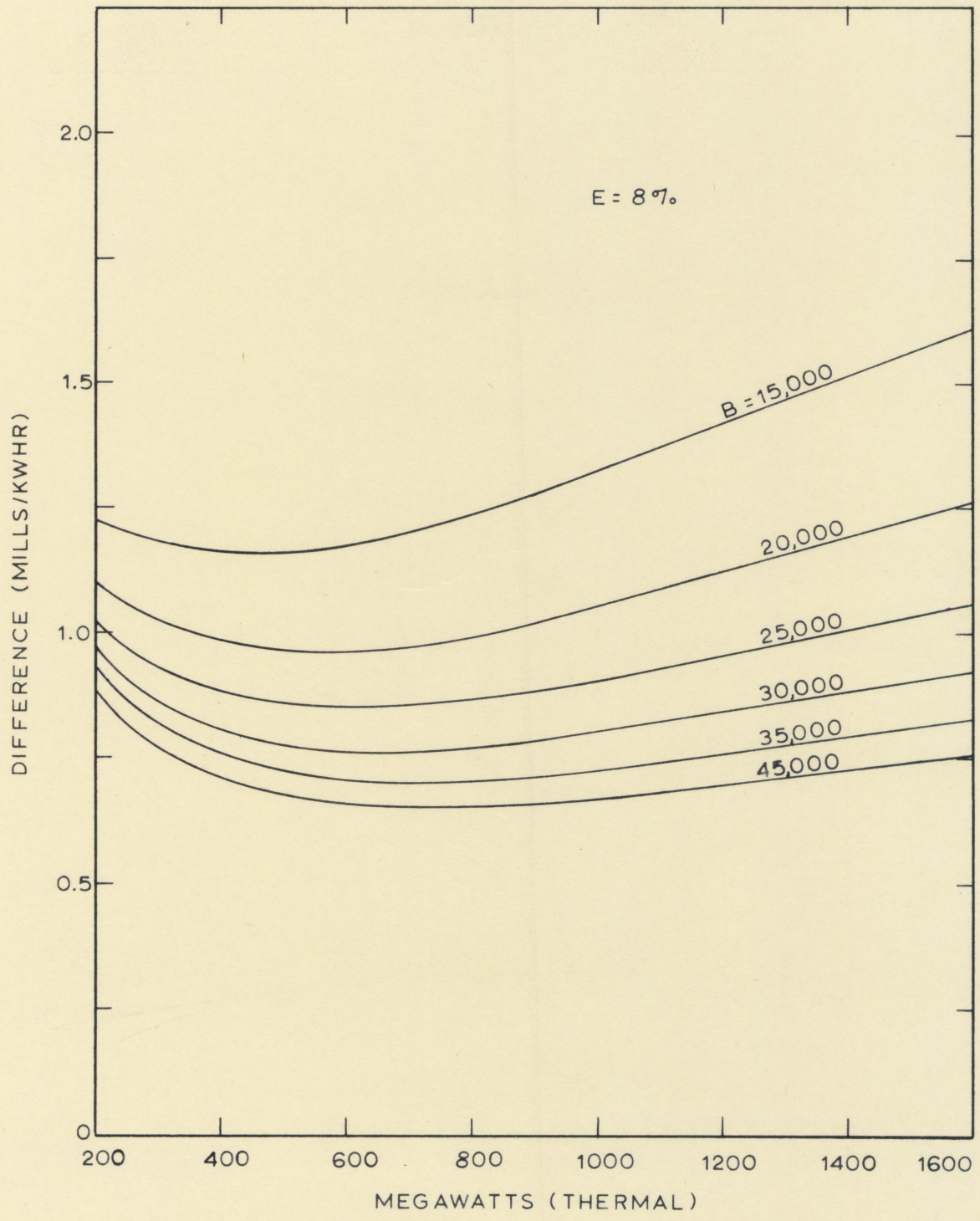

FIGURE 43. DIFFERENCE BETWEEN PRIVATE OWNERSHIP CASE WITH AND WITHOUT INTEREST CHARGED AS A FUNCTION OF SIZE AND BURNUP FOR E = 8%

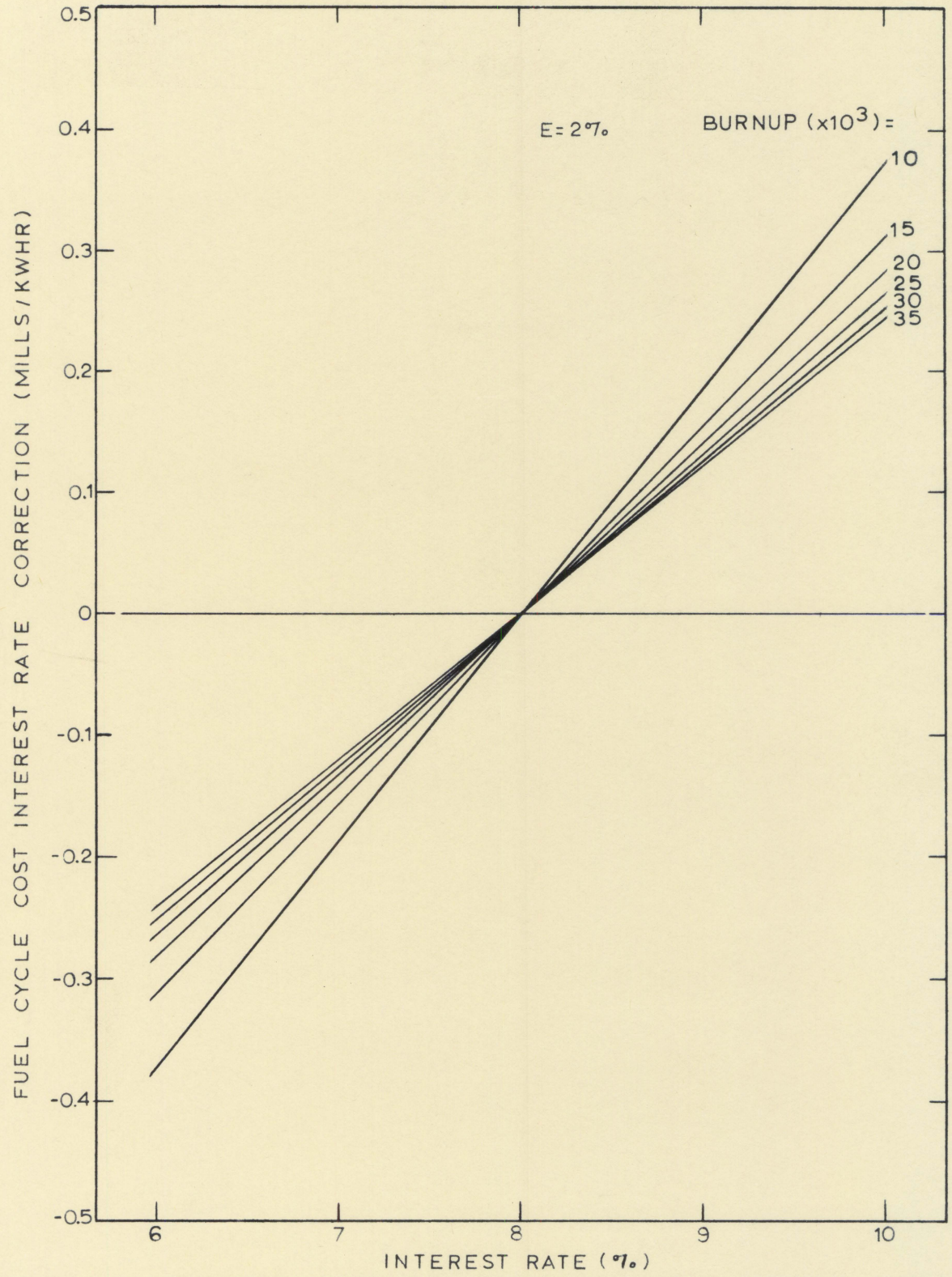

FIGURE 44. INTEREST RATE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF INTEREST RATE AND BURNUP FOR E=2%

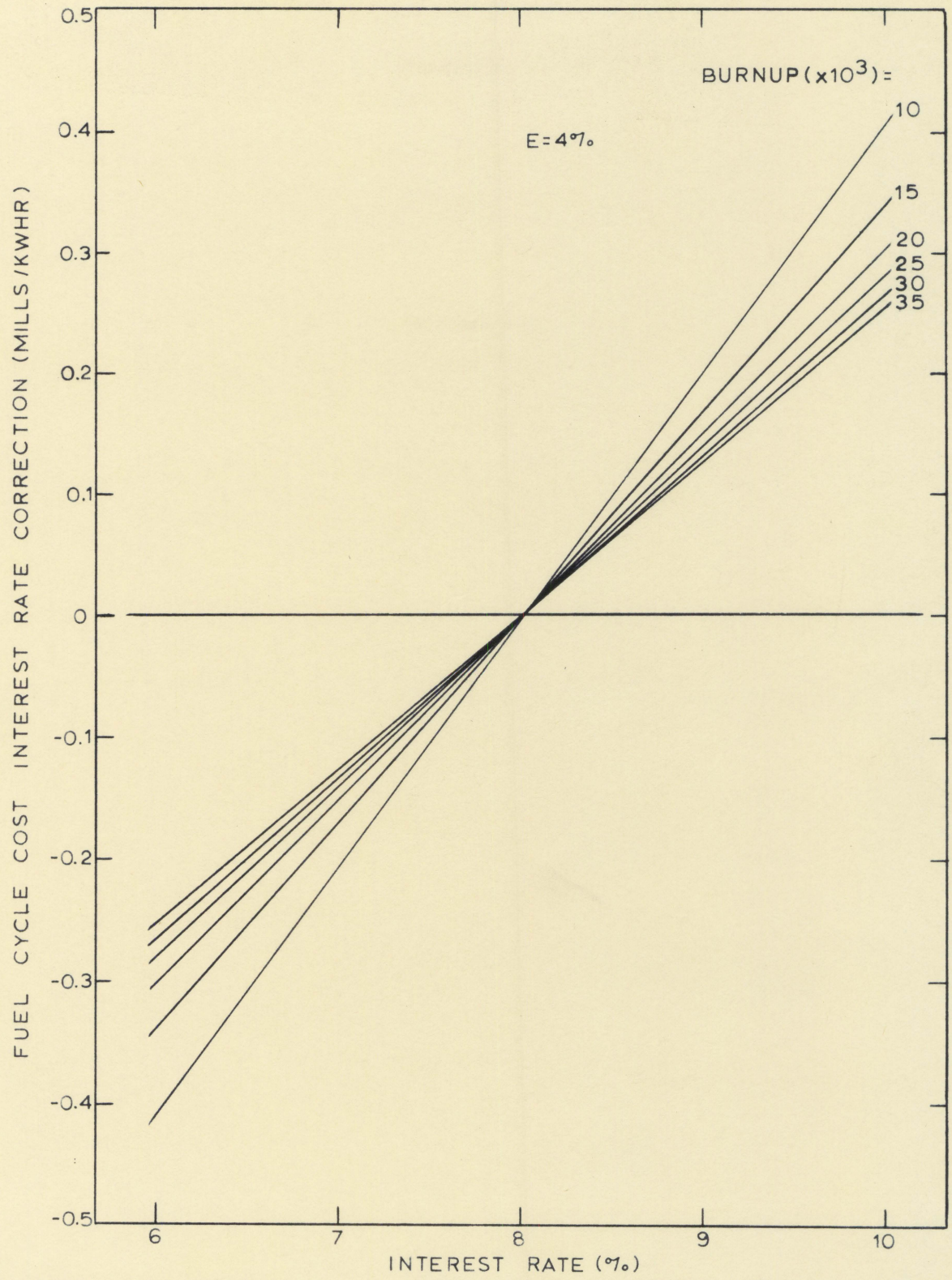

FIGURE 45. INTEREST RATE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF INTEREST RATE AND BURNUP FOR E=4%

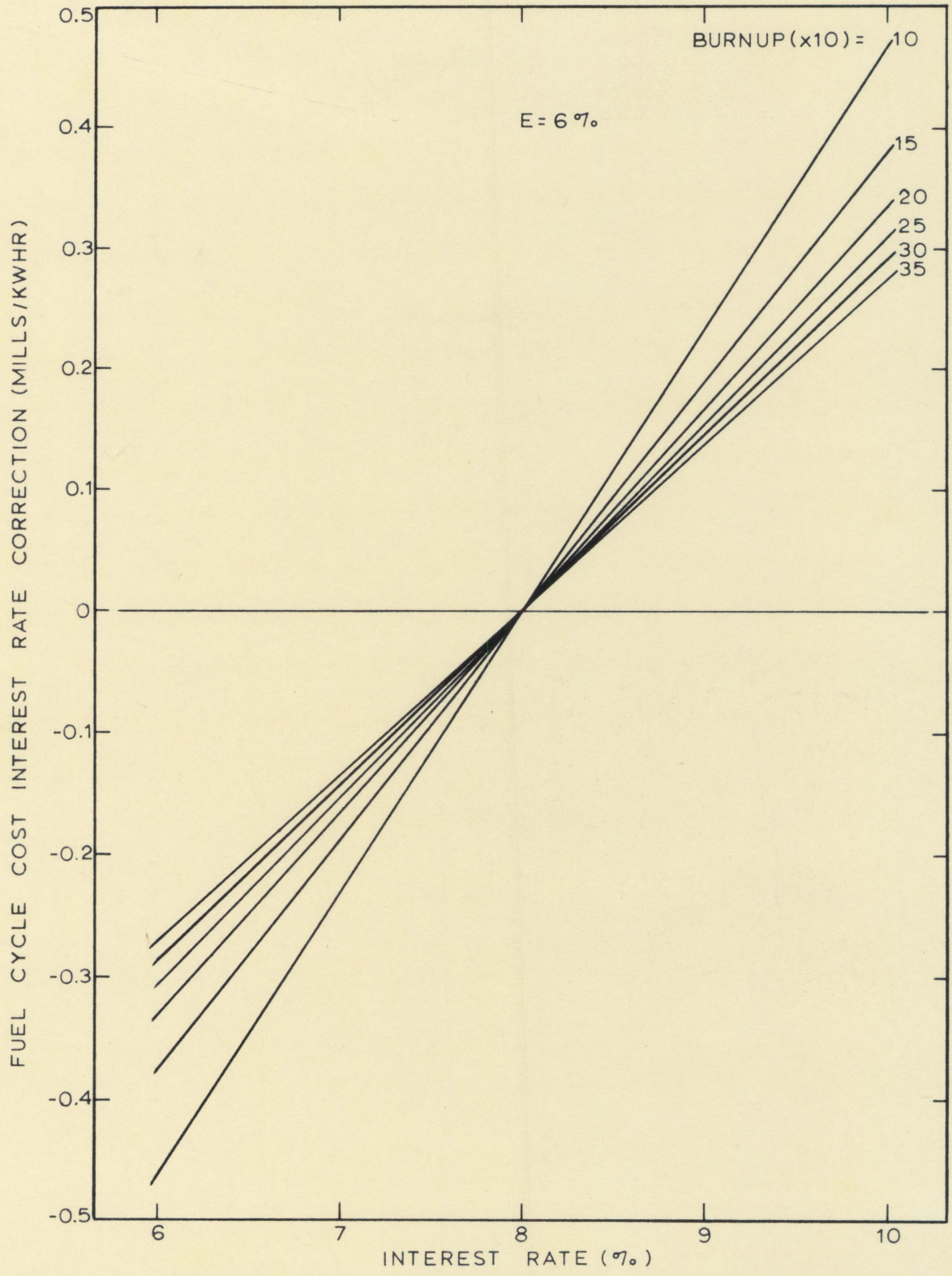

FIGURE 46. INTEREST RATE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF INTEREST RATE AND BURNUP FOR E=6%

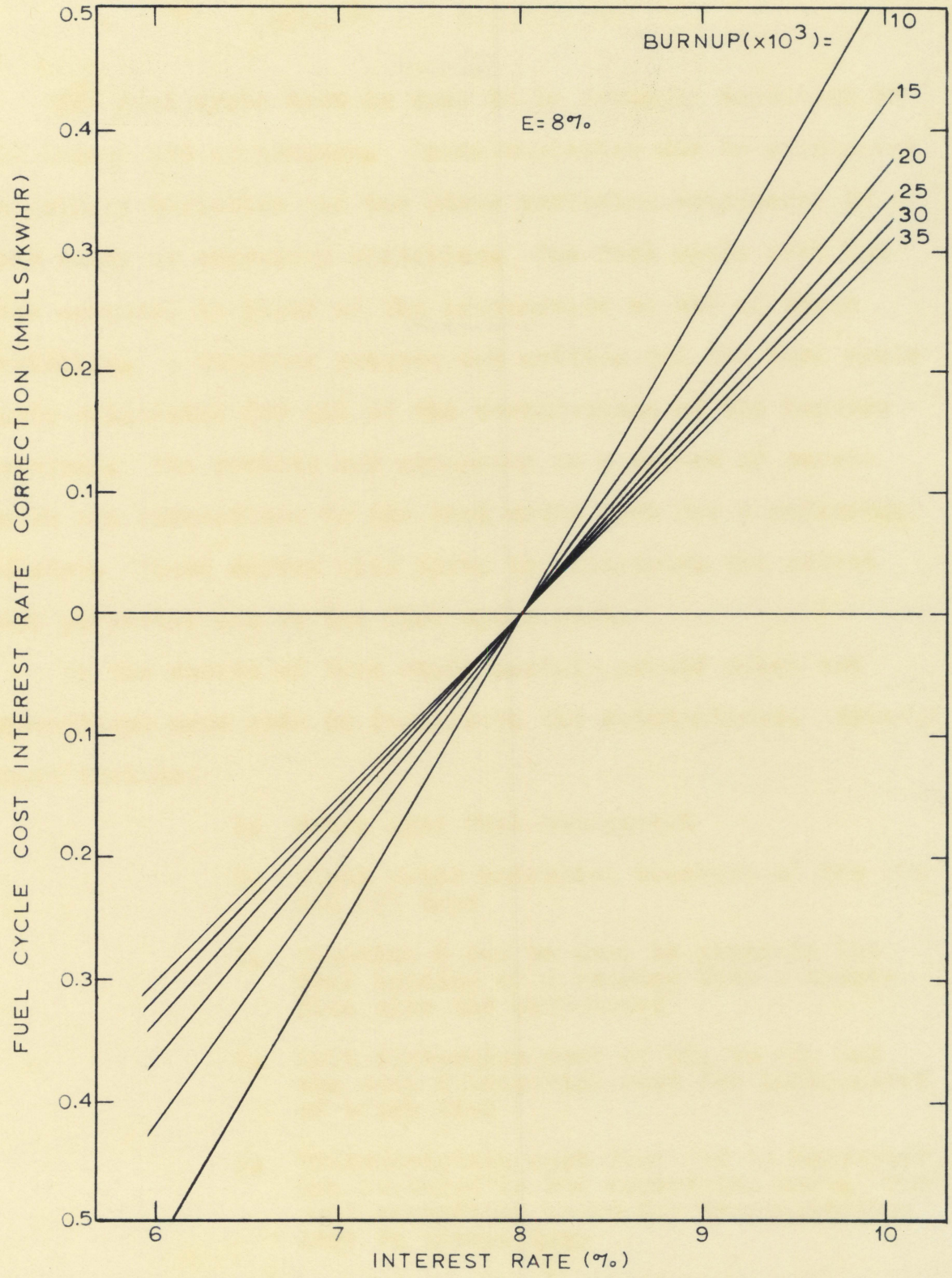

FIGURE 47. INTEREST RATE CORRECTION TO FUEL CYCLE COST AS A FUNCTION OF INTEREST RATE AND BURNUP FOR E=8%

SUMMARY AND CONCLUSIONS

The fuel cycle cost is seen to be strongly dependent on the burnup and enrichment. These variables can be considered as primary variables and the other variables considered in this study as secondary variables. The fuel cycle cost has been computed in light of the interaction of all of these variables. A computer program was written and the fuel cycle costs calculated for all of the combinations of the factors involved. The results are presented in a series of curves which are corrections to the fuel cycle cost for a reference reactor. These curves also serve to illustrate the effect each parameter has on the fuel cycle cost.

In the course of this study certain ground rules and assumptions were made to facilitate the calculations. Briefly these include:

1. Batch type fuel management
2. Light water moderated reactors of the BWR and PWR type
3. Equation 6 can be used to generate the fuel loading of a reactor with a specified size and enrichment
4. Unit conversion cost of UF_6 to UO_2 and the unit fabrication cost are independent of batch size
5. Transportation cost from AEC to converter are included in the conversion cost. The same assumption holds for transportation cost to fabricator.
6. Use charge rate set at 4.75%

7. All other values used in this study are consistent with values suggested by the AEC.

A comparison was made between the private ownership case and the use charge case. The fuel cycle cost is greater for private ownership due to the financing of the costs involved. The difference depends primarily on the fuel enrichment, average burnup and the effective interest rate for a given reactor size. It should be noted that for the use charge case the use charge is the only contribution to the cost over the bare case. For the private ownership case, the interest is computed on the fuel inventory and the pre-reactor costs. Since the fuel inventory cost is usually much greater than the pre-reactor costs (conversion, fabrication, and shipping), the comparison should be valid.

Other conclusions drawn from this study are concerned with the magnitude of the effect of changing certain of the parameters. The primary parameters have the greatest effect on the fuel cycle as could be expected. The best combination of these parameters occurs for the highest burnup possible and the lowest fuel enrichment. Of the secondary parameters, the fabrication cost and the plutonium price have the greatest effect on the fuel cycle cost.

This study has attempted to illustrate the variables which can be instrumental in lowering fuel cycle costs.

FUTURE STUDIES

Several ideas have been developed in the course of preparing this study that might warrant further research. The importance of interest rates and financing on the fuel cycle cost has been pointed out and future studies on financing methods and interest rates is needed. Because the results of this study were based on a linearized model, it should be possible to write a single equation involving all the variables and to optimize the fuel cycle cost. Also, the fuel management schemes need to be studied in greater detail as to their effect on the fuel cycle cost.

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ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. A. F. Rohach of the Department of Nuclear Engineering for his interest and helpful suggestions throughout this study, and also to Dr. Glenn Murphy, Head of the Department of Nuclear Engineering and to Iowa Power and Light Company for making this study possible.

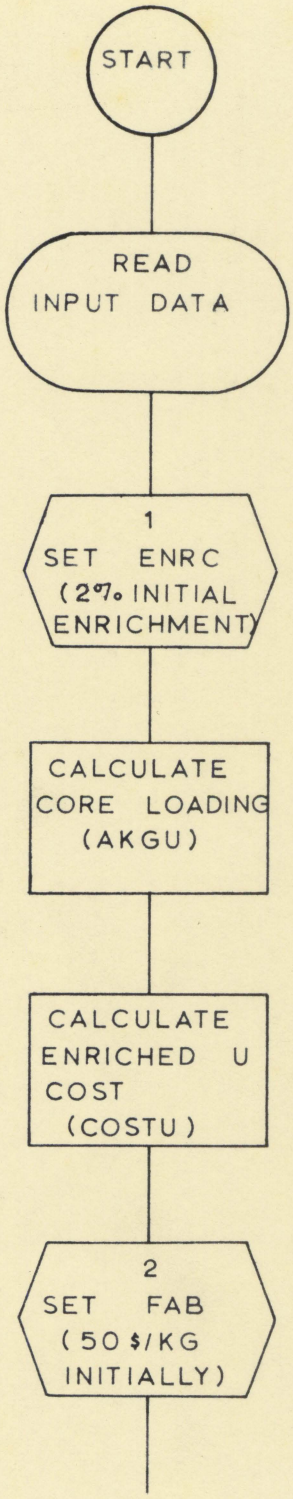
I also would like to thank my wife for her help in the preparation of this study.

APPENDIX A

Computer Flow Diagrams

The computer flow diagrams of the programs that were written for computing the fuel cycle costs are presented. These include the main program and the subprograms used to calculate plutonium buildup and enriched fuel cost.

Figure 48 shows the flow diagram of the main program used to calculate fuel cycle costs. It is set up to calculate both the private ownership and use charge cases. The initial value of each variable is listed at the point where each initiates its Do Loop. A brief description of each step is written beside the corresponding flow diagram symbol. In Figure 49 is illustrated the flow diagram used to compute the plutonium and fission product concentrations. This is based on equations given in Appendix B. Input data is based on values given in Table 7. Figure 50 shows the flow diagram of the ideal cascade equation which was used to compute enriched uranium costs. This program was also used to study the relation between the optimum waste concentration and feed cost.



INPUT DATA INCLUDES CROSS SECTIONS, LOSS FRACTIONS, AND CONSTANTS USED IN GENERATING EQUATIONS

THE ENRICHMENT DO LOOP IS SET AT ITS INITIAL VALUE

CORE LOADING IS COMPUTED BY EQUATION 6

ENRICHED URANIUM COST IS COMPUTED FROM EQUATION 8. FIGURE 50 ILLUSTRATES THE COMPUTER SOLUTION TO THIS EQUATION

THE FABRICATION COST DO LOOP IS SET AT ITS INITIAL VALUE

FIGURE 48. FLOW DIAGRAM FOR MAIN COMPUTER PROGRAM

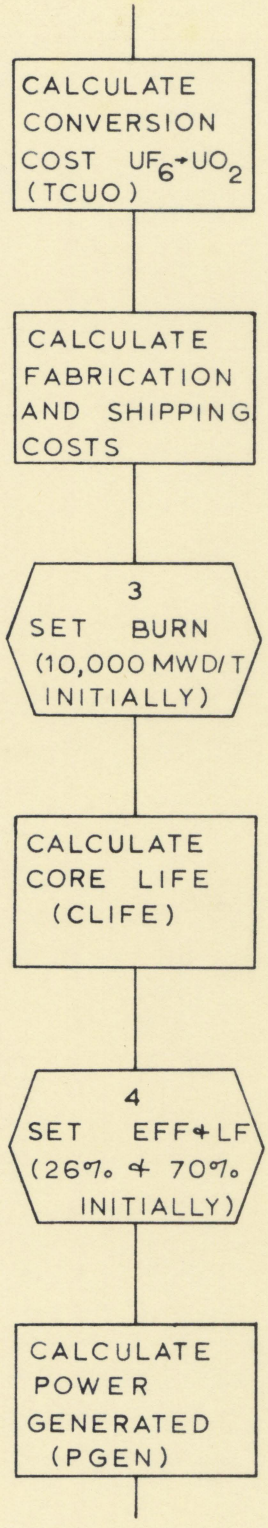
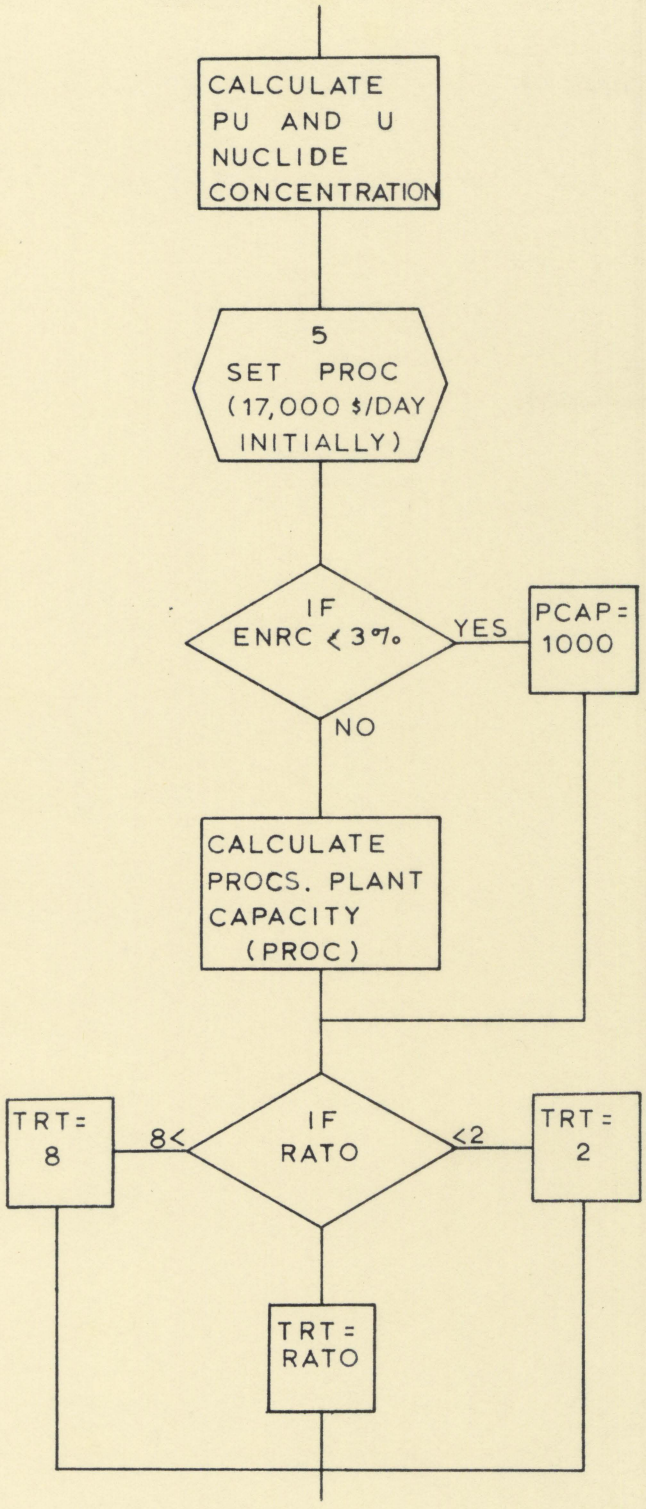


FIGURE 48 CONTINUED



SEE APPENDIX B AND THE FLOW DIAGRAM IN FIGURE 49

THE PROCESSING PLANT DAILY CHARGE DO LOOP IS SET AT ITS INITIAL VALUE

TEST THE VALUE OF ENRC AND BRANCH AS INDICATED

PROCESSING PLANT CAPACITY IS COMPUTED BY EQUATION 9

TEST RATO (W/R IN EQ. 2) AND BRANCH AS INDICATED

FIGURE 48 CONTINUED

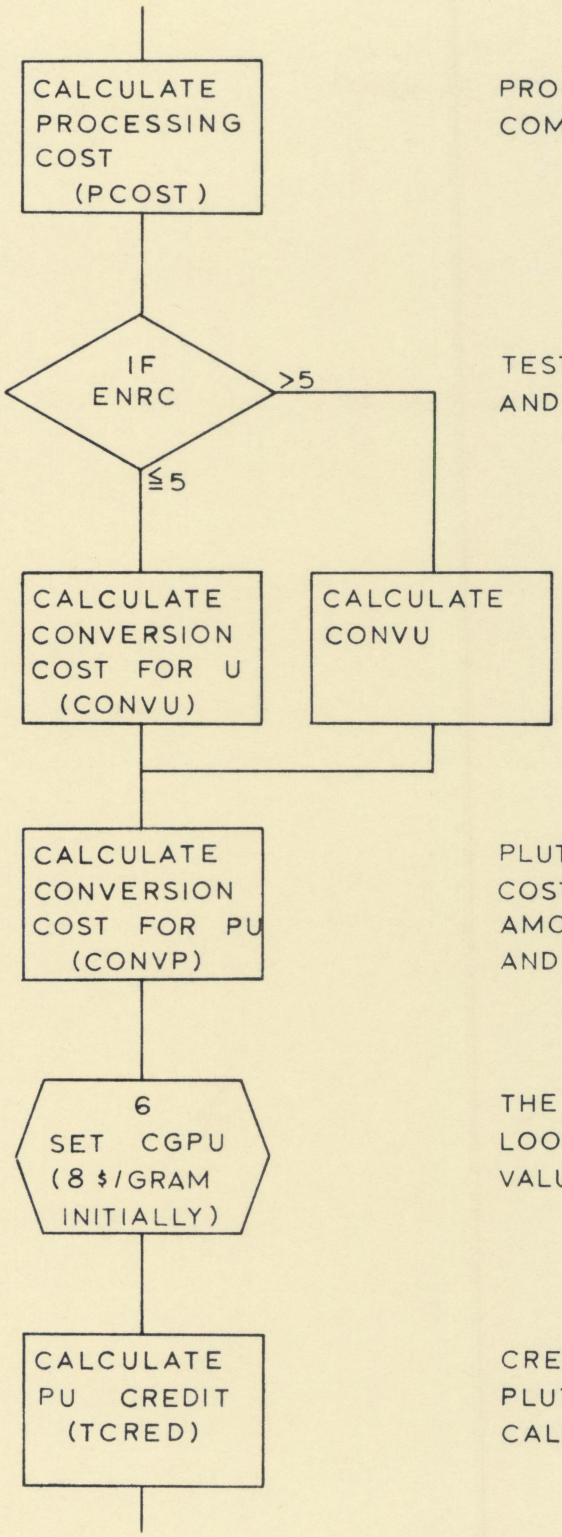


FIGURE 48 CONTINUED

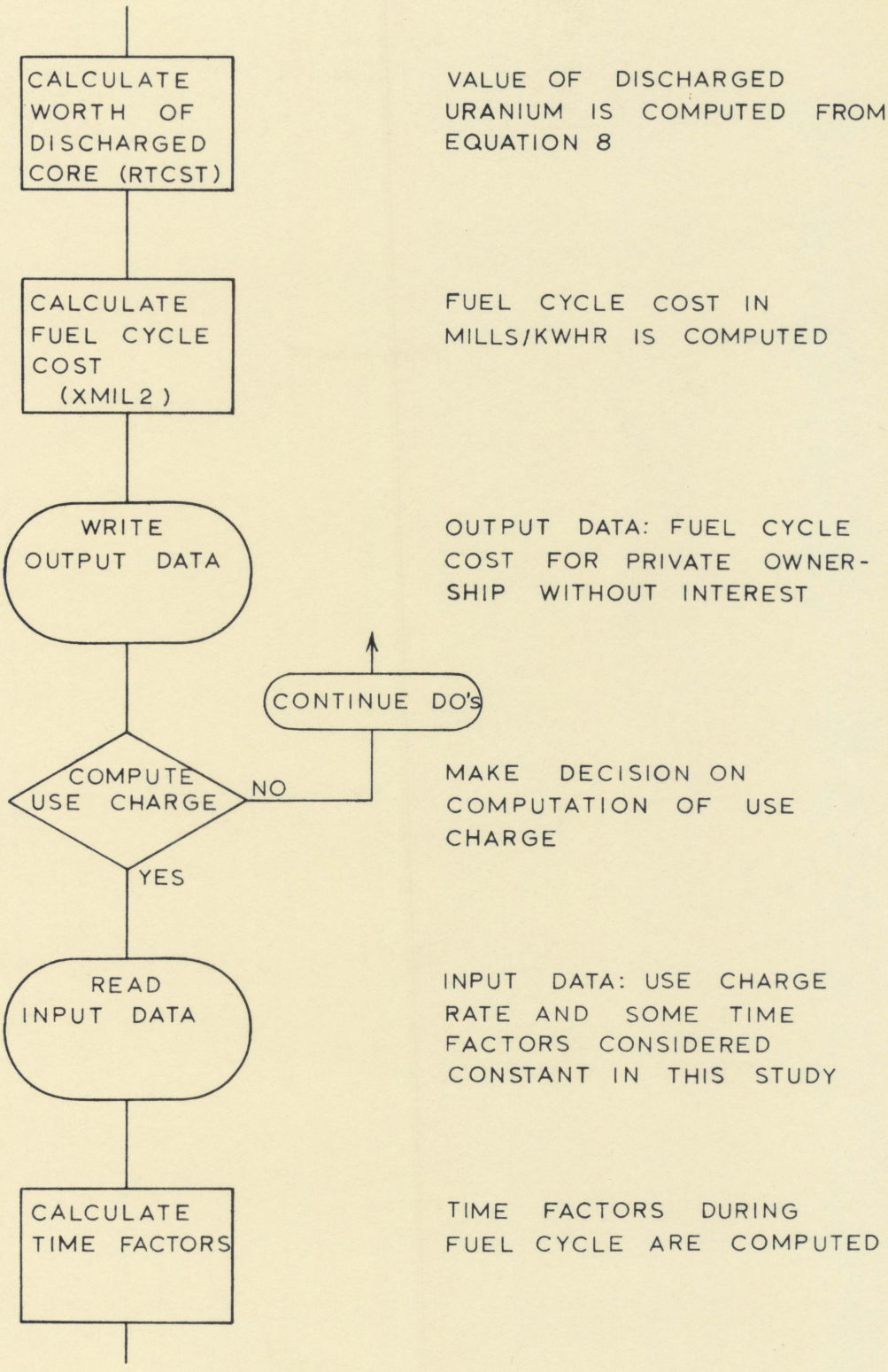


FIGURE 48 CONTINUED

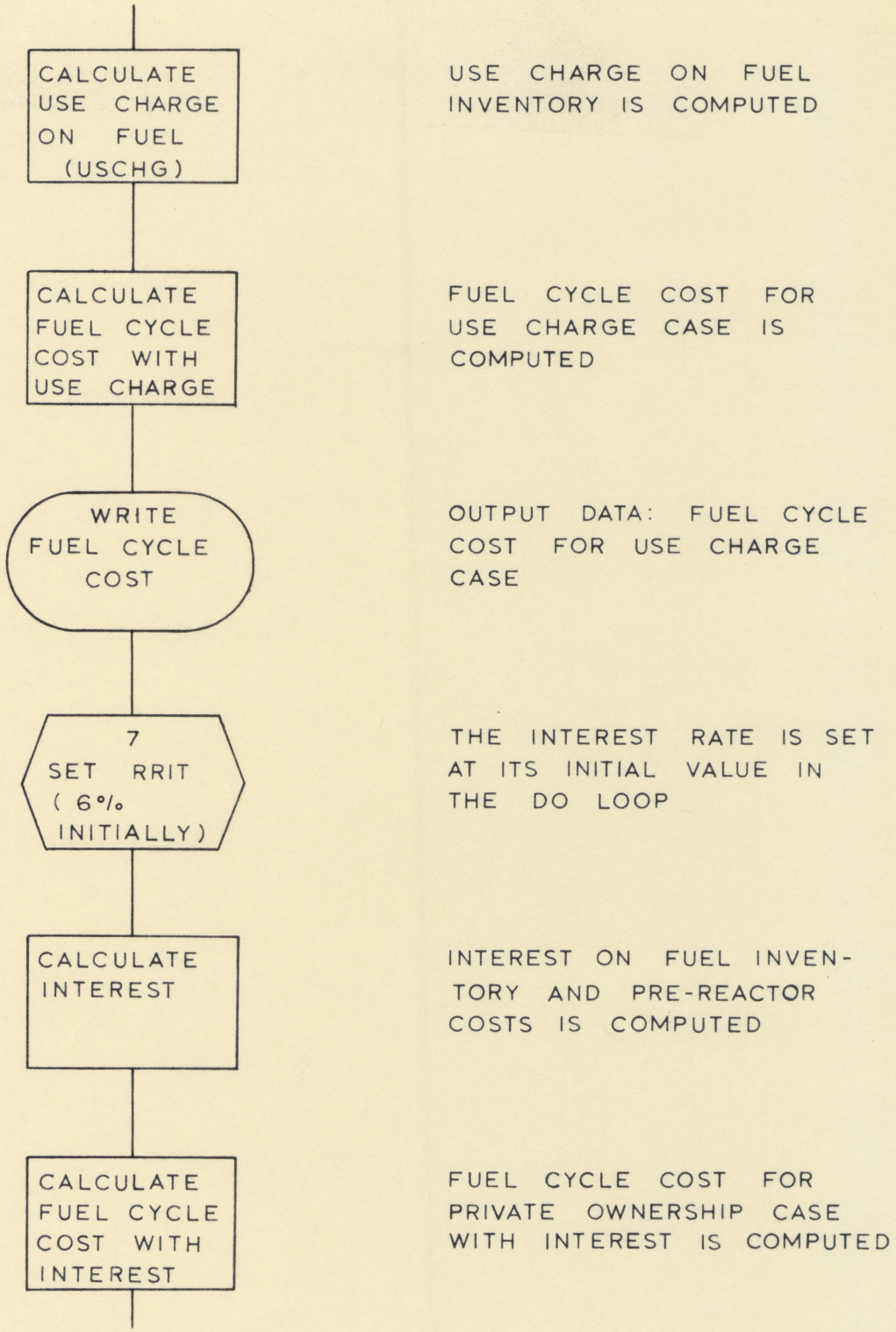
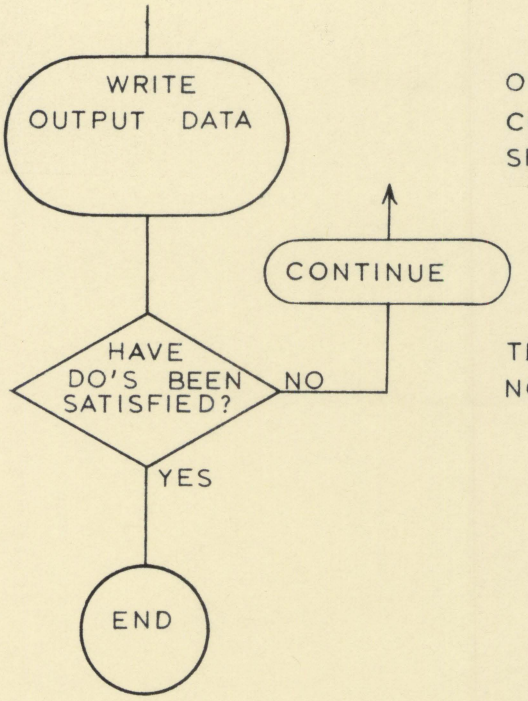


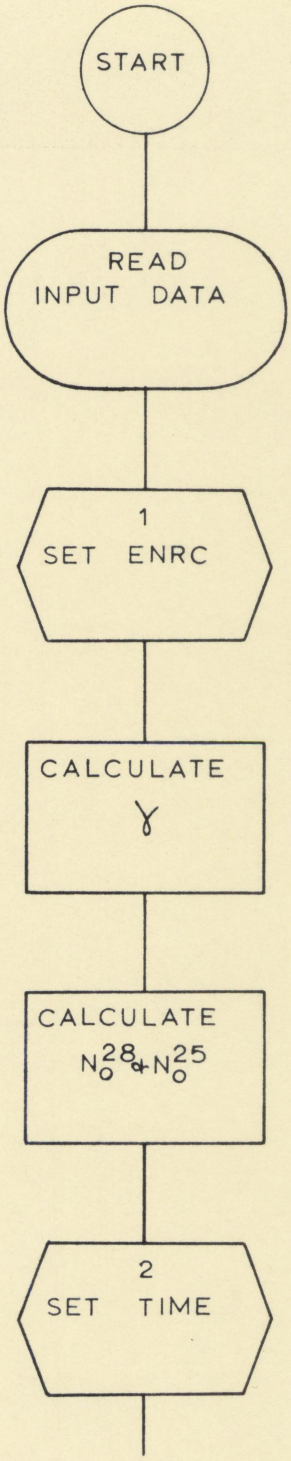
FIGURE 48 CONTINUED



OUTPUT DATA: FUEL CYCLE COST FOR PRIVATE OWNERSHIP CASE WITH INTEREST

TEST DO LOOP'S AND IF NOT SATISFIED, CONTINUE

FIGURE 48 CONTINUED



INPUT DATA: CROSS SECTIONS AND CONSTANTS

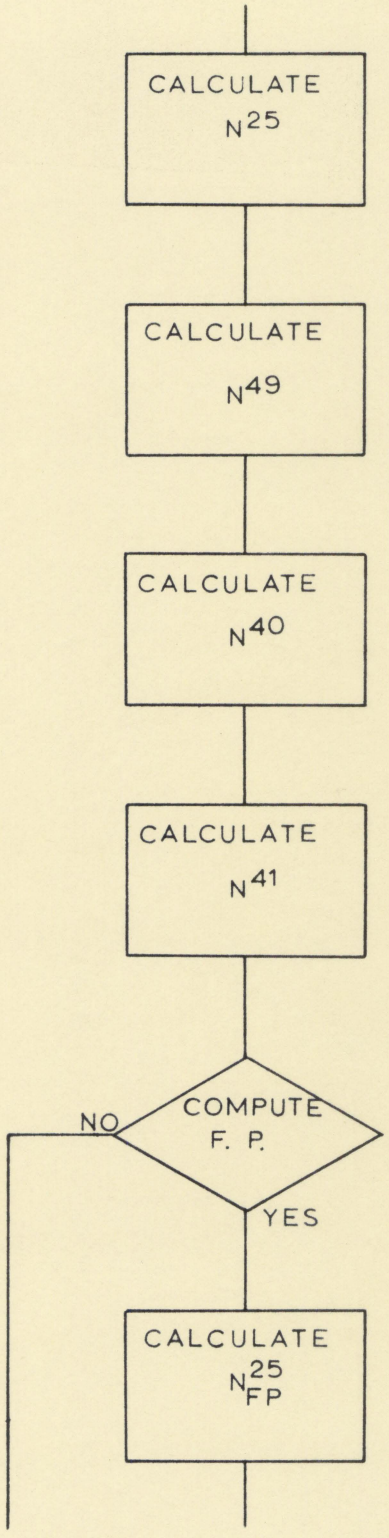
FUEL ENRICHMENT IS SET AT ITS INITIAL VALUE

$\gamma = 1 - \eta_{49} \epsilon P_1 (1-p)$

INITIAL U-235 AND U-238 CONCENTRATIONS COMPUTED

IRRADIATION TIME DO LOOP IS SET INITIALLY

FIGURE 49. FLOW DIAGRAM FOR SOLUTION OF PLUTONIUM BUILDUP EQUATIONS



U-235 CONCENTRATION IS COMPUTED BY EQUATION 11

PU-239 CONCENTRATION IS COMPUTED BY EQUATION 12

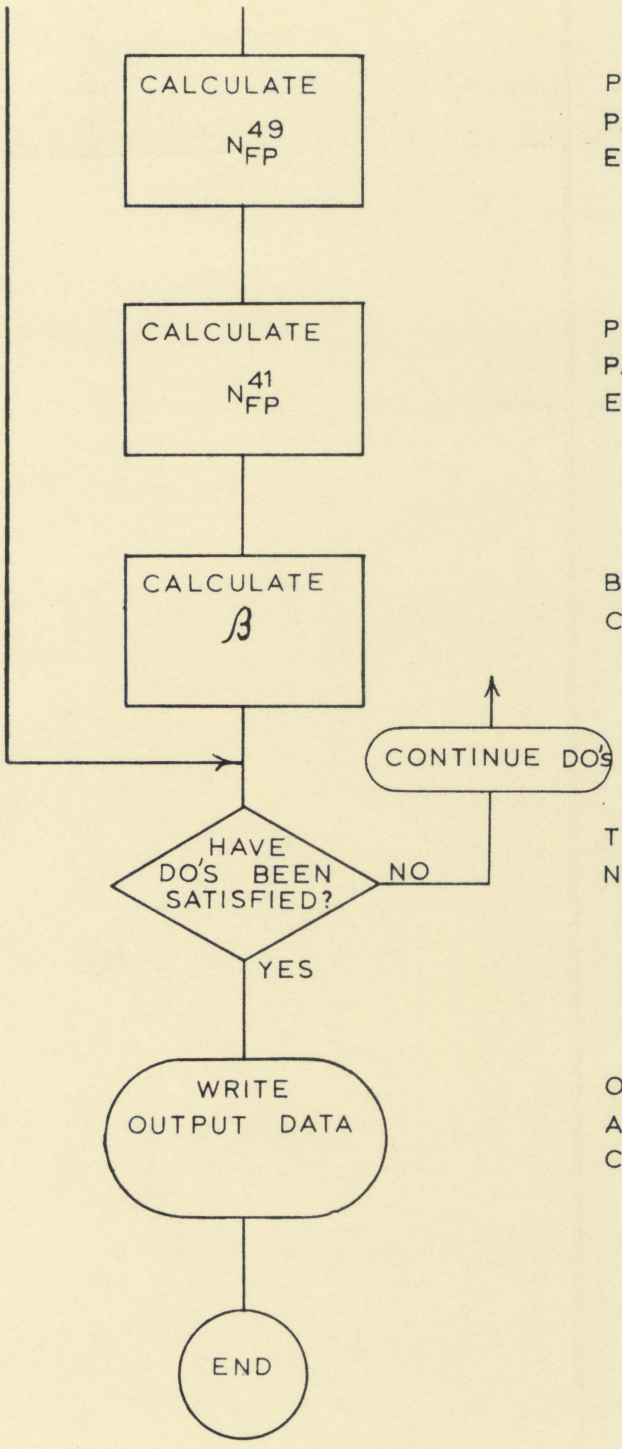
PU-240 CONCENTRATION IS COMPUTED BY EQUATION 13

PU-241 CONCENTRATION IS COMPUTED BY EQUATION 14

MAKE DECISION ON COMPUTATION OF FISSION PRODUCTS

U-235 FISSION PRODUCT PAIRS COMPUTED FROM EQUATION 15

FIGURE 49 CONTINUED



PU-239 FISSION PRODUCT PAIRS COMPUTED FROM EQUATION 16

PU-241 FISSION PRODUCT PAIRS COMPUTED FROM EQUATION 17

BURNUP FRACTION (β) IS COMPUTED BY EQUATION 18

TEST DO LOOP'S AND IF NOT SATISFIED, CONTINUE

OUTPUT DATA: ISOTOPE AND/OR FISSION PRODUCT CONCENTRATION

FIGURE 49 CONTINUED

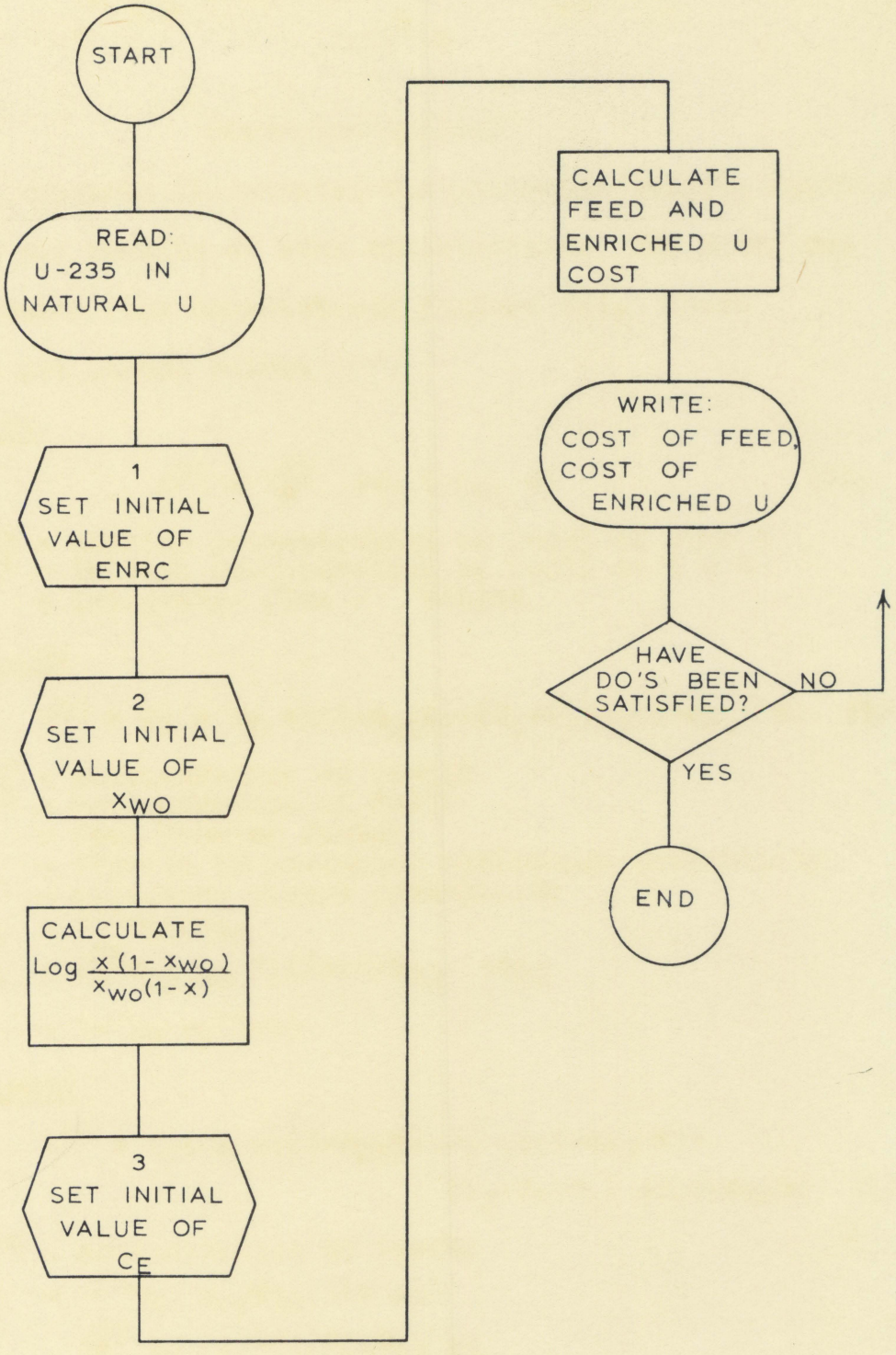


FIGURE 50. FLOW DIAGRAM FOR SOLUTION OF IDEAL CASCADE EQUATION

APPENDIX B

Plutonium Buildup

This appendix illustrates the plutonium buildup equation and gives the results of some computations. The equations used are taken from Benedict and Pigford (1). These equations are listed below.

Uranium-235

$$N^{25} = N_o^{25} \exp(-\sigma_{25}\theta) \qquad (11)$$

where, N^{25} = nuclide concentration of U-235 at time t
N_o^{25} = initial concentration of U-235 at t = 0
θ = integrated flux = $\int_0^t \phi(t)dt$

Plutonium-239

$$N^{49} = C_1 + C_2 \exp(-\sigma_{25}\theta) - (C_1+C_2)\exp(-\sigma_{49}\gamma\theta) \qquad (12)$$

where, N^{49} = concentration of Pu-239
N^{28} = concentration of U-238
ϵ = fast fission factor
P_1 = fission to resonance nonleakage probability
p = resonance escape probability
$C_1 = N^{28}\sigma_{28}/\sigma_{49}$
$C_2 = N_o^{25}\sigma_{25}\eta_{25}\epsilon P_1(1-p)/\sigma_{49}\gamma - \sigma_{25}$
$\gamma = 1-\eta_{49}\epsilon P_1(1-p)$

Plutonium-240

$$N^{40} = C_3+C_4 \exp(-\sigma_{25}\theta)+C_5 \exp(-\sigma_{49}\gamma\theta) - (C_3+C_4+C_5) \exp(-\sigma_{40}\theta) \qquad (13)$$

where, N^{40} = concentration of Pu-240
$C_3 = N^{28}\sigma_{28}\alpha_{49}/\sigma_{40}\ (1+\alpha_{49})$
$C_4 = \dfrac{N_o^{25}\ 25\ P_1(1-p)\sigma_{25}\sigma_{49}\alpha_{49}}{(1+\alpha_{49})(\sigma_{25}-\sigma_{49}\gamma)(\sigma_{25}-\sigma_{40})}$

$$C_5 = \frac{C_3\sigma_{40}}{\sigma_{49}-\sigma_{40}} - \frac{C_4(\sigma_{25}-\sigma_{40})}{\sigma_{49}-\sigma_{40}}$$

Plutonium-241

$$N^{41} = C_6+C_7\exp(-\sigma_{25}\theta)+C_8\exp(-\sigma_{49}\gamma\theta)+C_9\exp(-\sigma_{40}\theta)-(C_6+C_7+C_8+C_9)\exp(-\sigma_{41}\theta) \quad (14)$$

where, N^{41} = concentration of Pu-241
$C_6 = C_3\sigma_{40}/\sigma_{41}$
$C_7 = -C_4\sigma_{40}/(\sigma_{25}-\sigma_{41})$
$C_8 = -C_5\sigma_{40}/(\sigma_{49}-\sigma_{41})$
$C_9 = (C_3+C_4+C_5)\sigma_{40}/(\sigma_{40}-\sigma_{41})$

The computer program also calculates the fission product buildup during irradiation. These equations present the concentrations as a function of θ using many of the calculations from the isotope equations. These equations are listed below.

Uranium-235 fission products

$$N_F^{25} = N_o^{25}(1-\exp(-\sigma_{25}\theta))/(1+\alpha_{25}) \quad (15)$$

Plutonium-239 fission products

$$N_F^{49} = \frac{\sigma_{49}}{1+\alpha_{49}}\left[C_1\theta+C_2(1-\exp(-\sigma_{25}\theta))/\sigma_{25} - (C_1+C_2)(1-\exp(-\sigma_{49}\gamma\theta))/\sigma_{49}\right] \quad (16)$$

Plutonium-241 fission products

$$N_F^{41} = \frac{\sigma_{41}}{1+\alpha_{41}}\left[C_6\theta+C_7(1-\exp(-\sigma_{25}\theta))/\sigma_{25}+ C_8(1-\exp(-\sigma_{49}\gamma\theta))/\sigma_{49} + C_9(1-\exp(-\sigma_{40}\theta))/\sigma_{40} - (C_6+C_7+C_8+C_9)(1-\exp(-\sigma_{41}\theta))/\sigma_{41}\right] \quad (17)$$

Also the burnup fraction (β) was computed from the fission product concentration by the following equation.

$$\beta = N_F / N_o^{25} + N_o^{28} \qquad (18)$$

where, $N_F = N_F^{25} + N_F^{49} + N_F^{41}$

Figure 51 illustrates the change in plutonium isotope concentration as a function of flux-time (θ) and fuel enrichment. Figure 52 shows the corresponding fission product buildup. The amount of plutonium produced as a function of burnup(B) and enrichment is shown in Figure 53. Note that production increases with enrichment and goes through a maximum at a specific burnup. This corresponds to the point where the plutonium is being fissioned at a faster rate than it is being produced. These curves are based on the parameter values given in Table 7. It should be noted that cross sections, η, and α are for a temperature of 400° C. The other parameters are arbitrarily chosen to represent a typical water moderated power reactor.

Table 7. Parameters used in calculating plutonium buildup

ISOTOPE	σ_a	η	α
U-235	378 barns	2.08	0.184
U-238	1.64 barns	0	-
Pu-239	1660 barns	1.83	0.573
Pu-240	2249 barns	0	-
Pu-241	1409 barns	2.14	0.345

$\epsilon = 1.027$ $\quad p = 0.90$

$P_1 = 0.964$ $\quad \bar{\phi} = 3.75 \times 10^{13}$ n/cm^2-sec

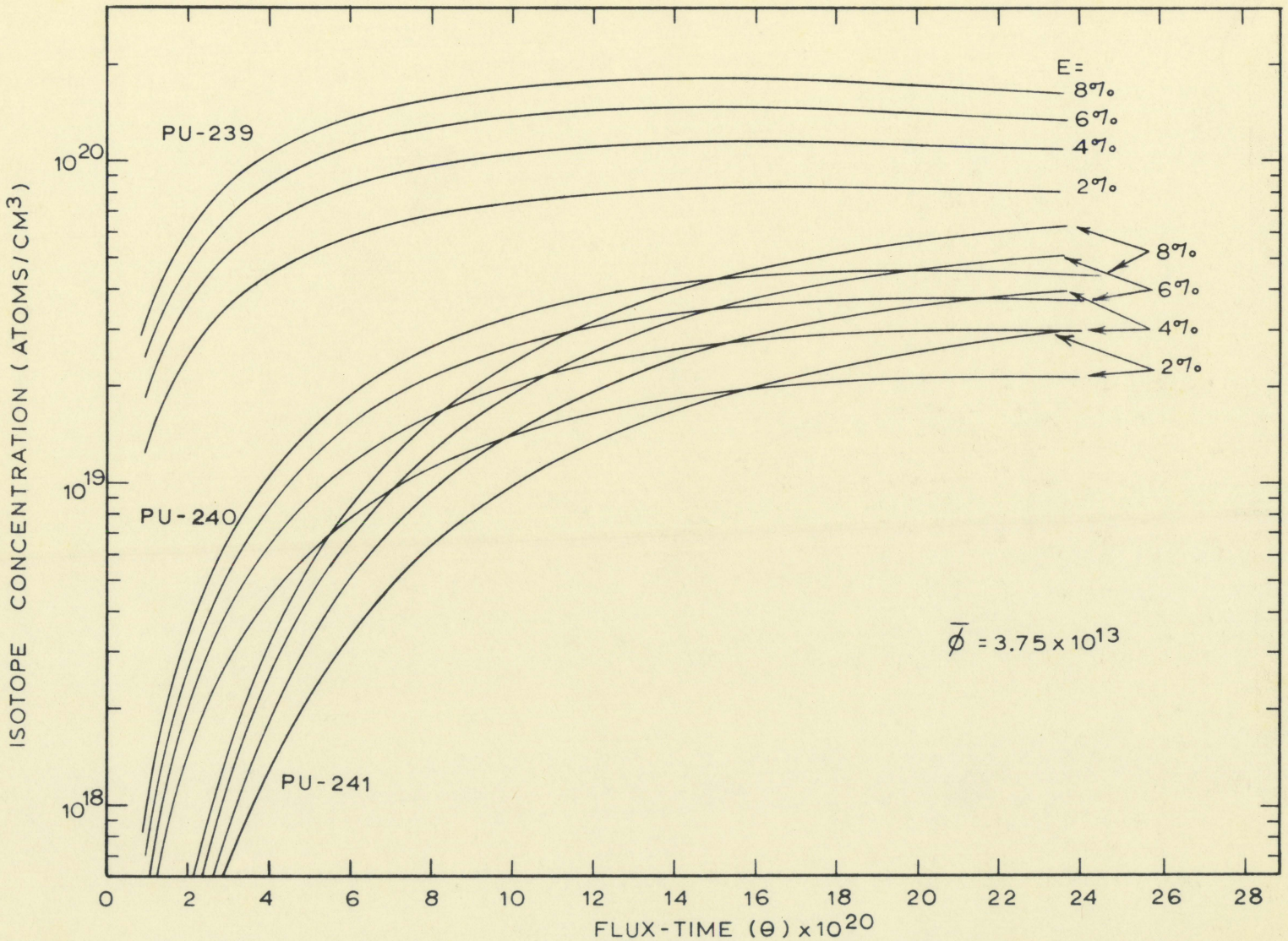


FIGURE 51. PLUTONIUM BUILDUP AS A FUNCTION OF FLUX-TIME AND ENRICHMENT

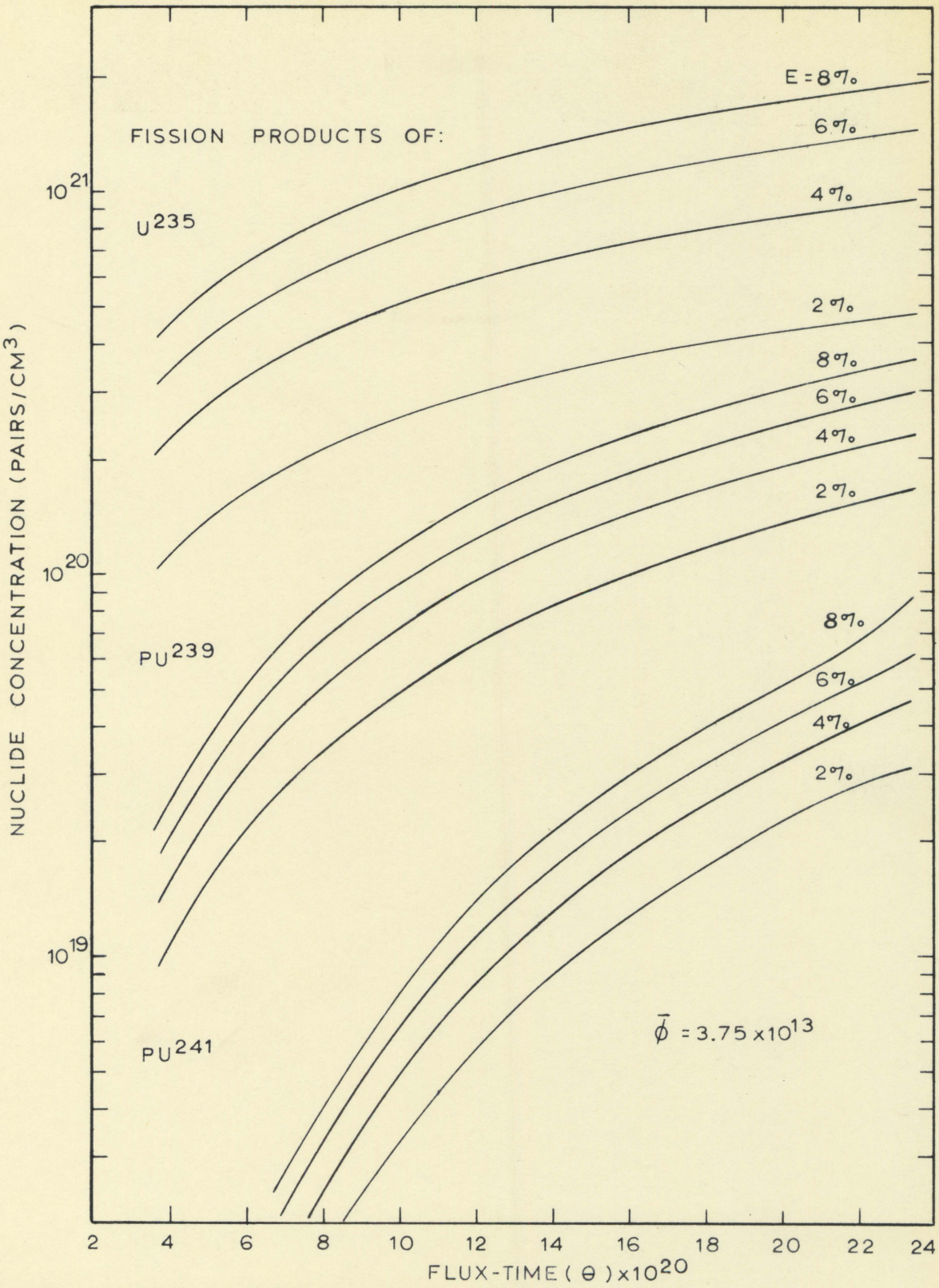


FIGURE 52. BUILDUP OF FISSION PRODUCT PAIRS

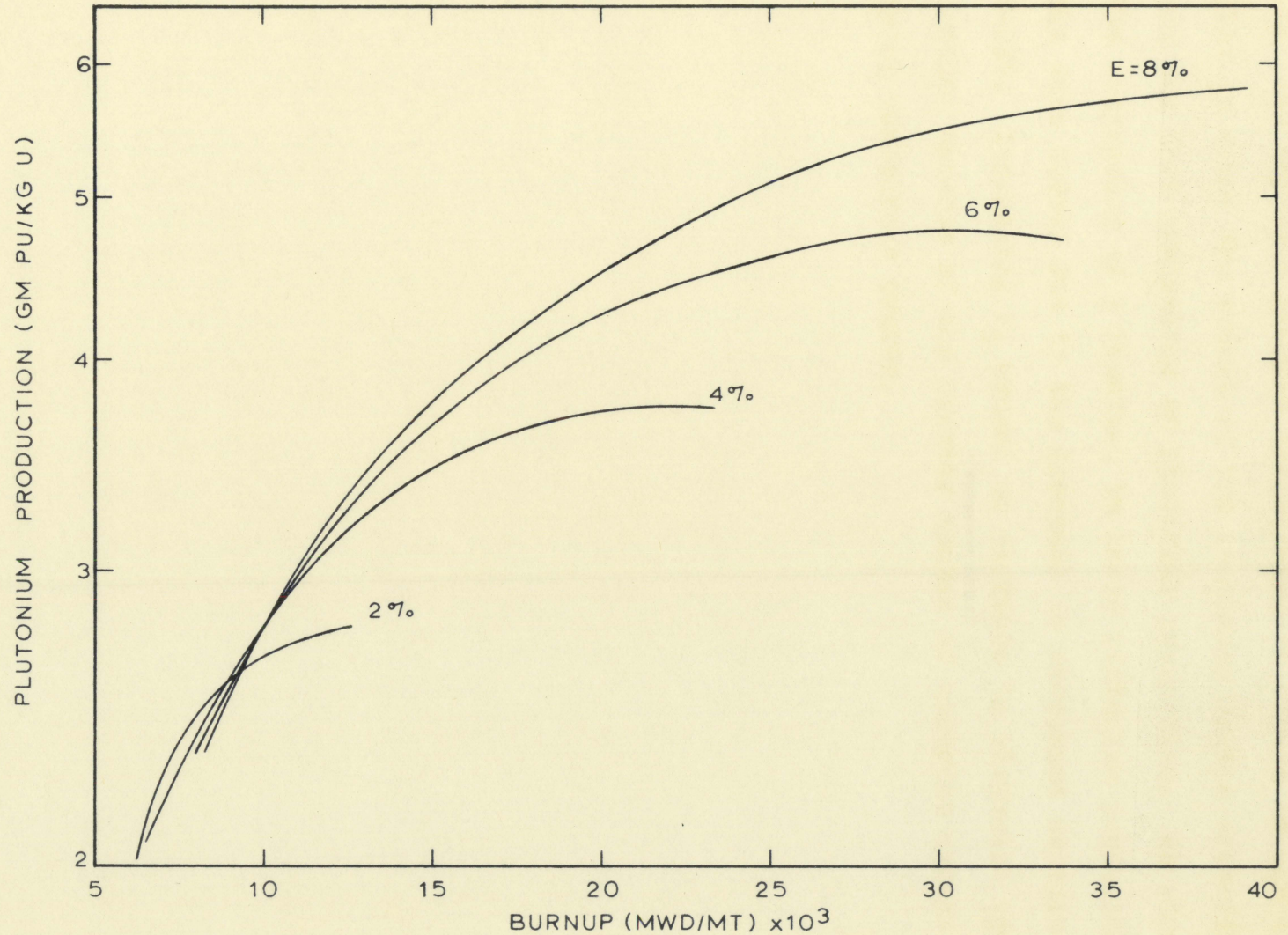


FIGURE 53. RELATIVE PLUTONIUM PRODUCTION AS A FUNCTION OF BURNUP AND ENRICHMENT

The computer program illustrated in Figure 49 was modified to study the effect of the resonance escape probability and the fast nonleakage on plutonium production. As expected the increasing of p resulted in lower plutonium production for the same burnup due to the decrease in resonance capture by U-238. Increasing P_1 caused an increase in plutonium production because of the greater number of neutrons undergoing nonleakage events.

APPENDIX C

Enriched Uranium Costs

In this appendix results from the computer program that was written for the cascade equation are presented. Figure 50 illustrates the flow diagram of this program. The separative cost and optimum waste concentration were varied to determine their effect on the final cost of enriched uranium. Also the relationship between the optimum waste concentration and natural uranium feed cost was studied using the same program.

Figures 54 through 56 give the cost of UF_6 as a function of enrichment (E) and separative cost (C_E) for three different values of optimum waste concentration (x_{wo}). The AEC price schedule can be obtained by setting C_E = \$30/kg and x_{wo} = 0.002531. This is illustrated in Figure 54. In comparing these curves it can be seen that a small change in the separative cost can cause a relatively large change in uranium cost especially for the larger values of enrichment. Also changing the optimum waste concentration has a similar effect, although the change will be basically due to a change in feed cost. The minimum cost for a given enrichment occurs when C_E is smallest and the value of x_{wo} is closest to the U-235 concentration of natural uranium.

In Figure 57 is illustrated a plot of feed cost as a function of optimum waste and separative cost. The curves

were obtained from the computer program by letting the feed be considered the desired product. As the cost of feed is decreased, the corresponding optimum waste concentration will rise. Thus if the price of natural uranium decreases, the optimum waste concentration will increase, resulting in a reduction of the cost of enriched uranium.

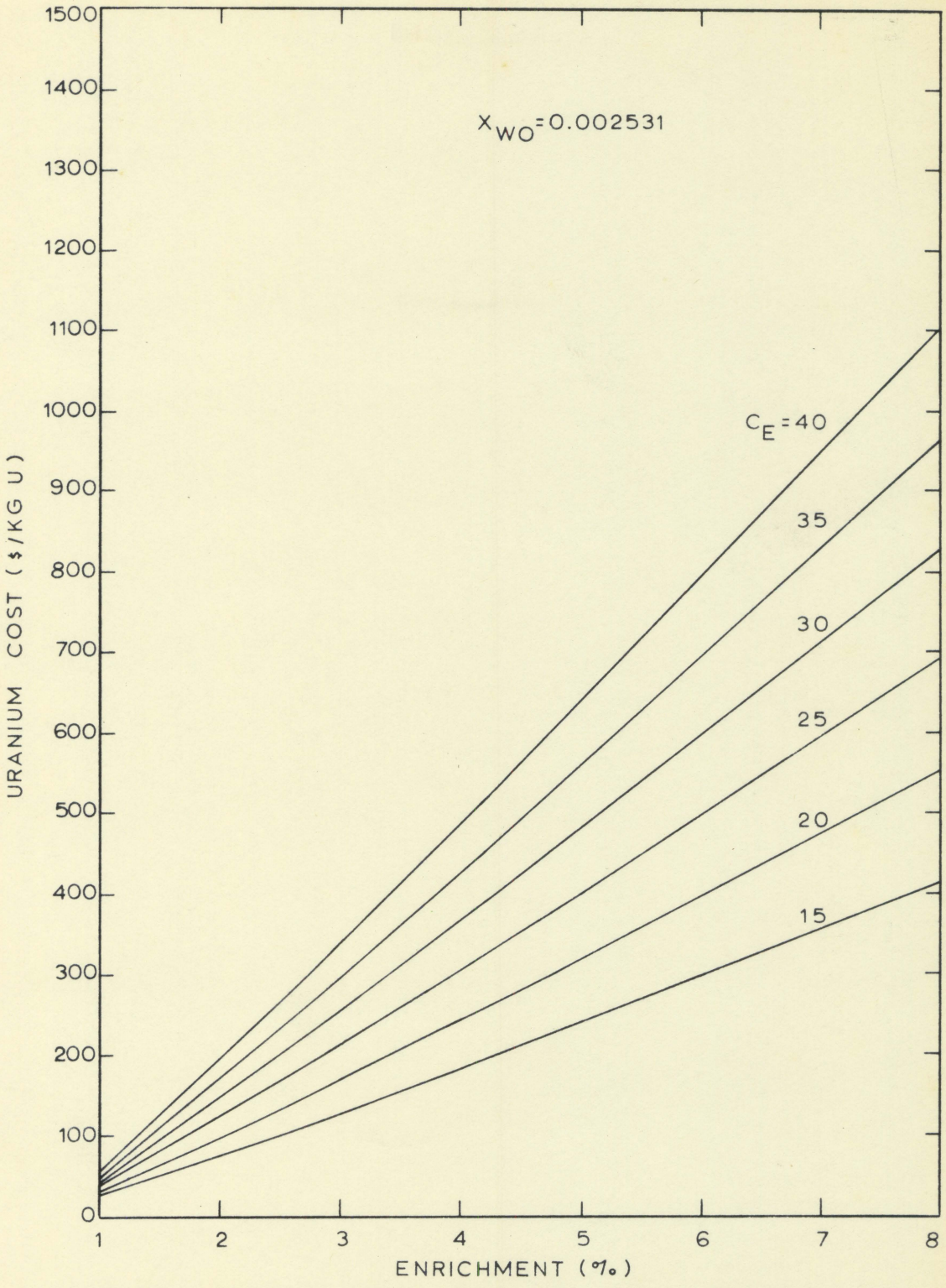


FIGURE 54. URANIUM COST FOR UF_6 AS A FUNCTION OF ENRICHMENT AND SEPARATIVE COST FOR X_{WO}=0.002531

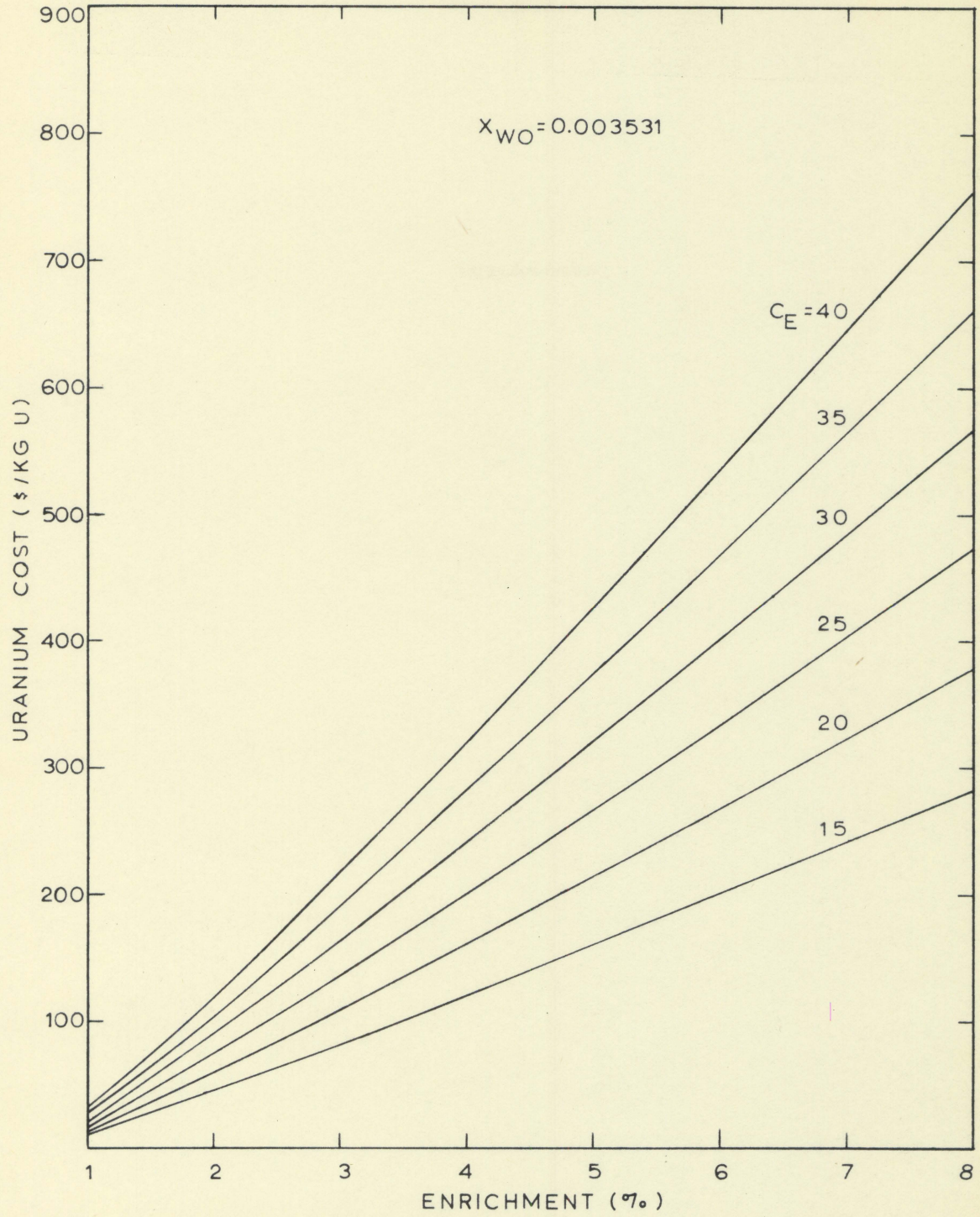


FIGURE 55. URANIUM COST FOR UF_6 AS A FUNCTION OF ENRICHMENT AND SEPARATIVE COST FOR X_{WO}=0.003531

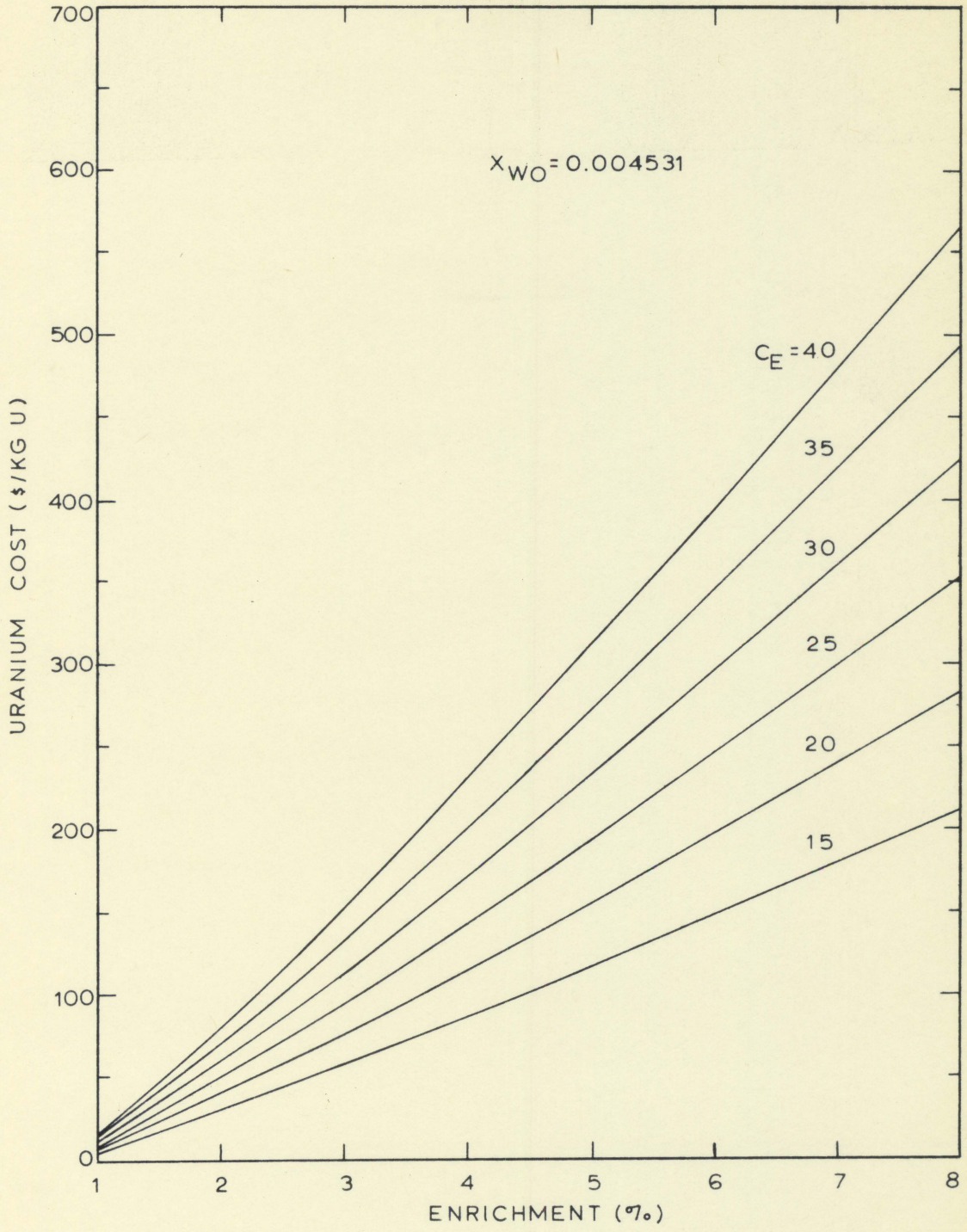


FIGURE 56. URANIUM COST FOR UF_6 AS A FUNCTION OF ENRICHMENT AND SEPARATIVE COST FOR X_{WO} = 0.004531

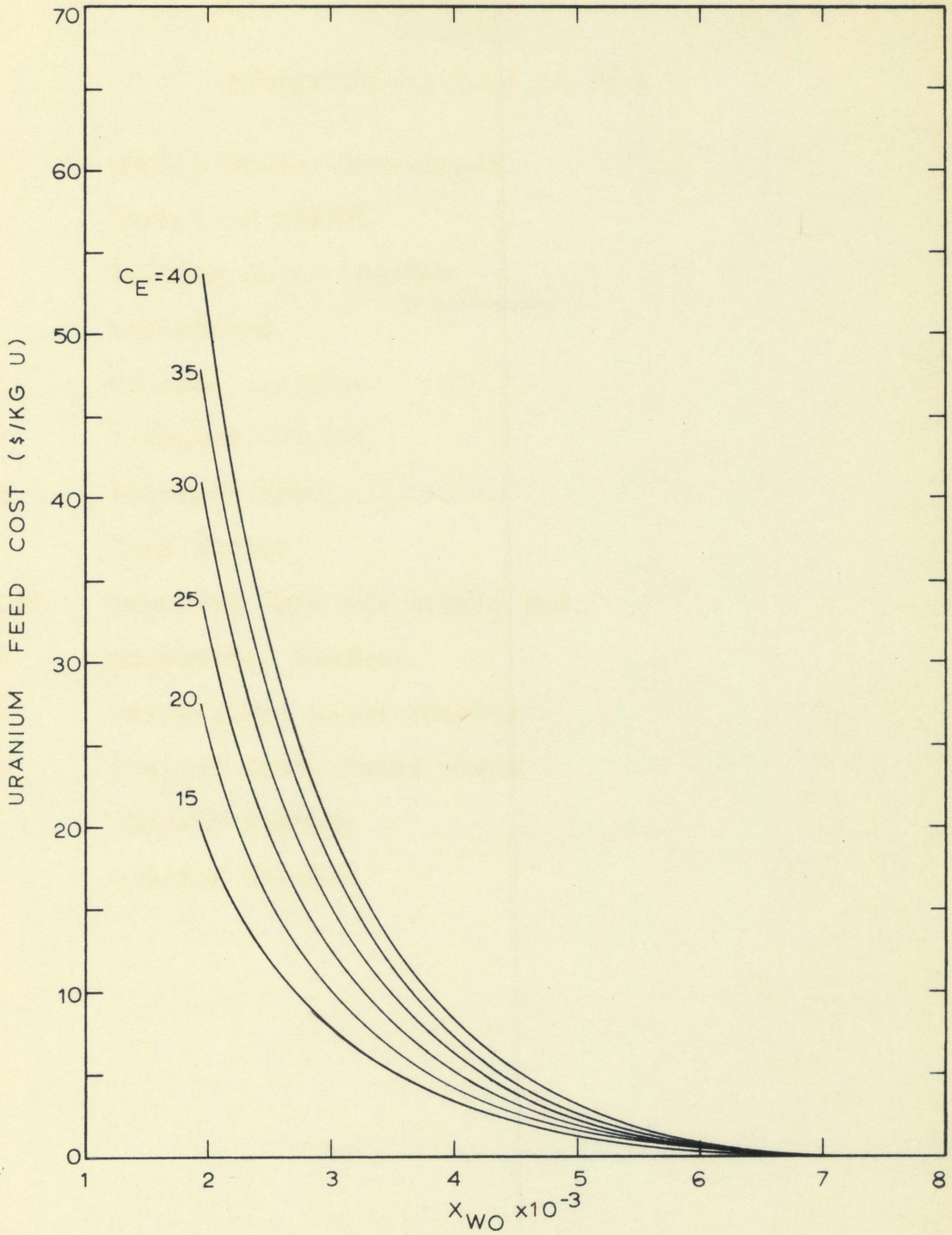


FIGURE 57. RELATIONSHIP BETWEEN OPTIMUM WASTE CONCENTRATION AND URANIUM FEED COST

APPENDIX D

Abbreviations Used in Text

AEC	Atomic Energy Commission
B	burnup in MWD/MT
BWR	boiling water reactor
E	enrichment
G.E.	General Electric
KG U	kilogram uranium
KWHR	kilowatt hour
LF	load factor
MWD/MT	megawatt days per metric ton
MWTH	megawatts, thermal
PWR	pressurized water reactor
SENN	Italian Ponta Fuime plant
UF_6	uranium floride
UO_2	uranium dioxide