MITNE-28

THE EFFECTS OF CHANGING ECONOMIC CONDITIONS ON FUEL CYCLE COSTS IN PRESSURIZED WATER REACTORS

A Report to East Central Nuclear Group, Inc.

By
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REACTOR TECHNOLOGY

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DEPARTMENT OF NUCLEAR ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 1, 1963

This work was done in part at the
MIT Computation Center, Cambridge, Massachusetts

This report was prepared for East Central Nuclear Group, Inc. whose member companies are:

Appalachian Power Company, Roanoke, Va.
The Cleveland Electric Illuminating Company, Cleveland, Ohio
Columbus and Southern Ohio Electric Company, Columbus, Ohio
The Dayton Power and Light Company, Dayton, Ohio
Indiana & Michigan Electric Company, Fort Wayne, Ind.
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Southern Indiana Gas and Electric Company, Evansville, Ind.
West Penn Power Company, Greensburg, Pa.

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1. Summary and Conclusions

This report describes a study made by MIT for ECNG of the effect of changing economic conditions on fuel cycle costs in nuclear power systems. Fuel cycle costs are computed for eight different cost bases, which may be used to represent the effect of most of the combinations of economic conditions likely to occur during the life of the reactor selected for study. This is an advanced pressurized-water reactor with free-standing stainless steel or Zircaloy fuel cladding, designed for a net electric output of 461 Mw.

This summary gives results for three of these cost bases, whose principal differences are:

Basis 1: Present (Jan., 1963) conditions, with the uranium price scale based on a cost of natural UF_6 of \$23.50/kgU (corresponding to concentrates priced at \$8.00/lb U_3O_8) and a cost of separative work of \$30.00/kgU, and with uranium leased by reactor operator from the AEC at a charge of 4.75%/yr.

Basis 2: The same as Basis 1, except that uranium is purchased from the AEC, with annual carrying charges of 6%/yr while uranium is handled by the fuel fabricator and 12%/yr while uranium is in possession of the reactor operator.

Basis 5: Uranium price scale reduced, with natural UF_6 costing \$12.93/kgU (corresponding to concentrates priced at \$4.00/lb U_3O_8) and separative work costing \$25.00/kgU, with private ownership of fuel as in Basis 2. In these three cost bases fuel fabrication costs are \$101.00/kgU for stainless steel cladding or \$140.00/kgU for Zircaloy; carrying charges on fabrication costs are 12%/yr; reprocessing costs are \$23.50/kgU; and plutonium credit, as nitrate, is \$8.00/g.

Equilibrium fuel cycle costs for these three cost bases are given below.

Cost Basis	1	2	5
Uranium obtained by	Lease	Purchase	Purchase
Uranium price scale	Present	Present	Reduced
Fuel cycle cost, mills/kwhe			
Stainless steel cladding			
20,000 mwd/t burnup	2.18	2.64	2.00
30,000	1.95	2.48	1.83
Zircaloy cladding			
20,000 mwd/t burnup	2.10	2.28	1.85
30,000	1.83	2.08	1.63

These costs are for 3-zone outin fueling. Studies were also made of batch fueling and 5-zone outin fueling. The trends of fuel cycle costs with changes in economic conditions are similar for all three methods of fueling.

The principal conclusions to be drawn from this summary table are

(1) Change from lease to purchase of uranium increases fuel cycle costs by about 0.5 mills/kwhe with stainless steel cladding, and about 0.2 mills with Zircaloy.

(2) The reduction in fuel cycle costs which would result from the reduction in uranium prices between Basis 2 and Basis 5 is greater than the increase in costs resulting from the requirement that uranium be purchased.

(3) Fuel cycle costs with stainless steel cladding are more sensitive to changes in cost bases than with Zircaloy cladding.

(4) A substantial decrease in fuel cycle costs can be obtained by going to burnups higher than 20,000 mwd/t.

(5) For all cost bases, fuel cycle costs with Zircaloy cladding are appreciably lower than with stainless steel. The difference is greater when uranium is purchased than when leased. This cost advantage of Zircaloy might not be present

if thin-walled cladding could be used rather than free-standing cladding.

Fuel cycle costs are sensitive to all the cost parameters considered in this study. Using cost basis 2, a burnup of 20,000 mwd/t and three-zone outin fueling as reference, an increase of 0.10 mills/kwhe in the fuel cycle cost would result from an increase of any single cost parameters as given in the table below.

Parameter	Increase in Parameter Which Would Increase Fuel Cycle Cost by 0.1 mills/kwhe: Stainless Steel Cladding	Zircaloy-4 Cladding
Cost of natural uranium	2.3 \$/kgU	3.3 \$/kgU
Cost of separative work	3.0 \$/kgU	5.0 \$/kgU
Fabrication cost	12.0 \$/kgU	12.0 \$/kgU
Reprocessing cost	15.0 \$/kgU	15.0 \$/kgU
Plutonium credit	-1.80\$/gPu	-2.10\$/gPu
Carrying charge on uranium after receipt of fuel from fabricator	1.6%/yr	4%/yr

From the above table, it is seen that fuel cycle costs for Zircaloy-4 cladding are less sensitive than costs for stainless steel cladding to the cost of natural UF_6, cost of separative work, carrying charge on UF_6 and plutonium credit. They are equally sensitive to changes in fuel fabrication cost and reprocessing cost.

The above table enables one to estimate the change in one fuel cycle cost parameter required to compensate for the effect of changes in a second parameter. For example, with stainless-steel cladding, a decrease of \$2.30/kg in the cost of natural uranium would compensate for an increase of 1.6%/yr in uranium carrying charges.

The present conclusions are strictly applicable only to the pressurized water reactor considered in this work. Fuel cycle costs for other types of reactors depend in a qualitatively similar manner on economic parameters, but with important quantitative differences.

2. Introduction

The nuclear fuel cycle costs presently quoted in industry are based on the existing policies of the United States Atomic Energy Commission regarding leasing of enriched uranium, reprocessing of spent fuel and buyback of plutonium, as well as on current fuel fabrication costs and carrying charges on fabrication working capital. The East Central Nuclear Group, Inc. (ECNG) commissioned the Nuclear Engineering Department of MIT to undertake the present study in order to determine the effects of various possible changes from present conditions on nuclear fuel cycle costs.

The reactor chosen for this analysis is a 461 MWe, advanced, pressurized water reactor with clad uranium oxide fuel elements. Through an arrangement with ECNG, the Westinghouse Electric Corporation supplied detailed design information for this reactor and recommended a procedure for estimating fuel fabrication costs. With this fixed reactor installation three operating variables are considered for purposes of fuel cycle analysis: the fuel enrichment (up to 5 w/o), the fuel element cladding material (stainless steel or Zircaloy 4) and the method of fueling (batch, three- or five-zone "outin"). Section 3 of this report gives additional information regarding the reactor and its fuel cycle behavior.

The procedure for evaluating fuel cycle costs was set in consultation with ECNG. The departure from the present economic situation is represented by a change in one or more of the following cost parameters: cost of natural uranium hexafluoride, cost of separative work, fuel fabrication cost, reprocessing cost, plutonium credit, carrying charges on uranium in possession of the reactor operator, and carrying changes on fuel fabrication working capital. ECNG requested that fuel cycle costs be evaluated for eight different combinations of these parameters which have been termed "cost bases." The procedure for evaluating fuel cycle costs and the eight cost bases studied are described in Section 4.

The results of fuel cycle cost calculations for the two types of cladding, three methods of fueling, and eight cost bases are given in Section 5. Section 6 describes a simple procedure for calculating fuel cycle costs for combinations of cost parameters different from the eight cost bases chosen for this work.

The present document constitutes the final report on this economic study. Two previous reports in this series give a more detailed account of the work done on the stainless steel (1)* and Zircaloy 4 (2) clad fuel reactors. Fuel cycle performance of the reactor was predicted by computer code FUELMOVE, (3), with the modified procedure for solving flux distribution equations given in Appendix C of (2).

The authors wish to express their appreciation to the East Central Nuclear Group for sponsoring this investigation, to Paul Dragoumis, Paul Martinka and William L. Webb of that organization for establishing the economic ground rules for this study, to Mr. Dragoumis for guiding the entire work, to Walter J. Dollard and Reid Wolf of the Westinghouse Electric Corporation for providing the reactor design data essential for this study, and to Donald L. Trapp for carrying out the first phase of this work on the stainless steel clad reactor. This work was done in part at the MIT Computation Center.

*References are listed in Appendix C.

3. Fuel Cycle Behavior of Reactor

3.1 The Reactor

Principal characteristics of the pressurized water reactor studied are given in Table 1. Fuel for the reactor consists of UO_2 pellets held in tubes of stainless steel or Zircaloy 4 cladding of sufficient thickness to withstand the coolant pressure of 2200 psia without collapse. Light water at this pressure serves as coolant and moderator. Fuel assemblies consist of bundles of 217 fuel tubes, each filled to a height of 309.68 cm with UO_2. The reactor core contains 156 such assemblies, so arranged that the fuel-bearing region of the reactor fills a roughly cylindrical core with an equivalent radius of 151.13 cm. The principal dimensional difference between the stainless steel and Zircaloy clad cases is that the stainless cladding is thinner than the Zircaloy, so that the volume and mass of fuel is greater with stainless than with Zircaloy. Uranium inventory is 68,078 kg with stainless and 63,423 kg with Zircaloy.

The reactor produces 1473 Mw of heat and 461 Mw of net electric power for a thermal efficiency of 31.3%.

3.2 Methods of Fueling

In batch fueling the reactor is charged initially with fuel of uniform composition. The reactor is made just critical by adjusting the concentration of boron, assumed distributed uniformly throughout the core, as may be approximated by dissolving a soluble boron compound in the coolant. As irradiation proceeds the U-235 content of the fuel decreases, the content of plutonium and fission products increases, and the fuel loses reactivity. These changes take place more rapidly in the center of the core than at the outside. Criticality is maintained during irradiation by decreasing the boron concentration uniformly throughout the core. Irradiation is terminated when the boron concentration drops to zero. In batch fueling,

Table 1: Reactor Design Data for Stainless-Steel and Zircaloy 4 Clad Cases

Item	Stainless Steel Cladding	Zircaloy 4 Cladding
Total heat output	1473 MWt	1473 MWt
Total electrical output, net	461 MWe	461 MWe
System pressure	2200 psia	2200 psia
Average coolant temperature (H_2O)	300°C	300°C
Fuel rod outside diameter (cold)	0.4119 in	0.4119 in
Cladding thickness (cold)	0.0162 in	0.0238 in
UO_2 pellet diameter (cold)	0.375 in	0.360 in
Rod lattice pitch, square (cold)	0.553 in	0.553 in
UO_2 density	10.309 gm/cm^3	10.309 gm/cm^3
Fractional volumes (hot)		
UO_2	0.33714	0.31408
H_2O	0.56402	0.55614
Metal		
Cladding	0.06533	0.09119
Structure	0.02069	0.03103
Void in fuel element	0.01282	0.00756
	1.00000	1.00000
Core geometry (cylindrical)		
Radius, equivalent	151.13 cm	151.13 cm
Height	309.68 cm	309.68 cm
Radial reflector savings	7.5 cm	7.5 cm
Axial reflector savings	7.5 cm	7.5 cm

the entire charge of irradiated fuel is discharged at this time and replaced by a fresh charge of fuel of the original uniform composition, and the batch cycle repeated.

With 3-zone outin fueling, the fuel assemblies are divided into 3 concentric zones, each containing the same number of assemblies. At the end of the first cycle of batch irradiation only the fuel assemblies in the central zone are removed. These will have experienced the greatest change in composition. Fuel from the intermediate zone is moved into the center zone, and fuel from the outside zone is moved into the intermediate zone. Fresh fuel of the original uniform composition is charged to the outside zone. A second irradiation cycle is carried out, with gradually decreasing uniform boron concentration until the reactor is just critical without boron. Fuel is again discharged from the center zone, the reloading cycle is repeated as before, and a third irradiation cycle is carried out. After about the fifth cycle an equilibrium situation is attained in which successive cycles are substantially identical.

With 5-zone outin fueling, the fuel assemblies are divided into 5 concentric zones, each containing the same number of assemblies. Reloading and irradiation are similar to 3-zone outin fueling except that only the central one-fifth of the fuel is removed at the end of each cycle. Equilibrium is attained after about the seventh cycle.

3.3 Burnup

Fig. 1 shows the relationship between the average burnup experienced by fuel discharged from the reactor after an equilibrium irradiation cycle and the enrichment of fuel charged to the reactor. Burnup is expressed as the number of megawatt-days of heat produced by fuel during irradiation, divided by the mass of fuel in metric tonnes of uranium (mwd/t). Broken lines refer to stainless steel cladding; full lines to Zircaloy. The enrichment needed to provide a given burnup is

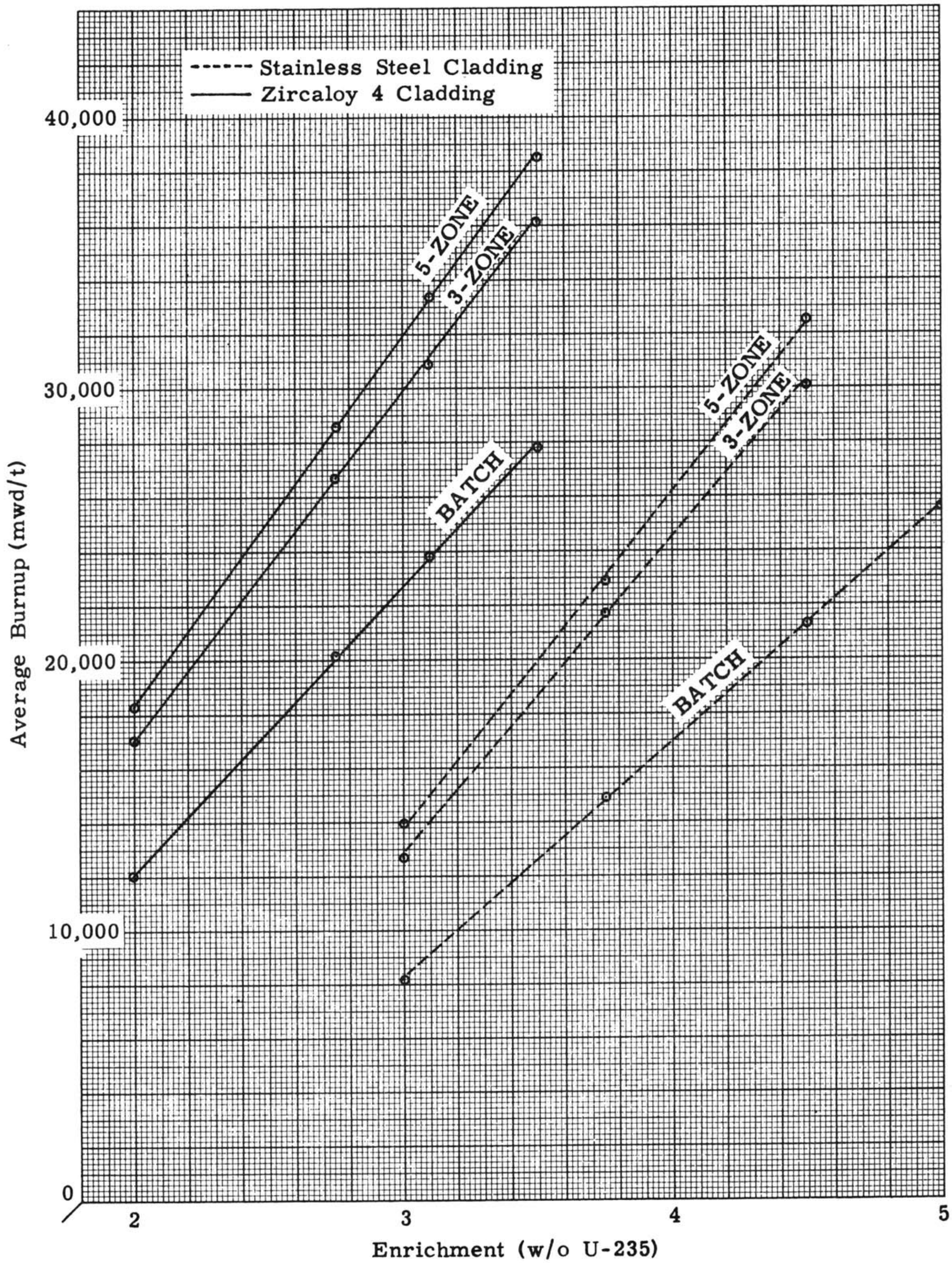

Figure 1: Equilibrium Burnup vs. Enrichment; SS and Zr Cladding; Batch, 3-Zone and 5-Zone Outin Fueling

greater for stainless steel than for Zircaloy. For each cladding material, the enrichment for a given burnup is greatest for batch fueling, smaller for 3-zone outin fueling, and smallest for 5-zone fueling. The difference between 3-zone and 5-zone fueling is not great, however.

The points plotted in this and succeeding figures represent calculations tabulated in (1) and (2).

4. Fuel Cycle Cost Analysis

4.1 Procedure for Calculating Fuel Cycle Cost

The computational procedure for fuel cycle costs is based on following each charge of fuel during its residence in the reactor. Quantities for each charge which enter fuel cycle cost calculations are the mass of fuel W, the weight fraction of U-235 in fresh fuel x_{in} and in spent fuel x_{out}, the kg of uranium and plutonium in spent fuel per kg of uranium charged to the reactor, Y_U and Y_P respectively, and the burnup B.

The total fuel cycle cost M in mills per kilowatt-hour of net electric output (mills/kwhe) is made up of the following components, also in mills/kwhe:

Cost of feed as UF_6, $M_{U,in}$
Credit for uranium in spent fuel as UF_6, $M_{U,out}$
Cost of fuel fabrication, M_{Fab}
Cost of shipping spent fuel, M_S
Cost of reprocessing and conversion, M_R
Credit for plutonium in spent fuel, M_P
Carrying charges on fabrication working capital, M_{IW}
Carrying charges on uranium, M_{IU}
Carrying charges on spare fuel elements, M_{Sp}

The total fuel cycle cost is the resultant of these components

$$M = M_{U,in} - M_{U,out} + M_{Fab} + M_S + M_R - M_P + M_{IW} + M_{IU} + M_{Sp} \qquad (4.1)$$

Equations (4.2) through (4.10) relate each component of the fuel cycle cost to the quantities listed in the first paragraph and to the principal fuel-cycle cost parameters discussed below.

Readers who are not interested in details of cost calculation equations should turn directly to Section 4.2, p. 15.

The fuel-cycle cost model from which these equations were derived is described in Chapters V and VI of (1). Numerical values used for various minor fuel-cycle parameters, such as the fractional recovery of uranium and plutonium in reprocessing operations and the time spent by fuel outside of the reactor, which is used in calculating carrying charges, are given in Table 4.4 of (2). Appendix B defines the nomenclature used in this report and relates it to the nomenclature of (1) and (2).

Net Cost of Uranium

$$M_U = M_{U,in} - M_{U,out} = \frac{1000}{24\gamma B}\left[C_{U,in} - 0.987\ Y_U C_{U,out}\right] \qquad (4.2)$$

$C_{U,in}$ is the unit cost of uranium in the form of UF_6 expressed in \$/kgU, in feed. $C_{U,out}$ is the corresponding cost of uranium in spent fuel. Each cost is a function of the corresponding enrichment of fuel, and depends on the cost of natural uranium C_F and the cost of separative work C_E as described in Appendix A. γ is the thermal efficiency.

Fabrication

$$M_{Fab} = \frac{1000}{24\gamma B}\left[C_{Fab} + C_{U,in}\left(G_{Fab} + \frac{T_2 I_{Fab}}{100}\right)\right] \qquad (4.3)$$

C_{Fab} is the cost of the fabrication operation proper, in \$/kgU. G_{Fab} is the fraction of uranium lost during fabrication. T_2 is the average time uranium is in the possession of the fuel fabricator, and I_{Fab} is his carrying charge on uranium, in %/yr.

Shipping

$$M_S = \frac{1000 C_S}{24\gamma B} \qquad (4.4)$$

The unit cost of shipping C_S has been taken as \$7/kgU in this work.

Reprocessing and Conversion

$$M_R = \frac{1000}{24\gamma B}\left[0.99\ C_R + 5.53\ Y_U + 1470\ Y_P\right] \qquad (4.5)$$

The first term gives the cost of producing uranyl and plutonium nitrates from spent fuel, the second term gives the cost of converting uranyl nitrate to UF_6, and the third term gives the cost of converting plutonium nitrate to metal.

For cost bases 1 to 8 used in Section 5, C_R was evaluated from the formula recommended by the AEC

$$C_R = \frac{17,100}{W}\left(8 + \frac{W}{1000}\right) \qquad (4.6)$$

This is based on an "assumed plant" capable of treating fuel containing less than 4w/o U-235 at a rate of 1000 kg/day with a turn-around time of 8 days, and a daily charge for plant use of $17,100/day. The effect of changes in C_R on fuel cycle cost is evaluated in Section 6.

Plutonium Credit

$$M_P = \frac{9.8 \times 10^5 Y_P C_P}{24\gamma B} \qquad (4.7)$$

C_P is the credit allowed for plutonium in $/g metal.

Carrying Charges on Fabrication Working Capital

$$M_{IW} = \frac{I_W M_{Fab}}{100}\left[\frac{T_1}{2} + 0.0767 + \frac{nWB}{2 \times 365,000\ \theta L}\right] \qquad (4.8)$$

I_W is the charge against working capital used for fuel fabrication costs, in %/yr.

The first two terms in brackets give the average time in years between purchase of fuel and the beginning of irradiation. The last term is one-half the number of years the fuel spends in the reactor producing heat at a rate of θ megawatts when operated with n-zone outin fueling, at a load factor of L.

Carrying Charges on Uranium in Possession of Reactor Operator

$$M_{IU} = \frac{10 I_U}{24\gamma B}\left\{\left[\frac{T_1}{2} + 0.0767 + \frac{nWB}{2 \times 365,000\ \theta L}\right] C_{U,in} + \left[0.4959 + \frac{W}{365,000} + \frac{nWB}{2 \times 365,000\ \theta L}\right] 0.987\ Y_U C_{U,out}\right\} \qquad (4.9)$$

I_U is the charge on the value of uranium paid by the reactor operator between the average time when he takes possession of fuel from the fabricator and the time when the fuel is processed for uranium recovery, in %/yr. This has the value 4.75%/yr. at present, when uranium can be leased at this rate from the AEC. I_U will be greater when the reactor operator is required to purchase uranium. A value of 12%/yr has been used for the private ownership bases in Section 5. The effect of changes in I_U on fuel cycle costs is investigated in Section 6.

The first three terms in brackets give the average time in years between receipt of fuel from the fabricator and the midpoint of its use to generate power. The last three terms in brackets give the time between the midpoint of use of fuel to generate power and recovery of uranium.

The model used to evaluate the times during which carrying charges are paid is explained in (1), pp. 36-39.

Carrying Charge on Spares

$$M_{Sp} = 0.0028\left[\frac{nWB}{365{,}000\ \theta L}\right]\left[M_{U,in} + M_{Fab}\right] \qquad (4.10)$$

The factor 0.0028 represents the carrying charge of 14%/yr on 2% of the full reactor charge retained as spares.

The second term in brackets is the number of years between the time when fuel is charged to the reactor and the time when it is discharged.

4.2 Fuel Cycle Cost Parameters

Table 2 gives values of parameters in these fuel cycle cost equations which were held constant throughout this work.

Table 3 gives values of parameters which were varied from one cost basis to another. Items underscored differ from basis 2. Cost basis 1 reflects present economic conditions, when UF_6 can be leased at 4.75%/yr from the AEC at today's uranium price scale. Basis 2 illustrates economic conditions when UF_6 at today's prices is purchased with private funds on which a carrying charge of 12%/yr is paid. Basis 3 reflects a change in the price of natural uranium concentrates from today's value of $8/lb U_3O_8 to $4/lb. Basis 4 reflects a reduction in separative work costs from today's value of $30/kgU to $25. Basis 5 reflects reduction in both natural uranium and separative work costs. Basis 6 shows the effect of eliminating plutonium credit from basis 5. Basis 7 shows the effect of using carrying charges of 6% instead of 12% with private ownership of uranium. Basis 8 shows the effect of changed fabrication costs.

Table 2. Fuel Cycle Cost Parameters Not Changed During Study

	Symbol	Stainless Steel	Zircaloy
Kg of U charged			
Batch fueling	W	68,078	63,423
3-zone outin	W	22,692.7	21,141
5-zone outin	W	13,615.6	12,685
Years during which fabrication costs are paid			
Full core charge	T_1	0.6667	0.6667
Partial core charge (1/3 or 1/5)	T_1	0.5000	0.5000
Years during fabrication in which carrying charges on uranium are paid			
Full core charge	T_2	0.5000	0.5000
Partial core charge (1/3 or 1/5)	T_2	0.3333	0.3333
Thermal efficiency	γ	0.3130	0.3130
Thermal power, Mw	θ	1473	1473
Load factor	L	0.8	0.8
Shipping cost, $/kgU	C_S	7.00	7.00

Table 3. Cost Input Data for 8 Cost Bases

Cost Parameter	Symbol	Units	Cost Basis 1	2	3	4	5	6	7	8
Cost of natural UF_6	C_F	\$/kgU	23.50	23.50	12.93	23.50	12.93	12.93	23.50	23.50
Weight fraction of U-235 in UF_6 of zero value	x_o	--	.002531	.002531	.003192	.002335	.002989	.002989	.002531	.002531
Cost of separative work	C_E	\$/kgU	30.00	30.00	30.00	25.00	25.00	25.00	30.00	30.00
Fabrication cost	C_{Fab}	\$/kgU								
Stainless steel			101.00	101.00	101.00	101.00	101.00	101.00	101.00	106.00
Zircaloy 4			140.00	140.00	140.00	140.00	140.00	140.00	140.00	104.00
$Pu(NO_3)_4$ to Pu cost		\$/gmPu	1.50	1.50	1.50	1.50	1.50	0.0	1.50	1.50
Pu credit	C_P	\$/gmPu	9.50	9.50	9.50	9.50	9.50	0.0	9.50	9.50
UF_6 carrying charge excluding time of fabrication	I_U	%/yr	4.75	12	12	12	12	12	6	12
UF_6 carrying charge during time of fabrication	I_{Fab}	%/yr	4.75	6	6	6	6	6	6	6
Carrying charge on fabrication cost	I_W	%/yr	12	12	12	12	12	12	6	12
UF_6 loss during fabrication	G_{Fab}									
Stainless steel			0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Zircaloy			0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.005

5. Fuel Cycle Costs

5.1 Transient Fuel Cycle Costs

The net fuel cycle costs for each fueling cycle in mills/kwhe were calculated using the methods described in Chapter 4. These costs are dependent on the economic parameters given in Table 3, the fuel enrichment and the method of refueling. For outin refueling, the net fuel cycle cost for the first few cycles is time-dependent, but reaches a constant value when the equilibrium state is reached. This behavior is displayed in Fig. 2 which shows the variation with time in the net fuel cycle cost for cost bases 1 and 2, stainless-steel clad fuel, with 3.75 and 4.5 w/o enrichment. The transient in fuel cycle cost comes from the fact that the fuel initially loaded in the outer zones has a high residence time in low power generating regions of the core. The carrying charges on fuel fabrication and on uranium are consequently higher. Depending upon the cases considered, the equilibrium state is reached after about the fifth cycle and a calendar time of 6 to 8 years. The net fuel cycle cost averaged over the plant lifetime is represented by the large circles. It is at most 3% higher than the equilibrium fuel cycle cost. Since this difference is so small, the remaining part of the study is based on the equilibrium net fuel cycle costs for each method of refueling.

5.2 Equilibrium Fuel Cycle Costs

The dependence of equilibrium fuel cycle costs (mills/kwhe) on equilibrium average burnup (mwd/t) is shown in Fig. 3 for cost basis 2 and the three methods of refueling. This graph clearly indicates the general behavior of fuel cycle cost with the method of refueling and average burnup. For batch fueling and stainless-steel cladding the equilibrium fuel cycle cost shows a sharp decrease from 4.31 to 3.03 mills/kwhe for an increase in average burnup from 8,200 to

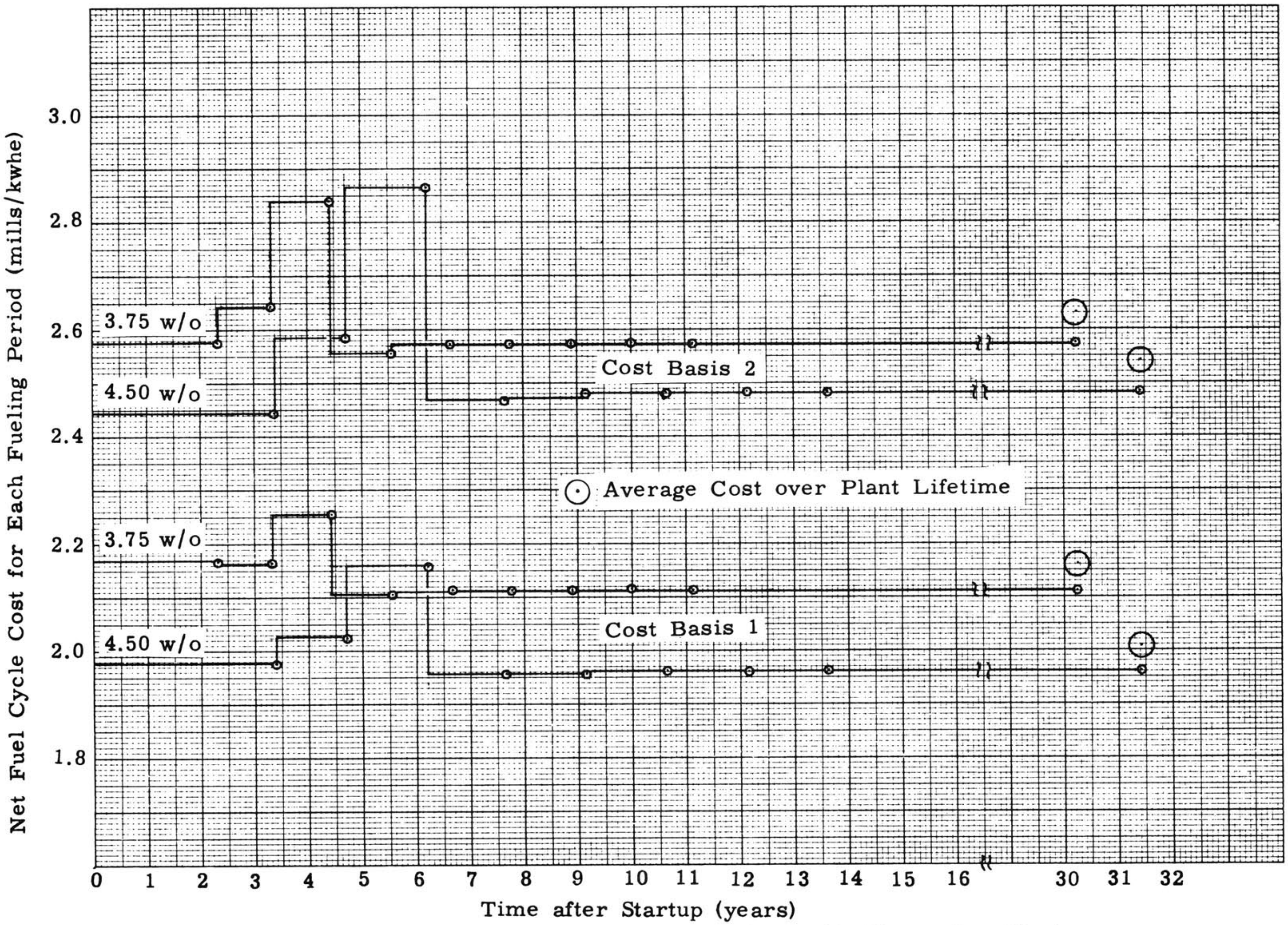

Figure 2: Variation of Net Fuel Cycle Cost with Time after Startup; 3.75 w/o and 4.50 w/o Enrichment; SS Cladding; 3-Zone Fueling; Cost Bases 1 and 2.

21,300 mwd/t, which corresponds to an increase in fuel enrichment from 3.0 w/o to 4.50 w/o. Further increase in fuel enrichment or burnup leads to a smaller decrease in net fuel cycle cost up to the maximum burnup of 26,000 to 28,000 mwd/t considered. Up to 20,000 mwd/t, the rapid decrease in cost with increasing burnup is due principally to the inverse dependence of fabrication and reprocessing costs on burnup. At higher burnups increases in the carrying charge on fuel inventory tends to reverse this trend.

Fig. 3 also indicates that the higher fabrication cost of Zircaloy 4 fuel elements ($140/kgU instead of $101/kgU) is more than offset by the improved neutron economy with Zircaloy, which permits use of less enriched fuel of lower cost for the same average burnup. For three-zone refueling and cost basis 2, a gain of about 0.4 mills/kwhe is realized in going from stainless-steel clad to Zircaloy 4 at all burnups.

Equilibrium fuel cycle costs are appreciably reduced when going from batch to three-zone fueling. For the cases considered in Fig. 3, costs decrease by 0.4 to 0.5 mills/kwhe for the stainless steel clad case and around 0.3 mills/kwhe for Zircaloy 4 cladding. Further but smaller decreases in cost of the order of 0.03 to 0.08 mills/kwhe are realized in going to five-zone fueling. This is due to the higher average burnup obtainable as the core fraction refueled decreases. A point of diminishing returns is reached, however, as the reactor downtime needed for refueling is greater with five-zone fueling. As no cost penalty was assessed for increased fueling downtime and as little gain is realized in going from three- to five-zone fueling, three-zone is close to the practical optimum. The remaining part of this study bears only on the three-zone fueling method.

The contribution of individual components of the fuel cycle cost to the total cost is illustrated in Table 4 for

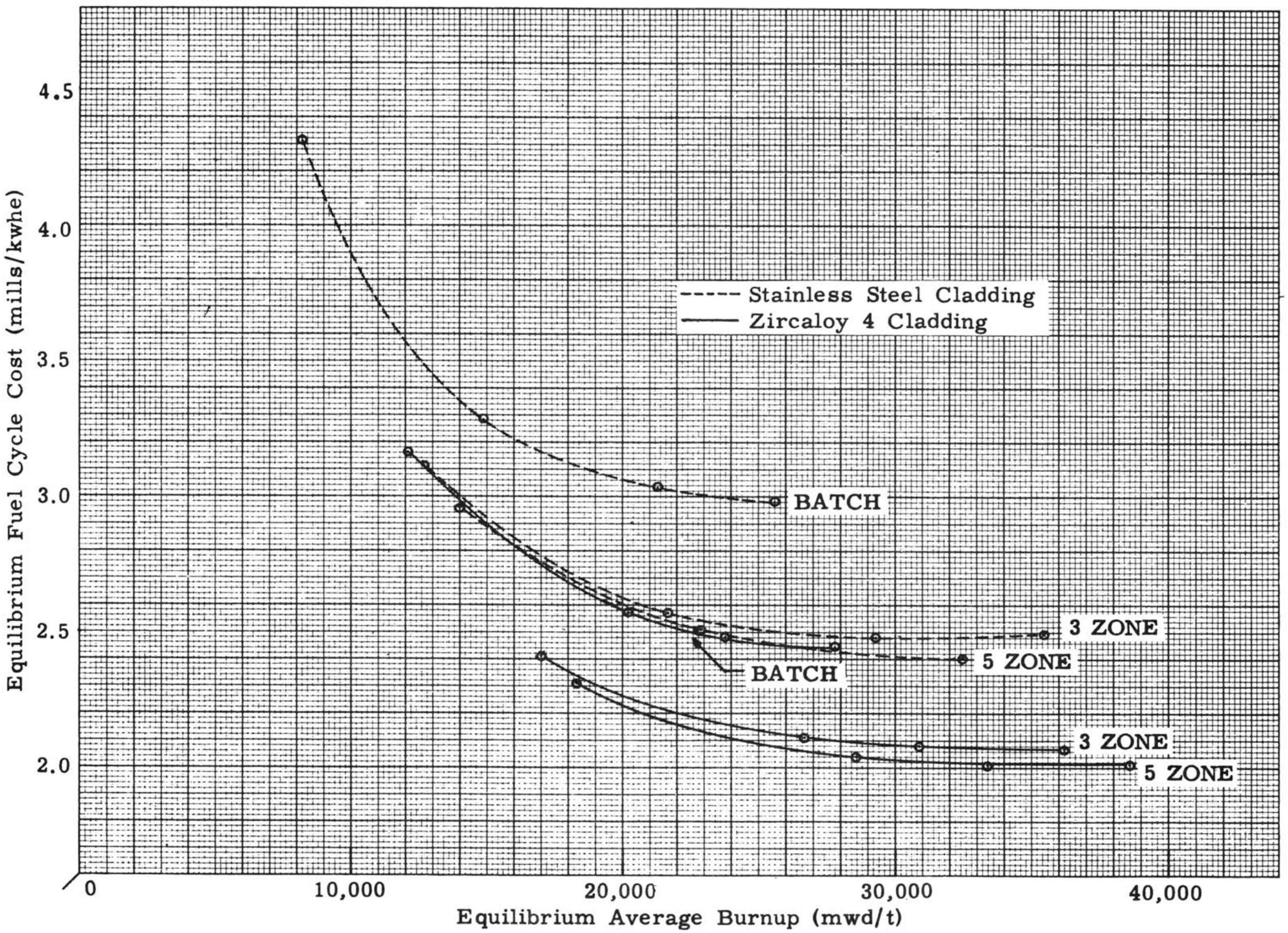

Figure 3: Equilibrium Fuel Cycle Cost vs. Burnup; SS and Zr Cladding; Batch, 3-Zone and 5-Zone Fueling; Cost Basis 2

Table 4. Breakdown of Fuel Cycle Costs Basis 2

Burnup, mwd/t	20,000		30,000	
Cladding	SS	Zr	SS	Zr
w/o U-235 in feed	3.61	2.23	4.47	3.01
w/o U-235 in spent fuel	2.06	0.845	2.25	0.971
Yields, kg/kgU in feed				
Uranium, Y_U	0.96977	0.97091	0.95624	0.95823
Plutonium, Y_P	0.008289	0.007114	0.010558	0.008713
Unit cost, $/kgU				
Feed, as UF_6, $C_{u,in}$	322.32	171.15	419.31	255.72
Spent fuel, as UF_6, $C_{U,out}$	153.16	34.26	173.28	45.11
Fabrication, C_{Fab}	101.00	140.00	101	140
Reprocessing, C_R	23.13	23.57	23.13	23.57
Breakdown of fuel cycle cost, mills/kwhe				
Uranium feed, $M_{U,in}$	2.147	1.140	1.860	1.137
Uranium credit, $M_{U,out}$	-0.976	-0.219	-0.725	-0.190
Plutonium credit, M_P	-0.514	-0.441	-0.436	-0.361
Net fuel cost	0.657	0.480	0.699	0.586
Fabrication, M_{Fab}	0.737	0.966	0.504	0.657
Shipping, M_S	0.047	0.047	0.031	0.031
Reprocessing	0.153	0.155	0.102	0.104
Conversion of nitrates	0.117	0.106	0.092	0.081
Fab. carrying charge, M_{IW}	0.167	0.208	0.162	0.198
U carrying charge, M_{IU}	0.735	0.297	0.852	0.405
Carrying charges on spares, M_{Sp}	0.025	0.017	0.031	0.022
Total, M	2.638	2.276	2.473	2.084

3-zone outin fueling with cost basis 2. To permit direct comparison between stainless steel and zircaloy, calculated fuel cycle characteristics and costs have been interpolated to even burnups of 20,000 and 30,000 mwd/t. The large reduction in costs for uranium consumption and uranium carrying charges in going from stainless-steel to zircaloy cladding is a salient feature. The reduction in fabrication cost in going from 20,000 to 30,000 mwd/t is also readily seen.

5.3 Effect of Changed Cost Bases

The effects of changing economic conditions on equilibrium fuel cycle costs are indicated in Fig. 4S for stainless steel cladding and in Fig. 4Z for Zircaloy 4 cladding. It is seen that the general trend of decreasing fuel cycle cost with increasing burnup is present for most of the cost bases considered except in particular for cost basis 8 (Zr cladding) where the cost reaches a minimum of 1.87 mills/kwhe at an average burnup of about 27,000 mwd/t. This is largely due to the low Zircaloy 4 fuel fabrication cost of $104/kgU used in this basis, compared with $140/kgU in all other bases.

The curve for cost basis 2 is used as a reference and represents the fuel cost for the present economic conditions but with carrying charges of 12% per year on uranium while fuel is in possession of the reactor operator. This charge is thought by ECNG to be representative of conditions when uranium is owned privately. On this basis minimum equilibrium fuel cycle cost with stainless steel cladding is 2.48 mills/kwhe at 32,000 mwd/t average burnup. The minimum cost for Zircaloy 4 cladding is 2.07 mills/kwhe at 36,200 mwd/t, the highest burnup investigated.

The effect of changing the uranium carrying charge from the value of 4.75%/yr now prevailing when UF_6 can be leased from the AEC at this rate, to the 12%/yr anticipated when uranium is owned privately may be seen by comparing the curves

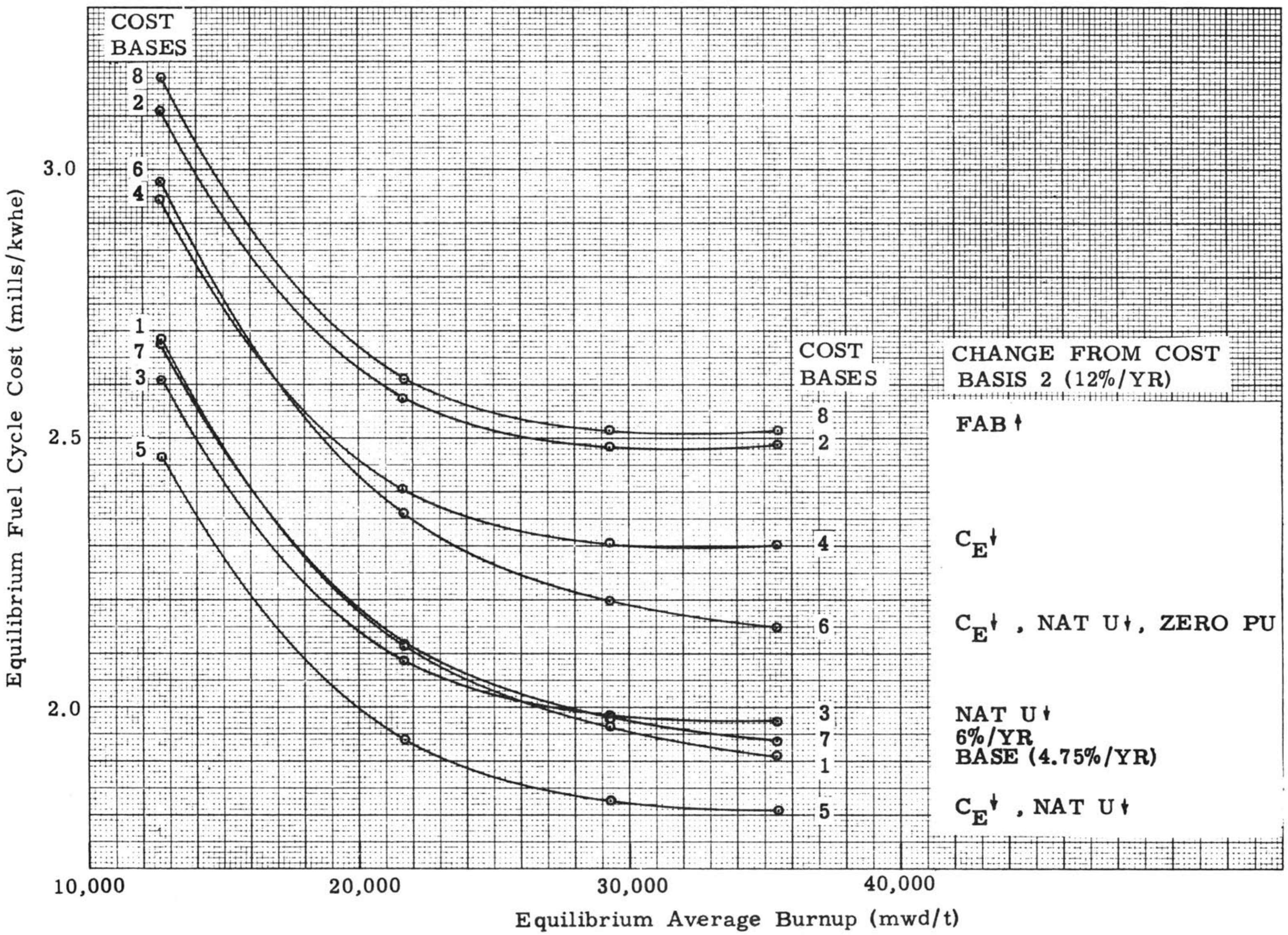

Figure 4S: Equilibrium Fuel Cycle Cost vs. Burnup;
3-Zone Fueling; SS Cladding; 8 Cost Bases

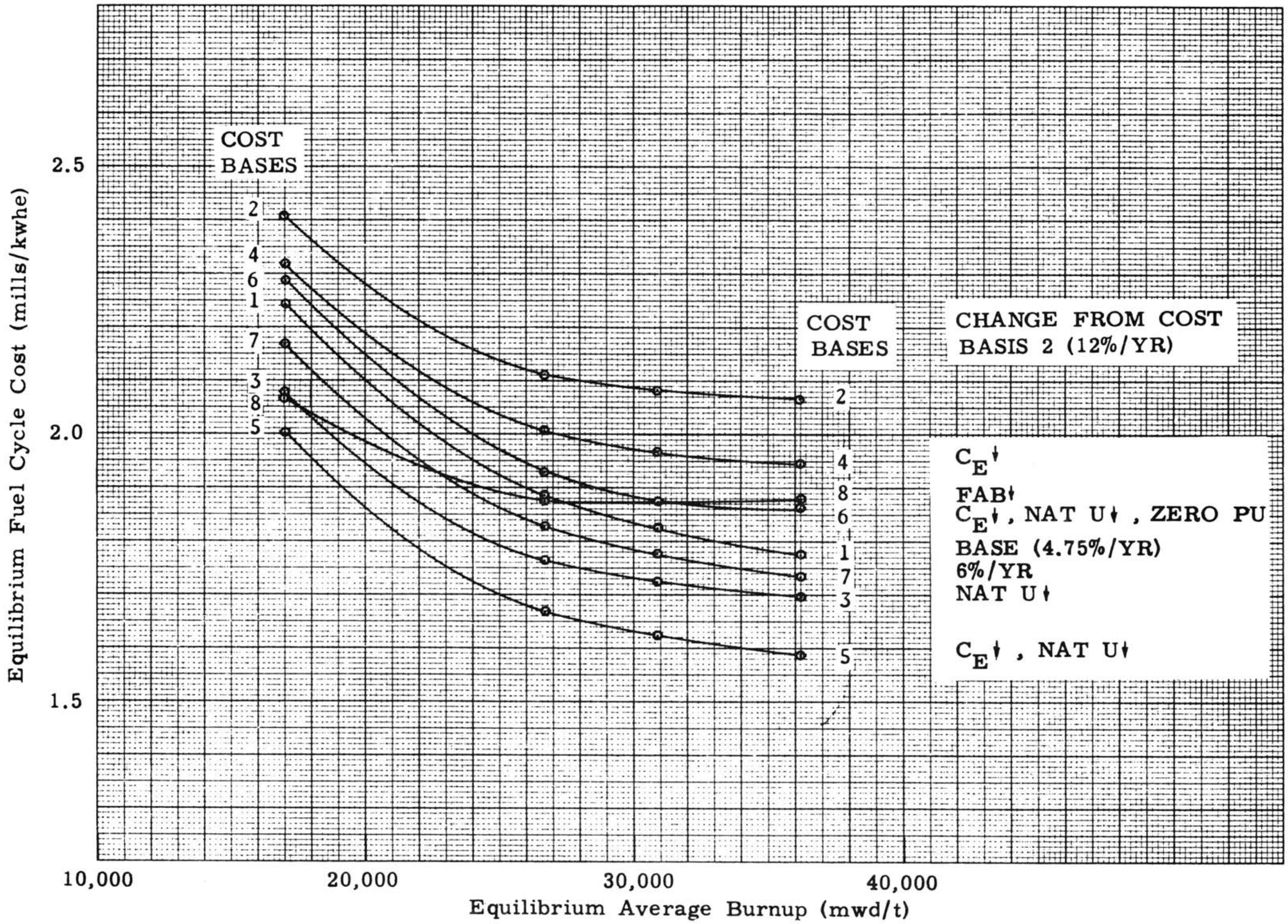

Figure 4Z: Equilibrium Fuel Cycle Cost vs. Burnup; 3-Zone Fueling; Zr Cladding; 8 Cost Bases for bases 1 and 2. The effect of the higher uranium carrying charge is to raise the fuel cycle cost by approximately 0.5 mills/kwhe with stainless steel cladding, and 0.25 mills/kwhe with Zircaloy. The optimum burnup is lower the higher the carrying charge on uranium.

The qualitative departure from cost basis 2 is indicated by the arrows at the right of Figs. 4S and 4Z, with an arrow pointed upward indicating an increase in a designated parameter and an arrow pointed downward a decrease, from cost basis 2. The lowest equilibrium fuel costs are obtained with cost basis 5, which reflects a decrease in the cost of natural uranium from the present \$23.50/kgU to \$12.93/kgU and a decrease in the cost of separative work from \$30.00/kgU to \$25.00/kgU while still retaining a 12% per year carrying charge on uranium in the possession of the reactor operator. These minimum fuel cycle costs are 1.82 mills/kwhe at 35,500 mwd/t with stainless steel cladding, and 1.59 mills/kwhe at 36,100 mwd/t with Zircaloy 4 cladding.

Fuel cycle costs with stainless steel or Zircaloy cladding are compared in Fig. 5, for the four most significant cost bases, 1, 2, 3 and 5. The fuel cycle cost for Zircaloy 4 are lower than for stainless steel cladding for all four cost bases considered. The difference between the two costs are more significant and of the order of 0.3 to 0.4 mills/kwhe when evaluated on cost basis 2 (uranium purchased). For the present cost basis 1, (uranium leased) the difference is much smaller, of the order of 0.1 mills/kwhe.

The fuel cycle costs for stainless steel and cost bases 1 and 3 cross over at about 26,000 mwd/t, which indicates that an increase in the UF_6 carrying charge from 4.75% to 12% can be offset by a decrease in the cost of natural UF_6 from \$23.50/kgU to \$12.93/kgU with a net reduction in the fuel cycle cost at burnups higher than 25,000 mwd/t. The fuel

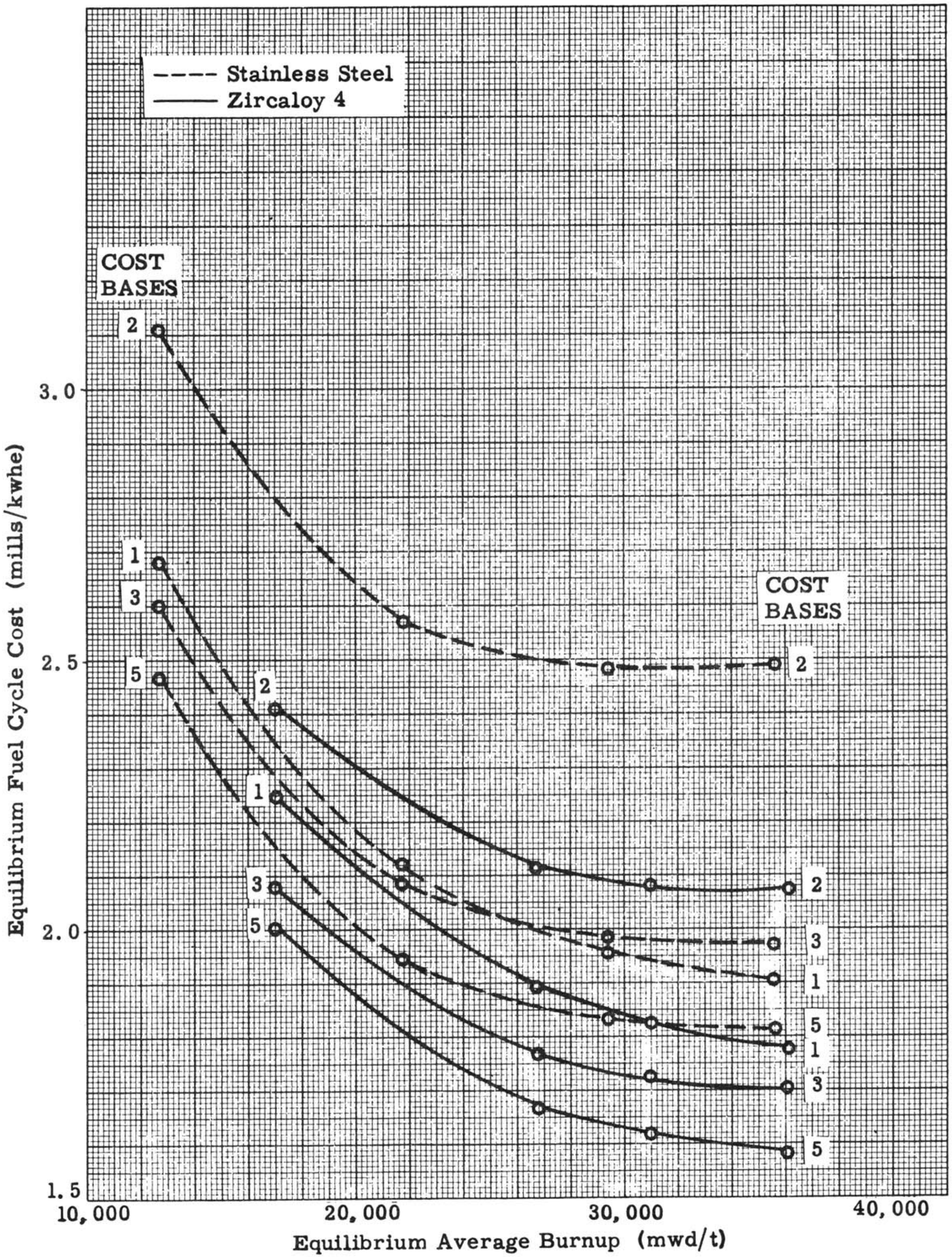

Figure 5: Equilibrium Fuel Cycle Cost vs. Burnup; 3-Zone Fueling, Cost Bases 1, 2, 3, 5.

cycle cost for Zircaloy cladding is less sensitive to change in cost of natural UF_6, and the cross over mentioned above is not present for cost bases 1 and 3. The cost changes indicated in Figs. 4S and 4Z are dependent on the magnitude of the variation of the cost parameters assumed. The variation of the fuel cycle cost with each parameter is discussed further in Section 6 with the aid of cost coefficients.

6. Effect of Changed Economic Conditions on Fuel Cycle Costs

In this section the results of this study are generalized to show how fuel cycle costs in this reactor can be evaluated for any combination of the following cost parameters, (1) uranium price scale, (2) uranium carrying charge, (3) fabrication cost, (4) reprocessing cost and (5) plutonium credit. This section also provides a comparison of fuel cycle costs between stainless steel and zircaloy cladding at the same burnup for various economic conditions.

6.1 Uranium Price Scale

Fig. 6 shows how fuel cycle costs at an equilibrium average burnup of 20,000 mwd/t vary with the two parameters which set the uranium price scale — the cost of natural uranium in the form of UF_6 and the cost of separative work, C_E. Results for stainless steel cladding are represented by the broken line; results for Zircaloy by the full line.

Cost parameters held constant in this figure are

Cladding	Fabrication Cost	Reprocessing Cost
Stainless Steel	$101/kg	$23.13/kg
Zircaloy 4	$140/kg	$23.57/kg

Carrying charges on uranium in possession of reactor operator, 12%/yr.

Plutonium metal credit, $9.5/g.

The above fuel fabrication costs are those considered by Westinghouse to be representative of present practice. The reprocessing costs are characteristic of the AEC's "assumed plant," in which the daily charge at a capacity of 1000 kg/day is $17,100/day. The carrying charge of 12%/yr on the value of uranium in possession of the reactor operator is the charge ECNG anticipates the reactor operator will incur with private ownership of fuel. The plutonium credit is equivalent to a credit of $8.00/g for plutonium in the form of nitrate, and

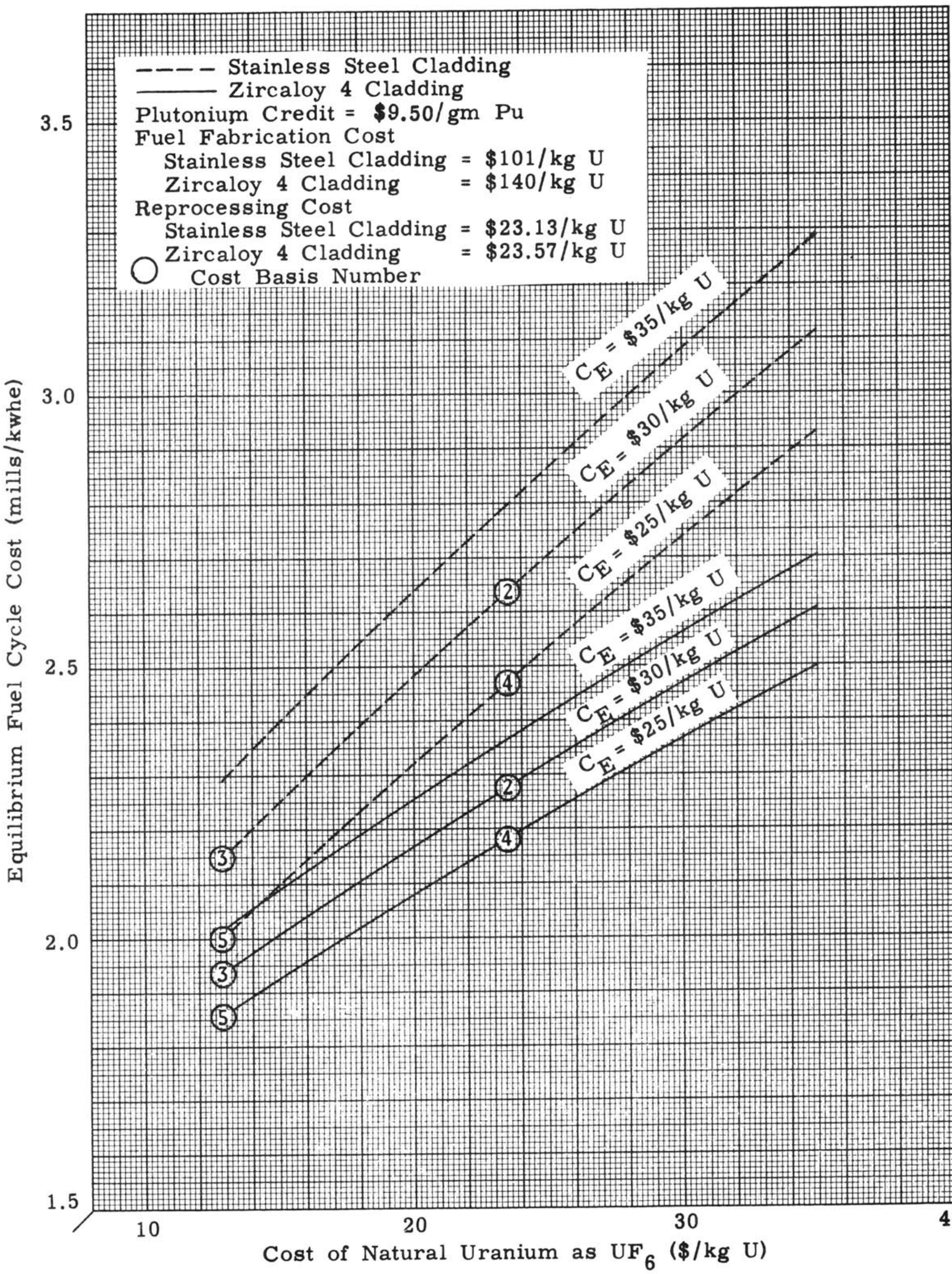

Figure 6: Equilibrium Fuel Cycle Cost vs. Cost of Natural Uranium and Cost of Separative Work; 3-Zone Fueling; SS and Zr Cladding; 12%/yr Carrying Charges on Uranium; 20,000 mwd/t Burnup

is the value the AEC is expected to set when the Atomic Energy Act is amended to permit pricing plutonium in accordance with its value as fuel in thermal reactors. Figs. 8-12 of this section show how changes in these cost parameters affect fuel cycle costs.

Each numbered circle in Fig. 6 denotes the fuel cycle cost basis corresponding to the designated combination of units costs of natural uranium and separative work. For example, the combination of a natural uranium cost of $12.93/kg and separative work of $25.00/kg is cost basis 5.

Fuel cycle costs at 20,000 mwd/t plotted in this figure were obtained by interpolating to this burnup information given in (1) and (2) on U-235 enrichment in feed and spent fuel and on yields of uranium and plutonium in spent fuel, as given in Table 4, and then re-evaluating fuel cycle costs from this interpolated information.

Fig. 7 presents similar information for a burnup of 30,000 mwd/t. Fuel cycle costs at burnups between 20,000 and 30,000 mwd/t may be obtained by interpolation between Figs. 6 and 7, using Figs. 4 and 5 to estimate the degree of non-linearity in such interpolation.

The following conclusions are drawn from these figures:

(1) Over the entire range of uranium price parameters studied fuel cycle costs in the stainless steel clad reactor are higher than in the zircaloy clad reactor.

(2) Fuel cycle costs in the stainless steel clad reactor are affected more by changes in the uranium price scale than are costs in the Zircaloy clad reactor.

(3) At 20,000 mwd/t the lowest fuel cycle costs are 2.00 mills/kwhe for stainless steel and 1.85 mills/kwhe for Zircaloy, at the most favorable uranium price scale considered (Basis 5). This is at a cost of separative work of $25.00/kgU (one-sixth under today's value) and a price for natural uranium of $12.93/kgU in the form of UF_6, corresponding to $4.00/lb U_3O_8

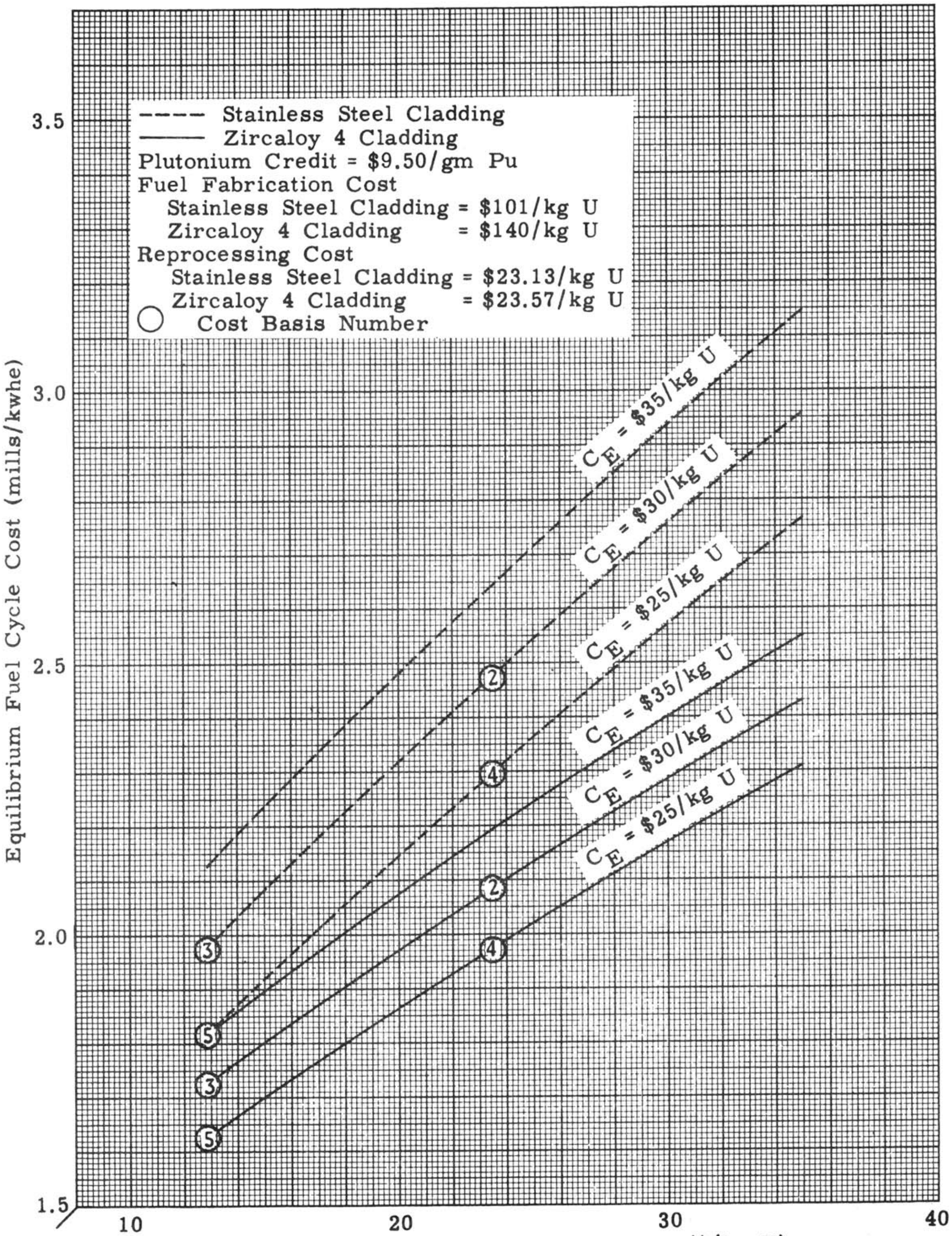

Figure 7: Equilibrium Fuel Cycle Cost vs. Cost of Natural Uranium and Cost of Separative Work; 3-Zone Fueling; SS and Zr Cladding; 12%/yr Carrying Charge on Uranium; 30,000 mwd/t Burnup

in the form of uranium concentrates.
(4) At 30,000 mwd/t, the corresponding costs are 1.83 mills/kwhe for stainless steel and 1.63 mills/kwhe for Zircaloy.
(5) The results quoted in (3) and (4) indicate the magnitude of the incentive to change from stainless steel to Zircaloy and to increase burnup from 20,000 to 30,000 mwd/t for the lowest likely uranium price scale. At higher uranium prices, the incentives are greater.

6.2 Cost Coefficients

The effect on fuel cycle costs of changes in the principal cost parameters held constant in Figs. 6 and 7 (carrying charge on uranium, fabrication cost, reprocessing cost and plutonium credit) is best shown with the aid of cost coefficients. These are defined as the change in fuel cycle cost for a unit change in one cost parameter, with all other cost parameters held constant. These cost coefficients are among the most important products of this study, as they may be used to calculate simply fuel cycle costs for any combination of fuel cycle cost parameters.

Sections 6.3, 6.4, 6.5 and 6.6 present graphs for the following cost coefficients:

Cost coefficient, a_{IU}, for carrying charges on uranium in possession of reactor operator.

Fabrication cost coefficient, a_{Fab}

Reprocessing cost coefficient, a_R

Plutonium credit cost coefficient, a_P.

The equations from which these cost coefficients have been evaluated are given in footnotes to these Sections. Use of these cost coefficients to evaluate fuel cycle costs for any combination of fuel cycle cost parameters is discussed in Section 6.7.

6.3 Cost Coefficient for Carrying Charge on Uranium

The cost coefficient a_{IU} for carrying charges on uranium in possession of the reactor operator is defined as the increase in fuel cycle cost in mills per kwh caused by an increase of 1%/yr in this carrying charge on uranium*. Figures 8 and 9 show this cost coefficient as a function of the costs of natural uranium and of separative work. Fig. 8

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*The cost coefficient a_{IU} for carrying charges on uranium in in possession of the reactor operator is evaluated by taking the derivative of the fuel cycle cost M in mills/kwhe with respect to the carrying charge for uranium I_U in %/yr, holding all other fuel cycle cost parameters constant. That is

$$a_{IU} \equiv \left(\frac{\partial M}{\partial I_U}\right)_{C_E, C_F, C_{Fab}, C_R, C_S, C_P, I_W, \text{etc.}} \tag{6.1}$$

As the only term of the fuel cycle cost equation (4.1) which depends on I_U is the term M_{IU} for uranium carrying charges, this may be simplified to

$$a_{IU} = \left(\frac{\partial M_{IU}}{\partial I_U}\right)_{C_E, C_F} \tag{6.2}$$

Through use of Eq. (4.9) for M_{IU}, with numerical values from Table 2, this becomes

$$a_{IU} = \frac{0.435\ C_{U,in} + 0.652\ Y_U C_{U,out}}{B} + \frac{(2.279 \times 10^{-6} C_{U,in} + 2.250 \times 10^{-6} Y_U C_{U,out})nW}{\theta} + \frac{3.65 \times 10^{-6} Y_U W C_{U,out}}{B} \tag{6.3}$$

For this reactor, θ = 1473 mw
W = 22,693 kg with stainless steel cladding, 3-zone fueling
W = 21,141 kg with Zircaloy cladding, 3-zone fueling.
Hence, with stainless steel cladding

$$a_{IU} = \frac{0.435\ C_{U,in} + 0.735\ Y_U C_{U,out}}{B} + 1.053 \times 10^{-4} C_{U,in} + 1.040 \times 10^{-4} C_{U,out} \tag{6.3S}$$

With Zircaloy cladding

$$a_{IU} = \frac{0.435\ C_{U,in} + 0.729\ Y_U C_{U,out}}{B} + 0.981 \times 10^{-4} C_{U,in} + 0.969 \times 10^{-4} Y_U C_{U,out} \tag{6.3Z}$$

This cost coefficient depends only on the uranium price scale and burnup.

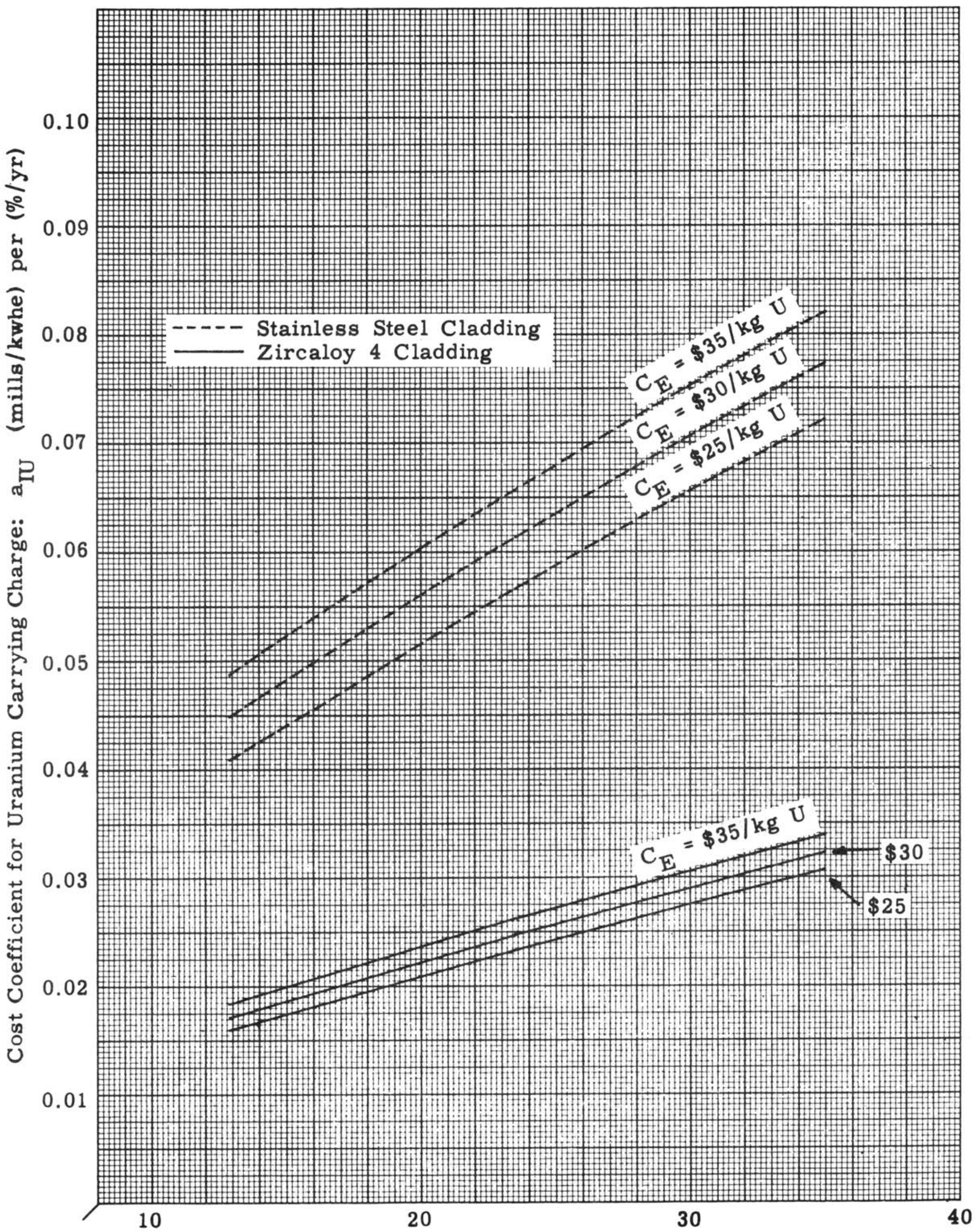

Figure 8: Cost Coefficient for Uranium Carrying Charge vs. Cost of Natural Uranium and Cost of Separative Work; 3-Zone Fueling; 20,000 mwd/t Burnup

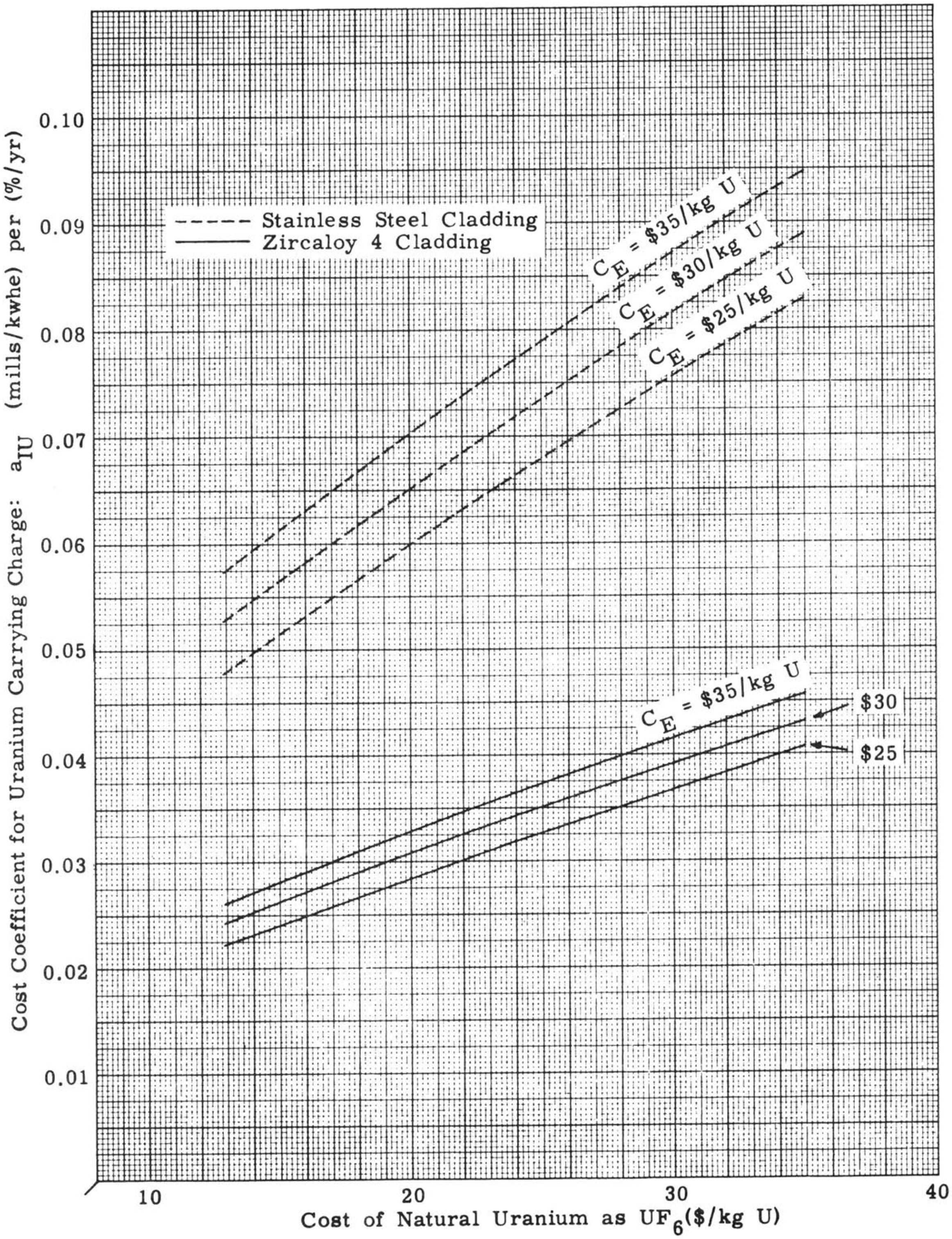

Figure 9: Cost Coefficient for Uranium Carrying Charge vs. Cost of Natural Uranium and Cost of Separative Work; 3-Zone Fueling; 30,000 mwd/t Burnup

refers to a burnup of 20,000 mwd/t; Fig. 9, to 30,000. Broken lines refer to stainless steel cladding; full lines, to Zircaloy. To illustrate the use of these figures and the significance of this cost coefficient, it may be noted from Fig. 8 that at a burnup of 20,000 mwd/t, with stainless steel cladding, with a natural uranium cost of $23.50/kg and a cost of separative work of $30/kg, an increase of 1%/yr in the carrying charge on uranium in possession of the reactor operator would increase fuel cycle cost by 0.062 mills/kwh. Similarly with Zircaloy cladding, such an increase in uranium carrying charge would increase fuel cycle costs by 0.025 mills/kwh. Stated another way, to change the fuel cycle cost by 0.1 mills/kwhe requires a change in uranium carrying charge of 1.6%/yr with stainless steel, or 4%/yr with Zircaloy. At all uranium prices the change in fuel cycle costs with uranium carrying charge is greater with stainless steel cladding than with Zircaloy.

6.4 Fabrication Cost Coefficient

The fabrication cost coefficient a_{Fab} is defined as the increase in fuel cycle cost in mills per kwh caused by an increase of $1/kg in fuel fabrication cost*. Fig. 10 shows this cost coefficient as a function of burrup. This cost coefficient is nearly the same for stainless steel as

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* $$a_{Fab} = \left(\frac{\partial M}{\partial C_{Fab}}\right)_{C_E, C_F, C_R, C_S, C_P, I_U, I_W, etc} = \left(\frac{\partial M_{Fab}}{\partial C_{Fab}}\right)_{C_E, C_F, I_W} \qquad (6.4)$$

Through use of Eq. (4.3) for M_{Fab},

$$a_{Fab} = \frac{138.3}{B} + \frac{2.863 \times 10^{-5} nW}{\theta} \qquad (6.5)$$

With stainless steel cladding

$$a_{Fab} = \frac{138.3}{B} + 0.00132 \qquad (6.5S)$$

With Zircaloy cladding

$$a_{Fab} = \frac{138.3}{B} + 0.00123 \qquad (6.5Z)$$

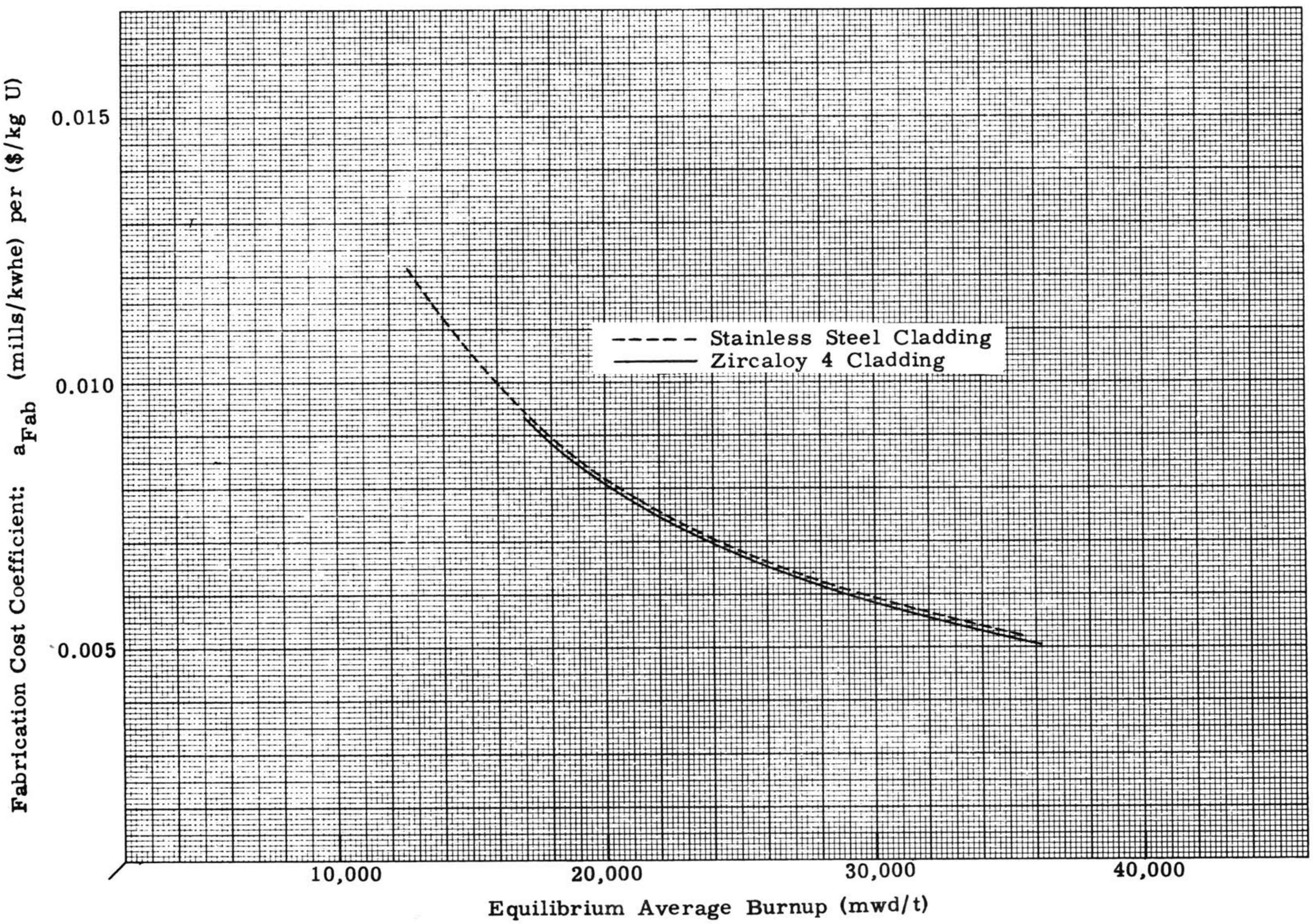

Figure 10: Fabrication Cost Coefficient vs. Burnup; 3-Zone Fueling

for Zircaloy, and varies inversely with burnup. A representative value, for a burnup of 20,000 mwd/t, is 0.0086 (mills/kwhe) per ($/kg). This means that the fuel cycle cost at this burnup is changed 0.1 mill/kwhe by a change in fabrication cost of $12/kg.

6.5 Reprocessing Cost Coefficient

The reprocessing cost coefficient a_R is defined as the increase in fuel cycle cost in mills/kwh caused by an increase of $1/kg in the cost of reprocessing fuel*. Fig. 11 shows the reprocessing cost coefficient a_R as a function of burnup. It is the same for stainless steel as for Zircaloy, and varies inversely with burnup. A representative value, for a burnup of 20,000 mwd/t, is 0.0066 (mills/kwhe) per ($/kg). This means that the fuel cycle cost at this burnup is changed 0.1 mills/kwhe by a change in reprocessing cost of $15/kg.

6.6 Plutonium Credit Cost Coefficients

The plutonium credit cost coefficient a_P is defined as the decrease in fuel cycle cost in mills/kwh caused by an increase of $1/g in the credit allowed for plutonium**. Fig. 12 shows the plutonium credit cost coefficient a_P as a function of burnup. Representative values, at a burnup of 20,000 mwd/t are 0.055 (mills/kwhe) per ($/gPu) with stainless steel cladding, and 0.0475 (mills/kwhe) per ($/gPu) with Zircaloy. This means that fuel cycle costs would be decreased 0.1 mill/kwhe by an increase in plutonium credit of $1.8/g with stainless steel cladding, or $2.1/g with Zircaloy.

$$* \quad a_R \equiv \left(\frac{\partial M}{\partial C_R}\right)_{C_E, C_F, C_{Fab}, C_S, C_P, I_U, I_W, etc} = \frac{dM_R}{dC_R} = \frac{132}{B} \qquad (6.6)$$

$$** \quad a_P \equiv \left(\frac{\partial M}{\partial C_P}\right)_{C_E, C_F, C_{Fab}, C_S, C_R, I_U, I_W, etc} = \frac{dM_P}{dC_P} = \frac{1.305 \times 10^5 Y_P}{B} \qquad (6.7)$$

where Y_P is the kg of plutonium discharged from the reactor per kg of uranium fed to it.

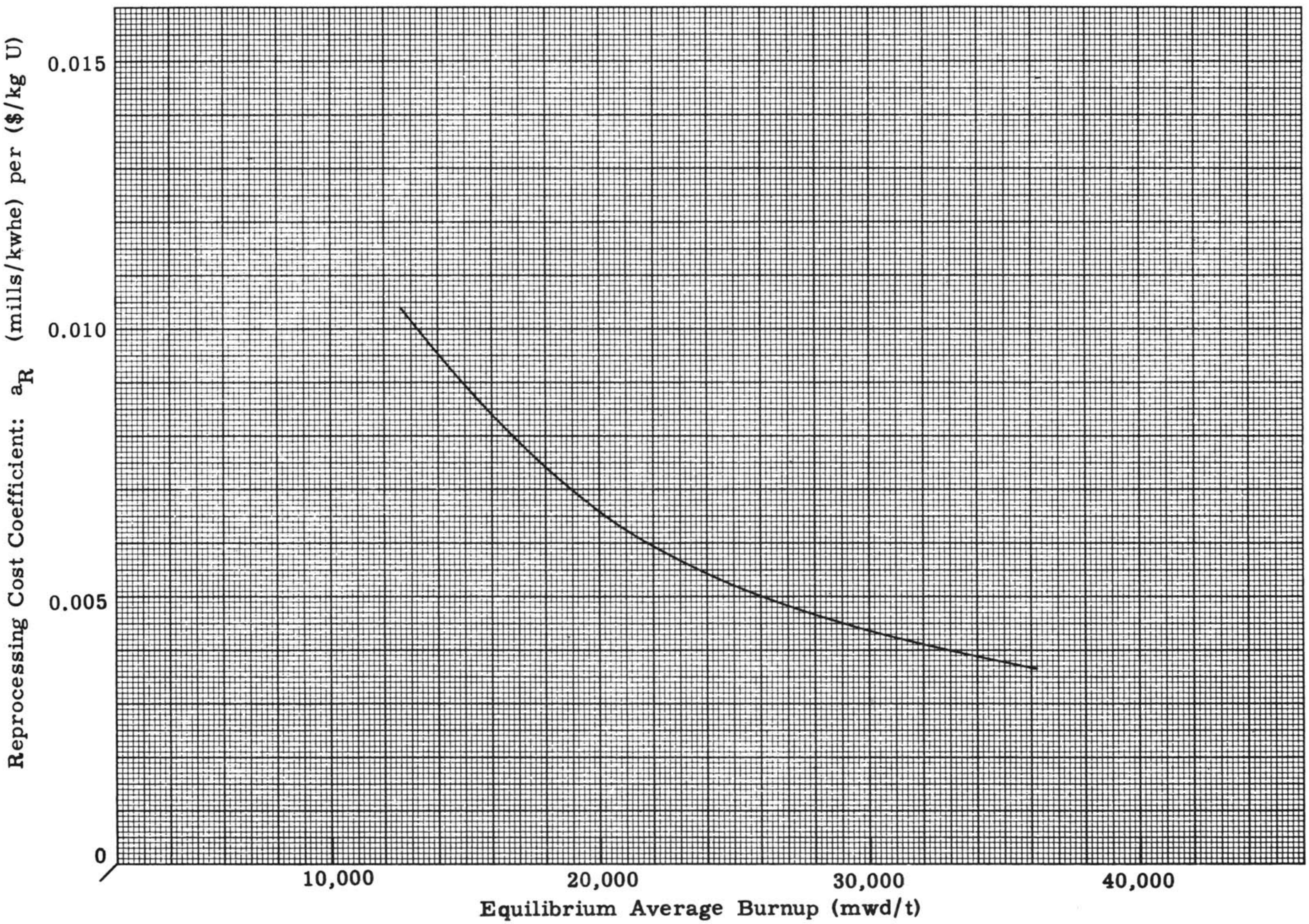

Figure 11: Reprocessing Cost Coefficient vs. Burnup; 3-Zone Fueling

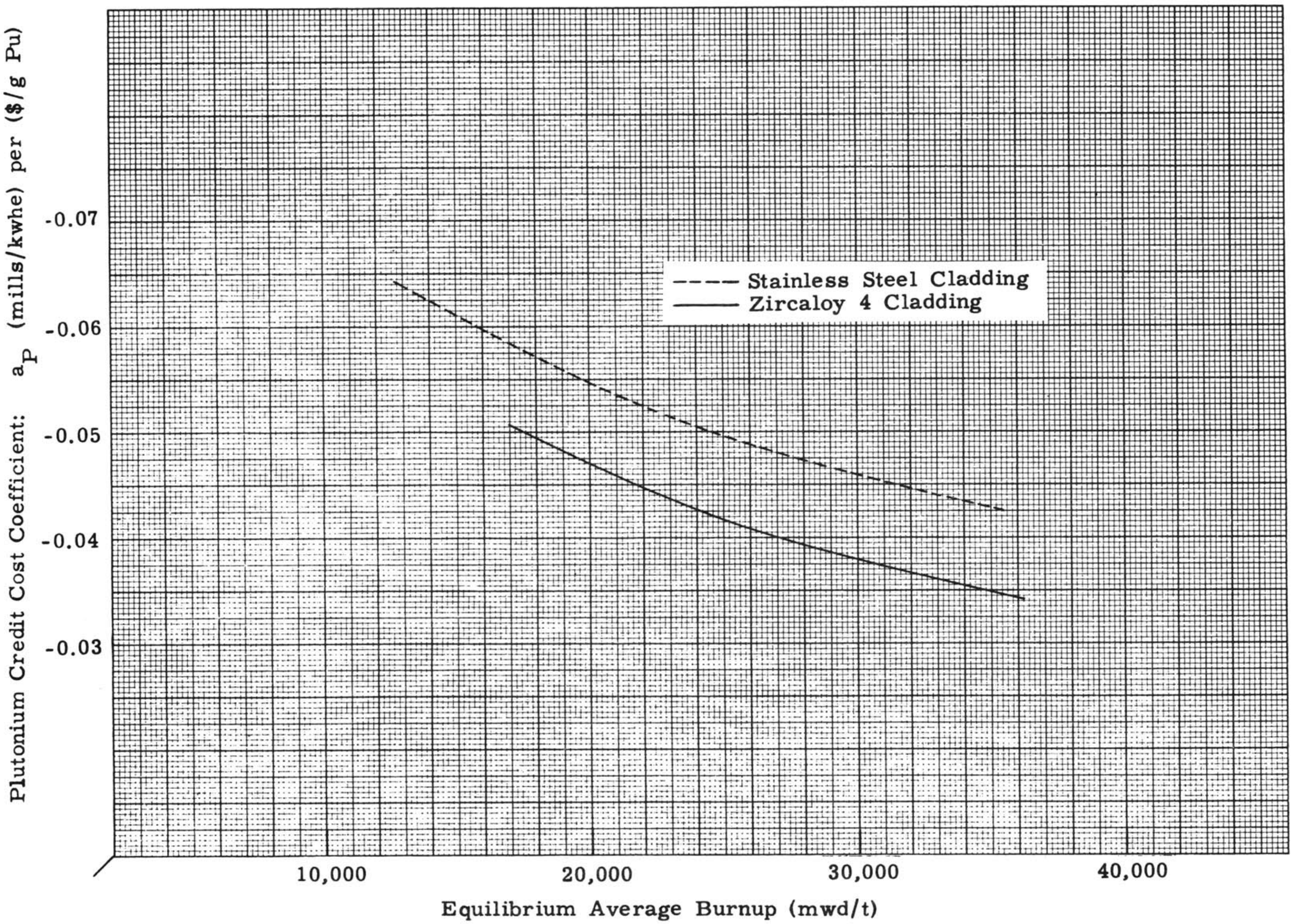

Figure 12: Plutonium Credit Cost Coefficient vs. Burnup; 3-Zone Fueling

6.7 General Fuel Cycle Costs

This section describes a simple procedure for using these cost coefficients in conjunction with Figs. 6 and 7 to calculate fuel cycle costs for any combination of the six fuel cycle cost parameters: 1) cost of natural uranium, 2) cost of separative work, 3) uranium carrying charge, 4) fabrication cost, 5) reprocessing cost and 6) plutonium credit. The procedure takes advantage of the fact that the cost coefficients are independent of the last four cost parameters named above, so that the fuel cycle cost is given exactly by

$$M = M^o + a_{IU}(I_U - I_U^o) + a_{Fab}(C_{Fab} - C_{Fab}^o) + a_R(C_R - C_R^o) + a_P(C_P - C_P^o) \quad (6.8)$$

Here M^o is the fuel cycle cost read from Fig. 6 or 7 for "standard" values of the cost parameters:

I_U^o, carrying charge on uranium = 12%/yr

C_{Fab}^o, fabrication cost = \$101/kgU (stainless steel)
= \$140/kgU (Zircaloy 4)

C_R^o, reprocessing cost = \$23.13/kgU (stainless steel)
= \$23.57/kgU (Zircaloy 4)

and C_P, plutonium credit = \$9.50/gPu

M is the fuel cycle cost for changed values of the cost parameters:

I_U, carrying charge on uranium

C_{Fab}, fabrication cost

C_R, reprocessing cost

C_P, plutonium credit

To illustrate use of Eq. (6.8), a sample calculation is given of fuel cycle costs for the following combination of conditions:

Zircaloy cladding

Burnup = 20,000 mwd/t

Cost of natural uranium, C_F = \$12.93/kg

Cost of separative work, C_E = \$25.00/kg
Uranium carrying charge, I_U = 9%/yr
Fabrication cost, C_{Fab} = \$100.00/kg
Reprocessing cost, C_R = \$30.00/kg
Plutonium credit, \$12.00/kg

We have already seen from Fig. 6 that the fuel cycle cost at the above values of C_F and C_E is

$$M^o = 1.85 \text{ mills/kwhe}$$

for 20,000 mwd/t burnup with Zircaloy cladding at the standard values of the remaining fuel cycle parameters listed earlier.

Values of the four cost coefficients are:

a_{IU} = 0.016 (mills/kwh) per (%/yr), Fig. 8
a_{Fab} = 0.0081 (mills/kwh) per (\$/kg), Fig. 10
a_R = 0.0066 (mills/kwh) per(\$/kg), Fig. 11
a_P = -0.047 (mills/kwh) per (\$kg), Fig. 12.

The fuel cycle cost M at the conditions of present interest is obtained by substituting in Eq. (6.8):

$$\begin{aligned} M &= 1.85 + 0.016(9-12) + 0.0081(100-140) + 0.0066(30.00-23.57) \\ &\quad - 0.047(12.00-9.50) \qquad (6.9) \\ &= 1.40 \text{ mills/kwhe} \end{aligned}$$

Fuel cycle costs for any other combinations of these six cost parameters can be evaluated simply by this procedure.

Appendix A

The price for uranium C_U as a function of weight fraction U-235 x is obtained from

$$C_U = C_E\left[(2x-1)\ln\frac{x(1-x_0)}{x_0(1-x)} + \frac{(x-x_0)(1-2x_0)}{x_0(1-x_0)}\right] \qquad (A.1)$$

The enrichment x_0 of uranium having zero value may be found from the cost of natural uranium C_F and the natural weight fraction of U-235

$$x_F = 0.007115 \qquad (A.2)$$

by substituting C_F for C_U and x_F for x in (A.1).

Equation (A.1) provides a good representation of the USAEC's price scale of July 1, 1962, with

$$C_E = \$30/\mathrm{kg} \qquad (A.3)$$

and

$$x_0 = 0.002531, \qquad (A.4)$$

which corresponds to

$$C_F = \$23.50/\mathrm{kg} \qquad (A.5)$$

Appendix B

Nomenclature

Symbol: This Report	Symbol: References (1), (2)	Definition
a_{Fab}	$\frac{d(\bar{C}_{total})}{d(C2)}$	Fabrication cost coefficient, $\frac{\text{mills/kwhe}}{\text{\$/kgU}}$
a_{IU}	$\frac{d(\bar{C}_{total})}{d(FU)}$	Uranium carrying charge cost coefficient, $\frac{\text{mills/kwhe}}{\%}$
a_P	$\frac{d(\bar{C}_{total})}{d(C8)}$	Plutonium credit cost coefficient, $\frac{\text{mills/kwhe}}{\text{\$/gm Pu}}$
a_R	-	Reprocessing cost coefficient, $\frac{\text{mills/kwhe}}{\text{\$/kgU}}$
B	B	Fuel burnup, megawatt days/tonne uranium
C_E	C_E	Unit cost of separative work, \$/kgU
C_F	C_F	Unit cost of natural UF_6, \$/kgU
C_{Fab}	C_2	Unit cost of the fabrication operation proper, \$/kgU
C^o_{Fab}	-	"Standard" unit fabrication cost on which M^o is based and from which a change in C_{Fab} is made when calculating a new value of M by use of the cost coefficients, \$/kgU
C_P	C_8	Unit credit for plutonium, \$/gm Pu
C^o_P	-	"Standard" unit credit for plutonium on which M^o is based and from which a change in C_P is made when calculating a new value of M by use of the cost coefficients, \$/gm Pu.
C_R	C_4	Unit cost of reprocessing, \$/kgU
C^o_R	-	"Standard" unit reprocessing cost on which M^o is based and from which a change in C_R is made when calculating a new value of M by use of the cost coefficients, \$/kgU
C_S	C_3	Unit cost of shipping, \$/kgU
$C_{U,in}$	C_1	Unit cost of uranium feed, \$/kgU
$C_{U,out}$	C_6	Unit credit for uranium in spent fuel, \$/kgU

Symbol: This Report	Symbol: References (1), (2)	Definition
G_{Fab}	FLS	Fractional loss of UF_6 in fabrication
I_{Fab}	100 FUFB	UF_6 carrying charges during time of fabrication, % per year
I_U	100 FU	Carrying charges on uranium in possession of reactor operator, %/yr
I_U^o	-	"Standard" carrying charge on uranium on which M^o is based and from which a change in I_U is made when calculating a new value of M by use of the cost coefficients, %/yr
I_W	100 FW	Carrying charge on fabrication working capital, %/yr
L	FLOAD	Plant load factor, the ratio of the amount of energy produced during a period to the amount which could have been produced if the plant had operated at full power during the same period.
M	$\bar{C}$	Total fuel cycle cost, mills/kwhe
M^o	-	"Standard" total fuel cycle cost from which quantities are added and subtracted when calculating a new total fuel cycle cost by use of the cost coefficients, mills/kwhe.
M_{Fab}	$\bar{C}_2$	Contribution of fabrication costs to the total fuel cycle cost, mills/kwhe
M_{IU}	$\bar{C}_{10} + \bar{C}_{12}$	Contribution of the uranium carrying charges to the total fuel cycle cost, mills/kwhe
M_{IW}	$\bar{C}_{11} + \bar{C}_{13}$	Contribution of the fabrication carrying charges to the total fuel cycle cost, mills/kwhe
M_P	$-\bar{C}_8$	Contribution of the credit for plutonium to the total fuel cycle cost, mills/kwhe
M_R	$\bar{C}_4 + \bar{C}_5 + \bar{C}_7$	Contribution of the reprocessing and conversion charges to the total fuel cycle cost, mills/kwhe
M_S	$\bar{C}_3$	Contribution of the shipping charges to the total fuel cycle cost, mills/kwhe
M_{Sp}	$\bar{C}_9$	Contribution of the carrying charges on spares to the total fuel cycle cost, mills/kwhe
M_U	$\bar{C}_1 + \bar{C}_6$	Contribution of the net charge for uranium to the total fuel cycle cost, mills/kwhe

Symbol: This Report	Symbol: References (1), (2)	Definition
$M_{U,in}$	$\tilde{C}_1$	Contribution of the cost of uranium feed to the total fuel cycle cost, mills/kwhe
$M_{U,out}$	$-\bar{C}_6$	Contribution of the credit for uranium in the spent fuel to the total fuel cycle cost, mills/kwhe
n	-	Number of equal volume zones in n-zone outin fueling
T_1	TFBP	Time during which fabrication payments are made, years
T_2	TFBU	Average time for basing UF_6 capital carrying charges paid by fabricator, years
W	WTF	Batch size of fuel loaded in each reactor cycle, kgU
x	X	Weight fraction on U-235 in enriched UF_6
x_0	X0	Weight fraction of U-235 at which uranium in the form of UF_6 has zero value
x_{in}	-	Weight fraction of U-235 in fuel fed to the reactor
x_{out}	-	Weight fraction of U-235 in fuel discharged from the reactor
Y_P	W_7	Ratio of the amount of plutonium in spent fuel to the amount of uranium in the same fuel when it was charged to the reactor
Y_U	W_5	Ratio of the amount of uranium in spent fuel to the amount of uranium in the same fuel when it was charged to the reactor
γ	γ	Net electrical efficiency
θ	-	Thermal power of the reactor, megawatts

Appendix C

References

(1) Trapp, D. L., "The Effects of Changing Economic Conditions on Energy Costs in Stainless Steel Clad Pressurized Water Reactors," SM Thesis, Department of Nuclear Engineering, MIT, September 1962.

(2) Richardson, M. C., "The Effects of Changing Economic Conditions on Energy Costs in Zircaloy 4 Clad Pressurized Water Reactors," MITNE 27, Dec. 1, 1962.

(3) McLeod, N. B., M. Benedict et al., "The Effect of Fuel and Poison Management on Nuclear Power Systems," NYO 9715.