MIT-2073-6
MITNE-90
Vol. 1

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF NUCLEAR ENGINEERING
Cambridge, Massachusetts 02139

THE EFFECT OF URANIUM-236 AND NEPTUNIUM-237 ON THE VALUE OF URANIUM AS FEED FOR PRESSURIZED WATER POWER REACTORS

by

D.A. Goellner, M. Benedict and E.A. Mason

December, 1967

For the
U.S. Atomic Energy Commission
Under Contract AT(30-1)-2073

MIT-2073-6
MITNE-90
Vol. 1

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF NUCLEAR ENGINEERING
Cambridge, Massachusetts 02139

THE EFFECT OF URANIUM-236 AND NEPTUNIUM-237 ON THE VALUE OF URANIUM AS FEED FOR PRESSURIZED WATER POWER REACTORS

by

D. A. Goellner, M. Benedict and E. A. Mason

December, 1967

For the
U. S. Atomic Energy Commission
Under Contract AT(30-1)-2073

THE EFFECT OF URANIUM-236 AND NEPTUNIUM-237 ON THE VALUE OF URANIUM AS FEED FOR PRESSURIZED WATER POWER REACTORS

ABSTRACT

Until now uranium fuel for power reactors has consisted principally of the naturally occurring isotopes U-235 and U-238. This fuel has contained so little reactor-produced U-236 that it has been possible to establish a price scale based only on its U-235 content. In the future, however, uranium fuel for power reactors may contain significant amounts of U-236, and it will be necessary to take the U-236 content into account in determining the value of the fuel.

The major economic effects of U-236 in fuel charged to a reactor are as a thermal neutron poison and as a target for the production of Np-237, with the relative importance of the two effects being governed by the unit price at which byproduct Np-237 can be sold. The purpose of this study is to develop procedures for determining the unit value of uranium over wide ranges of isotopic compositions and Np-237 prices and to apply the procedures to the case where the uranium is used as feed for typical pressurized water reactor (PWR) fuel flow schemes.

The San Onofre PWR is used as the reference reactor. Two uranium recycle schemes are considered, both of which are examined only under steady-state recycling conditions. In one scheme, recycled uranium is re-enriched by blending with uranium feed having high U-235 content, while the other scheme involves the re-enrichment of recycled uranium in a gaseous diffusion plant prior to mixing it with the requisite low-enrichment feed uranium. Steady-state operating characteristics for the reactor and recycle flowsheets were calculated over ranges of feed isotopic compositions using the codes

CELL and MOVE, the latter modified to simulate scatter refueling of the reactor. The effect of U-236 on separative work requirements and the distribution of U-236 in diffusion plant product and tails streams are considered in detail.

The value of feed uranium having a given isotopic composition and used for a particular fuel flow scheme is determined by requiring that the fuel cycle cost using this feed uranium be equal to the lowest fuel cycle cost which can be obtained for the same fuel flow scheme when feed uranium contains no U-236 and is priced on the AEC scale.

In addition to the basic recycle modes of operation, wherein feed uranium is sent, as purchased, to the fabrication plant, the unit value of feed uranium is also calculated for the case where feed is pre-enriched prior to fabrication and for the case where feed is blended with natural uranium prior to fabrication.

In addition to the effects of isotopic composition, operating mode, and Np-237 price, the effects on unit feed value of changing natural U_3O_8 price, unit costs of fabrication and reprocessing, and irrecoverable losses during fabrication are also examined.

Two definitions of a U-236 penalty, in dollars per gram of U-236, are investigated in an attempt to correlate the feed value results and present the U-236 and Np-237 effects in more tractable form.

ACKNOWLEDGMENTS

This report is based on a thesis submitted by Donald A. Goellner to the Nuclear Engineering Department at Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Financial support from the U.S. Atomic Energy Commission under contract AT(30-1)-2073 and in the form of Mr. Goellner's AEC Fellowship is gratefully acknowledged.

All calculations were performed at the MIT Computation Center.

Thanks are due Dr. Harvey W. Graves of Westinghouse Electric Corporation for information on the San Onofre reactor.

TABLE OF CONTENTS

VOLUME 1

TABLE OF CONTENTS
VOLUME 2
APPENDICES

LIST OF FIGURES

VOLUME 1

VOLUME 2

LIST OF TABLES

VOLUME 1

VOLUME 2

Page

I. INTRODUCTION

A. Description of Problem

Procedures presently used to determine power reactor fuel cycle costs treat the price of uranium as a function only of its U-235 content and as independent of the amount of U-236 present. Until private ownership of enriched uranium was permitted, there was no alternative pricing procedure, because the U. S. Atomic Energy Commission, which had been the only U. S. source of uranium of other than natural enrichment and the only purchaser of uranium discharged from power reactors, set a price scale which considered U-236 as equivalent to U-238 and which made the price dependent only upon the U-235 content of uranium.(1)

Under private fuel ownership, however, the prices at which uranium is purchased need not necessarily be those set by the AEC, because there are alternative sources, including natural uranium and uranium discharged from reactors. Fuel of any enrichment desired for a reactor may be obtained by having the AEC enrich purchased uranium for a toll or fee or by blending purchased uranium of two different enrichments spanning the desired enrichment. These alternatives are available in addition to direct purchase of uranium containing no U-236 from the AEC on the AEC's price scale.

Uranium recovered from discharged reactor fuel will often contain a substantial proportion of U-236, owing to the trend toward higher fuel burnup and repeated recycling of uranium. It will therefore be important to know the isotopic composition of uranium to be purchased and to determine the value of uranium having that particular isotopic composition. This will set the maximum price which could be paid for this uranium without leading to fuel cycle costs any higher than if uranium free of U-236 were to be purchased from the AEC on the AEC's price scale.

This price will not be the same as it would be if U-236 were taken as being equivalent to U-238, for the following reasons:

a. U-236 is a neutron poison whereas U-238 is a fertile material, so that they affect reactivity lifetime differently;

b. the presence of U-236 increases the amount of separative work expended in a gaseous diffusion plant to produce uranium of a specified U-235 content, since separation of U-235 from U-238 is less costly than separation of U-235 from an equal amount of U-236; and

c. the presence of U-236 increases the amount of Np-237 produced during irradiation. Neptunium-237 has value as a target material for the production of Pu-238, which is in demand as a radioisotopic power source. There is little doubt that the near-future Pu-238 requirement for space-power applications will be considerable(2) and will result in significant prices for both

Pu-238 and Np-237. Current estimates of fuel cycle costs do not include credits for the sale of Np-237, but recovery of Np-237 from irradiated power reactor fuel will soon be routinely performed by Nuclear Fuel Services, Inc.,(3) and its sale will tend to improve reactor economics. Increased Np-237 production is thus a favorable consequence of the presence of U-236.

The purpose of this study is to establish the value of uranium over wide ranges of isotopic compositions and Np-237 prices, when the uranium is used as feed for a typical pressurized-water reactor (PWR). For this study, "feed" refers to uranium which is purchased as makeup material for a given fuel cycle and which can contain U-236, as well as U-235 and U-238. The effect on feed uranium value of changing U_3O_8 price, unit fabrication and reprocessing costs, and irrecoverable uranium losses is also examined.

The prominence of the PWR in the expanding nuclear power industry justifies its use as a basis for this study. However, the presence of U-236 in feed uranium will affect fuel cycle economics differently for other reactor types and for different fuel management schemes. Although the numerical results reported herein apply to specific cases, the procedures developed could be utilized to estimate feed values for other reactor types and fuel cycles, with only minor revision.

This has been done at MIT(4,5) in other parts of this study conducted under AEC contract AT(30-1)-2073.

The effect of U-236 and Np-237 on the value of uranium feed has not been examined in detail by other workers. The important effects of Np-237 sale on fuel cycle economics and on the specification of fuel management procedures have been recognized for some time(6), but most attention has been concentrated on maximizing Np-237 production, either by core design modifications(7) or by appropriate tailoring of the fuel cycle for this purpose.(8) Estimates have been made of U-236 and Np-237 values based on their use in reactors as target isotopes for the production of Pu-238,(9) but the economic penalty for having U-236 present when Np-237 is not sold has not been calculated.

B. Scope of Study and Major Assumptions

The principle used in determining the value of feed uranium having a given isotopic composition is that the fuel cycle cost which results from its use in a specified fuel flow model shall equal the lowest fuel cycle cost which can be obtained for the same fuel flow model when feed uranium contains no U-236 and is priced on the AEC price scale. If the price of uranium is set equal to the value so determined, it will be a matter of indifference whether the fuel cycle is fed with uranium of optimum enrichment containing no U-236 priced on the AEC scale or with uranium of a different composition priced according to this principle.

The reference PWR chosen for the study is the 430 MWe (1346 MW thermal) San Onofre reactor.(10) Zircaloy-4 is used as the reference cladding material. To provide a flattened core power distribution, modified four-batch scatter refueling is used as the fuel reloading scheme. This procedure differs from complete scatter refueling(11) in that fresh fuel is first irradiated in an outer annular region consisting of one quarter of the core volume, from which it is fed scatter-wise to the remaining three quarters of the core.

Two basic fuel cycle flow schemes are considered. The first, shown in Figure I.1, involves the recycle of reprocessed uranium directly to the fabrication plant, where it is blended with purchased feed uranium to form the reactor charge. The second scheme, shown in Figure I.2, involves the re-enrichment of recycled uranium in a gaseous diffusion plant, with subsequent mixing of the requisite feed with the diffusion plant product to form the reactor feed uranium. The nomenclature used is given on the flowsheet diagrams. The full-power output of the plant is P MWe. Flow rates F_i are time-averaged values for uranium at various points. The weight ratio of U-235 to U-238 is denoted by R_i, while

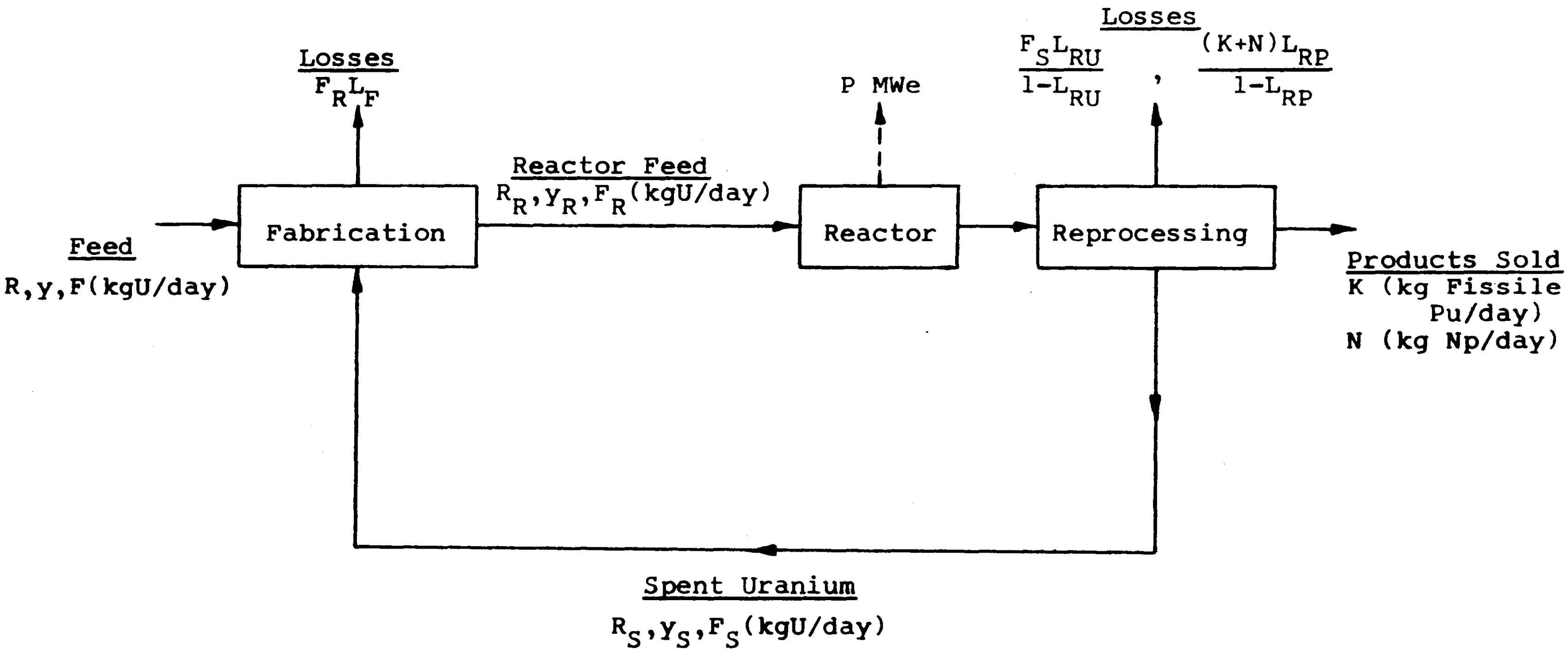


FIGURE I.1 Flowsheet for Recycle of Uranium to Fabrication

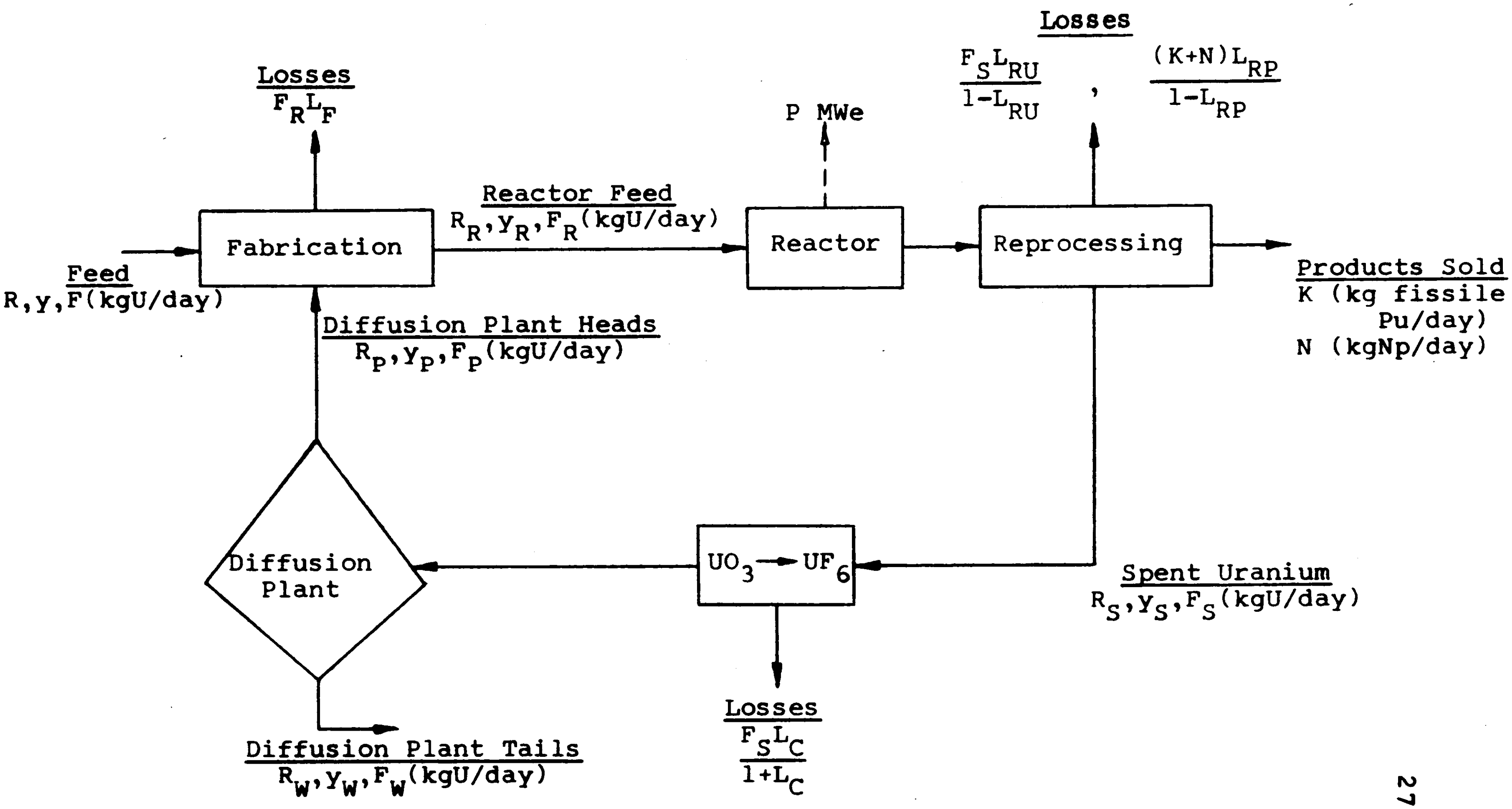


FIGURE I.2 Flowsheet for Recycle of Uranium to Gaseous Diffusion Plant

y_i represents the weight fraction of U-236 in uranium. Irrecoverable loss fractions are given by L_F, L_{RU}, L_{RP}, and L_C. The use of R and y to describe feed uranium composition, rather than some alternative variables, enables one to examine directly the effect on feed value which results from changes in U-236 content and not from changes in the relative amounts of U-235 and U-238 present.

In both schemes, Np-237 and plutonium are sold immediately after reprocessing and uranium is assumed to be recycled, as UO_3. The recycling of reprocessed uranium, rather than selling it, is necessary to avoid having to assume a price for this material arbitrarily. [Note: T. Golden(4) has calculated the value of uranium feed for a PWR fuel cycle wherein spent uranium from the PWR is credited at the value it would have as feed for a heavy-water moderated, organic-cooled reactor (HWOCR). Feed values for the HWOCR have been determined by D. Bauhs(5)].

Economic analyses are performed only for steady-state operation of the fuel cycle flowsheets since this eliminates an arbitrary choice of operating restrictions for transient cycles and provides a unique common basis upon which to compare the values of feed uranium having different isotopic compositions. The assumption of steady-state operation fixes the period of reactor operation as the mid-1970's.

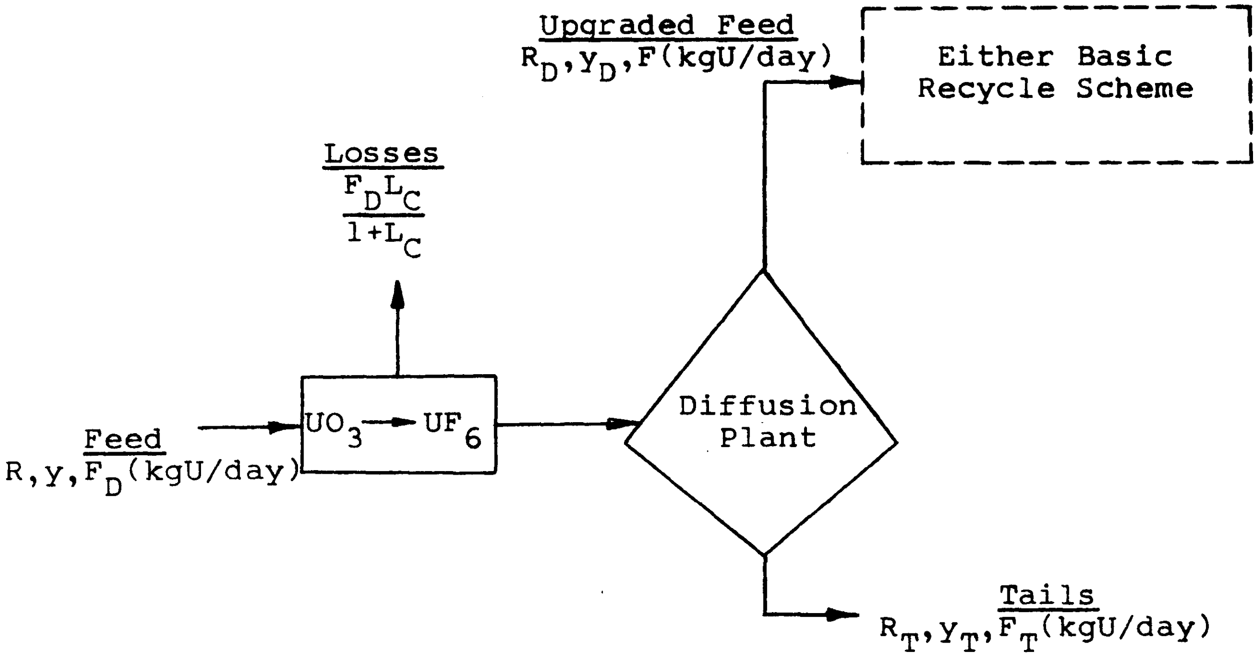
In Figure I.2, the condition is imposed that the U-235 to U-238 weight ratio of purchased uranium equals that of recycled uranium product from the diffusion plant, so that $R = R_R = R_P$. This is consistent with the assumption that the diffusion plant is operated as a "matched-R" cascade(12). In such a cascade, at each point where two streams are mixed, the weight ratios of U-235 to U-238 in the two streams are equal. The distribution of U-236 between the heads and tails streams of the diffusion plant and the effect of U-236 on separative work requirements are accounted for using methods developed by de la Garza et al(12) for such a cascade. For each natural uranium (U_3O_8) price considered, the corresponding optimum tails weight ratio R_W is used, so that zero value is maintained for the tails stream. Due to the impossibility of predicting the composition and size of all possible feed and product streams during a future diffusion plant operation, an assumption which is unavoidable is that the only streams entering or leaving the diffusion plant are those involved in the particular fuel cycle under consideration.

At steady-state, the feed uranium purchased serves to replace all uranium isotopes which leave the fuel cycle due to depletion and irrecoverable losses during fabrication and reprocessing. In Figure I.2, the diffusion plant tails stream and the uranium lost during conversion of UO_3 to UF_6 must also be balanced by the feed. The absence of a strong U-238 sink in the recycle-to-fabrication flowsheet makes it necessary to have relatively high U-235 concentrations in the feed uranium. As a result the values of R examined for Figure I.1 (R = 0.4 to R = 1.0) are much higher than for Figure I.2 (R = 0.02 to R = 0.08). The diffusion plant tails stream acts as a strong U-238 sink, but also carries appreciable U-236 from the cycle of Figure I.2. Due to the discharge of tails uranium, higher feed rates are required for Figure I.2 than for Figure I.1. Consequently, the buildup of U-236 throughout the cycle of Figure I.1 will exceed that for Figure I.2, per unit of feed.

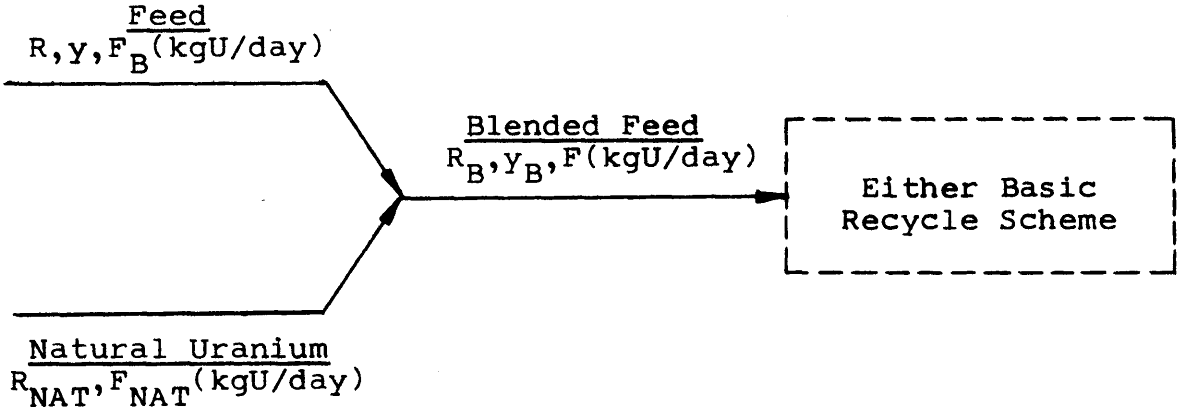
Uranium flow rates and isotopic compositions throughout both basic recycle schemes can be determined for steady-state operation once R and y are specified for the feed. All depletion and recycle calculations required to predict steady-state characteristics were carried out using the codes CELL(13) and MOVE(14), where MOVE has been modified to include the scatter refueling scheme selected for the reactor. After flowsheet characteristics are determined over ranges of R and y, feed values can be calculated by applying the principle described above.

It is apparent that neither of the basic recycle schemes permit determination of feed value over the entire range of R important in power reactors, i.e., from R = 0.005 to R = 15. Modifications which can be made to either of the basic schemes are shown, with nomenclature, in Figure I.3. By means of these modified operating modes, value can be affixed to feed whose isotopic composition would be otherwise unsuitable for use in the basic recycle schemes; in addition, the value of uranium can often be increased by using it as feed for one of the modified modes rather than for the basic scheme directly. In Figure I.3, the unit value and flow rate of the upgraded feed stream or the blended feed stream are known from the analysis performed for the basic recycle scheme being considered. By an overall value-and-cost balance, the unit value of feed can be calculated for either of the modified modes. In addition to specifying R and y, one extra degree of freedom exists for each modified flowsheet. When feed is pre-enriched in a gaseous diffusion plant (assumed to be operated as a matched-R cascade), the weight ratio of U-235 to U-238 for diffusion plant product R_D can be optimized to give the maximum unit value of feed having specified R and y. When feed is blended with natural uranium, giving $R_B < R$, the maximum unit value of feed can be maximized by proper choice of the fraction of natural uranium used for blending F_{NAT}/F.

In calculating minimum fuel cycle costs for the basic recycle schemes, it is assumed that feed containing



(a) Pre-Enrichment by Gaseous Diffusion



(b) Blending with Natural Uranium

FIGURE I.3 Modified Modes of Operation

no U-236 (y=0) is purchased as UF_6 on the AEC price scale. However, feed value is determined for uranium in the form of UO_3. The assumption is made that the unit costs of converting UF_6 to UO_2 and UO_3 to UO_2 are the same.

Table I.1 gives values selected for the major economic variables. Since an established price for Np-237 does not exist and since this price is likely to vary considerably before stabilizing at some future date, a range of prices from $0/g to $100/g is considered. These Np-237 prices do not include the cost of recovering Np-237, and therefore represent the <u>net</u> credit realized by the operator, per gram of Np-237. A "high unit cost" case uses unit costs of $60, $40, and $6/kg respectively for fabrication, reprocessing, and shipping, while a "low unit cost" case uses corresponding unit costs of $40, $25, and $3/kg. Two loss fractions during fabrication - 0.01 and 0.002 - are examined.

Prices of $6, $8, and $10/lb are considered for U_3O_8. For all diffusion plant operations, the unit charge for separative work is assumed to be $30/kgU.

For a natural uranium price of $8/lb U_3O_8 and a charge for separative work of $30/kgU, the price schedule for enriched uranium is consistent with the AEC price scale in effect in August, 1967.(1) In this

TABLE I.1

Values for Major Economic Parameters

Reactor inventory (kgU)	53,000
Net electrical power output (MW), P	430
Load factor	0.8
Np-237 price (\$/g), C_N	variable, between 0 and 100
U_3O_8 price (\$/lb), $C_{U_3O_8}$	6,8,10
Cost of separative work (\$/kgU)	30
Fixed charge rate on inventory (yr^{-1})	0.10
Fabrication cost (\$/kg)	60,40
Reprocessing cost (\$/kg)	40,25
Spent fuel shipping cost (\$/kg)	6,3
Cost of converting UO_3 to UF_6 (\$/kg)	4
Fractional losses:	
Fabrication, L_F	0.01,0.002
Reprocessing, uranium L_{RU}	0.01
Reprocessing, Pu + Np, L_{RP}	0.01
Conversion of UO_3 to UF_6, L_C	0.003

study, when the price of U_3O_8 is changed, it is assumed that the optimum tails weight ratio of U-235 to U-238, R_W, and the AEC price scale are adjusted to correspond to the new U_3O_8 price. For uranium having weight ratio R, the unit price on this scale is given by $C_{AEC}(R)$, \$/kgU. Calculation of R_W and $C_{AEC}(R)$ was carried out for each natural uranium price using well-established procedures.(15) Throughout this work, the "AEC price scale" is therefore not necessarily the scale currently used by the AEC, but is the price scale corresponding to a separative work charge of \$30/kgU and the U_3O_8 price under consideration - either \$6/lb or \$8/lb or \$10/lb. The credit for fissile plutonium at a given U_3O_8 price is taken as 10/12 the price, in \$/g, of U-235 at 90% enrichment as given by the AEC price scale corresponding to that U_3O_8 price.

Uranium value results are correlated and the U-236 and Np-237 effects are presented in more tractable form by calculating a "U-236 penalty," defined as the reduction in total feed value per gram of U-236 when y kg of U-236 are added to (1-y) kg of U-235 + U-238 at a constant U-235 to U-238 weight ratio.

II. SUMMARY OF RESULTS

Throughout this section, the designation of "reference conditions" will apply to a U_3O_8 price $C_{U_3O_8}$ of \$8/lb, a fabrication loss fraction L_F of 0.01, and the set of high unit costs, all taken together. Major emphasis is placed on results obtained for these reference conditions, as they are representative of results obtained for other sets of conditions considered and illustrate all important trends.

The minimum fuel cycle cost when feed containing no U-236 is purchased as UF_6 on the AEC price scale is denoted by C_E^* and the corresponding optimum U-235 to U-238 weight ratio in such feed is given by R^*. Table II.1 presents a summary of results obtained for C_E^* and R^* for all cases examined. The average burnup B which corresponds to R^* is also listed. It is important to note the difference in the general level of R^* between the two recycle schemes, with R^* for recycle to fabrication being considerably higher for the reasons expressed in Section I. A further increase in the level of R^* occurs for recycle to fabrication when L_F is reduced from 0.01 to 0.002.

The variation of C_E^* with the unit price for Neptunium-237 C_N is shown in Figure II.1 for three U_3O_8 prices and for both recycle schemes. For each U_3O_8 price, two major characteristics are apparent:

TABLE II.1

Summary of Minimum Fuel Cycle Cost Results

					Recycle to Fabrication			Recycle to Diffusion Plant		
L_F	Unit Costs	$C_{U_3O_8}$ (\$/lb)	C_N^I (\$/gNp-237)	C_N	C_E^* (m/kwhr)	R*	B (MWD/T)	C_E^* (m/kwhr)	R*	B (MWD/T)
0.01	high	6	54.01	0	1.863	0.571	25682	1.470	0.0318	28232
				60	1.248	0.552	24281	1.292	0.0325	28975
		8	57.41	0	2.028	0.557	24692	1.614	0.0309	26976
				20	1.823	0.551	24250	1.552	0.0311	27191
				60	1.410	0.539	23400	1.429	0.0315	27665
				100	0.996	0.528	22615	1.305	0.0319	28132
		10	60.53	0	2.183	0.545	23851	1.750	0.0300	25855
				60	1.563	0.529	22662	1.559	0.0307	26618
	low	8	52.58	0	1.812	0.497	20481	1.417	0.0270	22599
				60	1.181	0.480	19331	1.237	0.0275	23235
0.002	high	8	54.94	0	2.052	0.694	24360	1.604	0.0307	26742
				60	1.375	0.669	22715	1.417	0.0316	27667

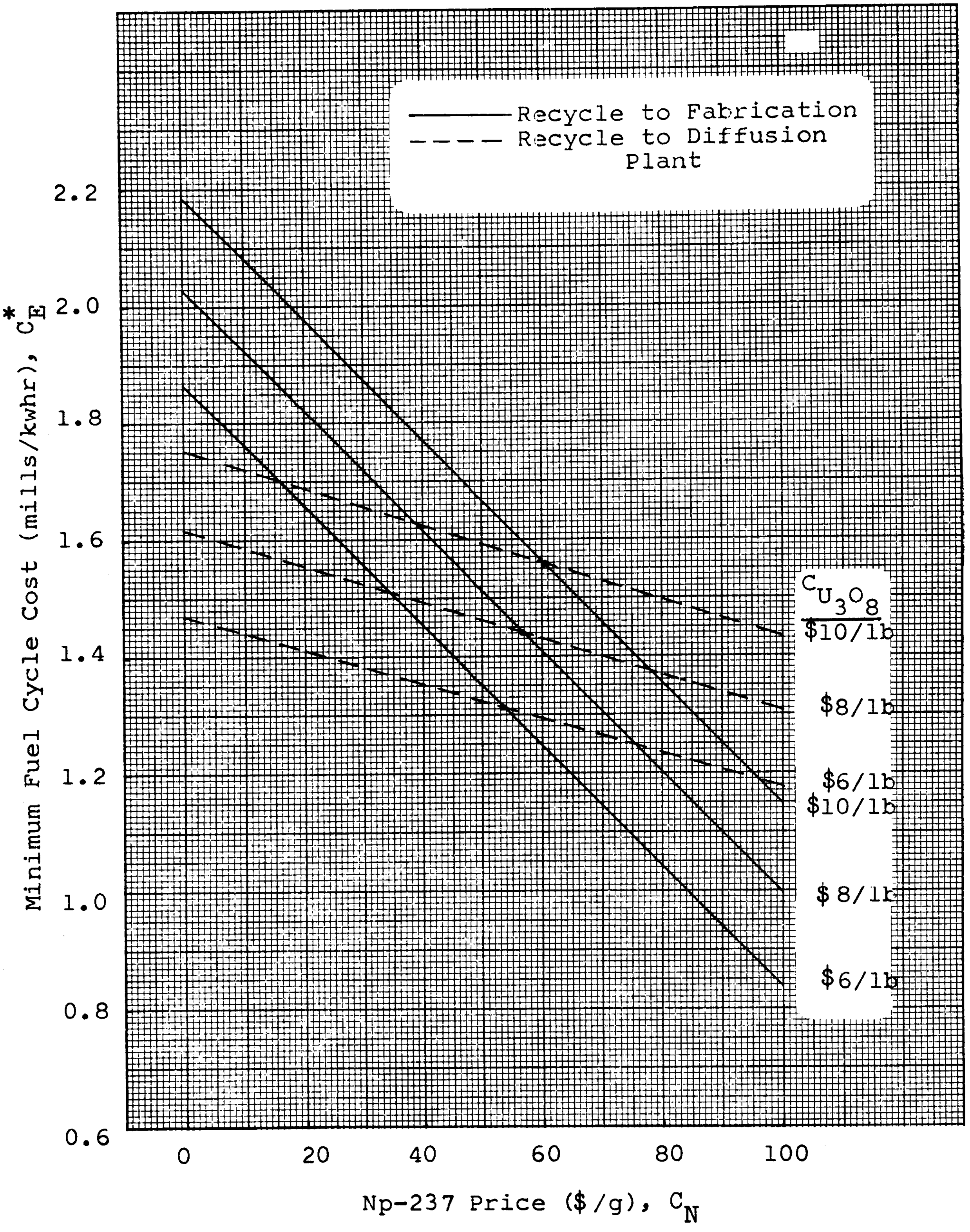


FIGURE II.1 Effect of Np-237 Price on Minimum Fuel Cycle Cost: High Costs, $L_F = 0.01$

a. at $C_N = 0$, C_E^* is about 0.4 mills/kwhr higher when recycling to fabrication; and,

b. the decrease of C_E^* with increasing C_N is significantly greater for recycle to fabrication so that the values of C_E^* for both recycle schemes become equal at a price C_N^I of around \$55/g, at which it is a matter of indifference whether spent uranium is recycled to fabrication or through a diffusion plant. Results for this neptunium indifference price C_N^I are also given in Table I.1.

These two characteristics can be explained by considering Table I.2, where various steady-state characteristics for Figures I.1 and I.2 are given for y=0 and y=0.01 when R is close to R*. For y=0, the substantially higher y_R values when recycling to fabrication make it necessary for the reactor feed to have a higher U-235 content, hence higher R_R, in order to maintain a reasonable burnup level. This fact plus the loss of value incurred in mixing the feed and recycled uranium streams - which have drastically different U-235 concentrations - lead to higher C_E^* results for the recycle-to-fabrication scheme when C_N = \$0/g. However, the higher Np-237 production rate at y=0 when recycling to fabrication leads to a greater sensitivity of C_E^* to changes in Np-237 price than for recycle to a diffusion plant and causes the intersection at $C_N = C_N^I$.

When the Np-237 price is equal to C_N^I, it is a matter of indifference which recycle scheme is employed.

TABLE II.2

Change of Major Fuel Cycle Characteristics with Addition of U-236 to Feed

$(C_{U_3O_8} = \$8/\text{lb})$

	Recycle to Fab.; L_F=0.01, R=0.55		Recycle to Fab.; L_F=0.002, R=0.70		Recycle to Diff. Plant; L_F=0.01, R=0.03	
	y=0	y=0.01	y=0	y=0.01	y=0	y=0.01
R_R	0.0381	0.0388	0.0403	0.0400	0.03	0.03
y_R	0.0307	0.0380	0.0354	0.0423	0.0050	0.0269
B(MWD/T)	24172	22612	24728	22561	26034	17370
F(kgU/day)	2.536	2.630	2.182	2.259	29.66	34.33
N(kg Np/day)	0.109	0.127	0.119	0.136	0.033	0.108
$F_R y_R/F$	0.539	0.688	0.707	0.894	0.007	0.049
F_R/F	17.56	18.11	19.96	21.13	1.395	1.806
N/F	0.0428	0.0483	0.0545	0.0602	0.0011	0.0031

If C_N is less than C_N^I, it is economically advantageous to recycle uranium to a diffusion plant and permit the discharge of some U-236 with the tails stream, while for C_N greater than C_N^I, it is preferable to maximize U-236 retention by recycling to fabrication.

Figures II.2 through II.5 show the unit value V(R,y) of UO_3 feed having isotopic composition R,y for both of the basic recycle schemes of Figures I.1 and I.2 when C_N = \$0/g and \$60/g, using the reference conditions. Results are given at higher values of R for recycle to fabrication than for recycle to a diffusion plant due to the lower U-238 feed requirement of the former. When C_N = \$0/g, U-236 has effect only as a neutron poison and the reduction of V(R,y) as y increases can be seen at all R for both recycle schemes. However, when C_N is increased to \$60/g, the value at each point with $y > 0$ is considerably greater than the corresponding value when C_N = \$0/g; in fact, for recycle to fabrication (Figure II.3), the feed value at any R increases with increasing y over the y-range investigated. Of course, if y were increased further at a given R, a point would eventually be reached at which the U-236 poisoning becomes so severe that an additional increase of y would then decrease V(R,y), regardless of how high a Np-237 price is

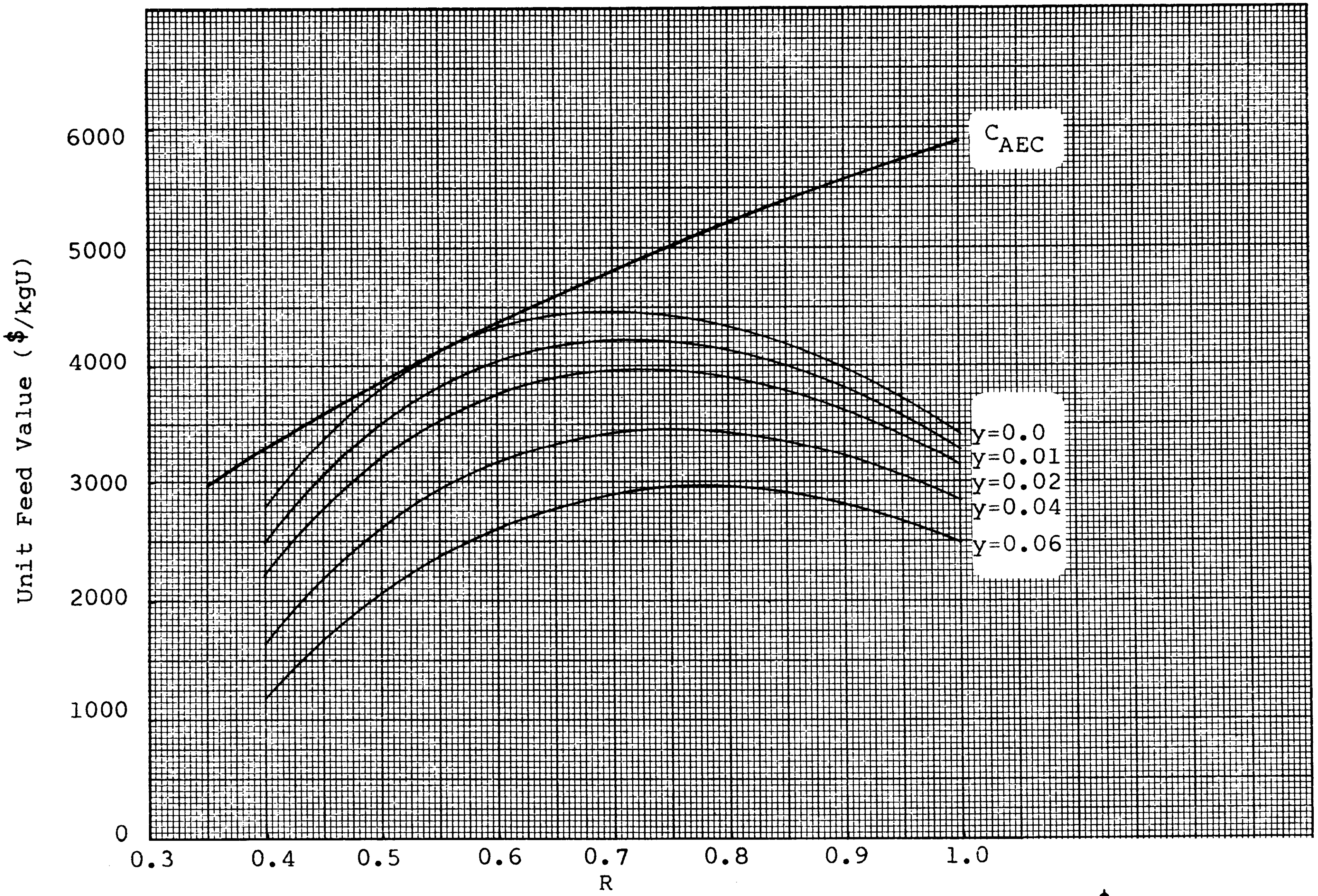


FIGURE II.2 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.01

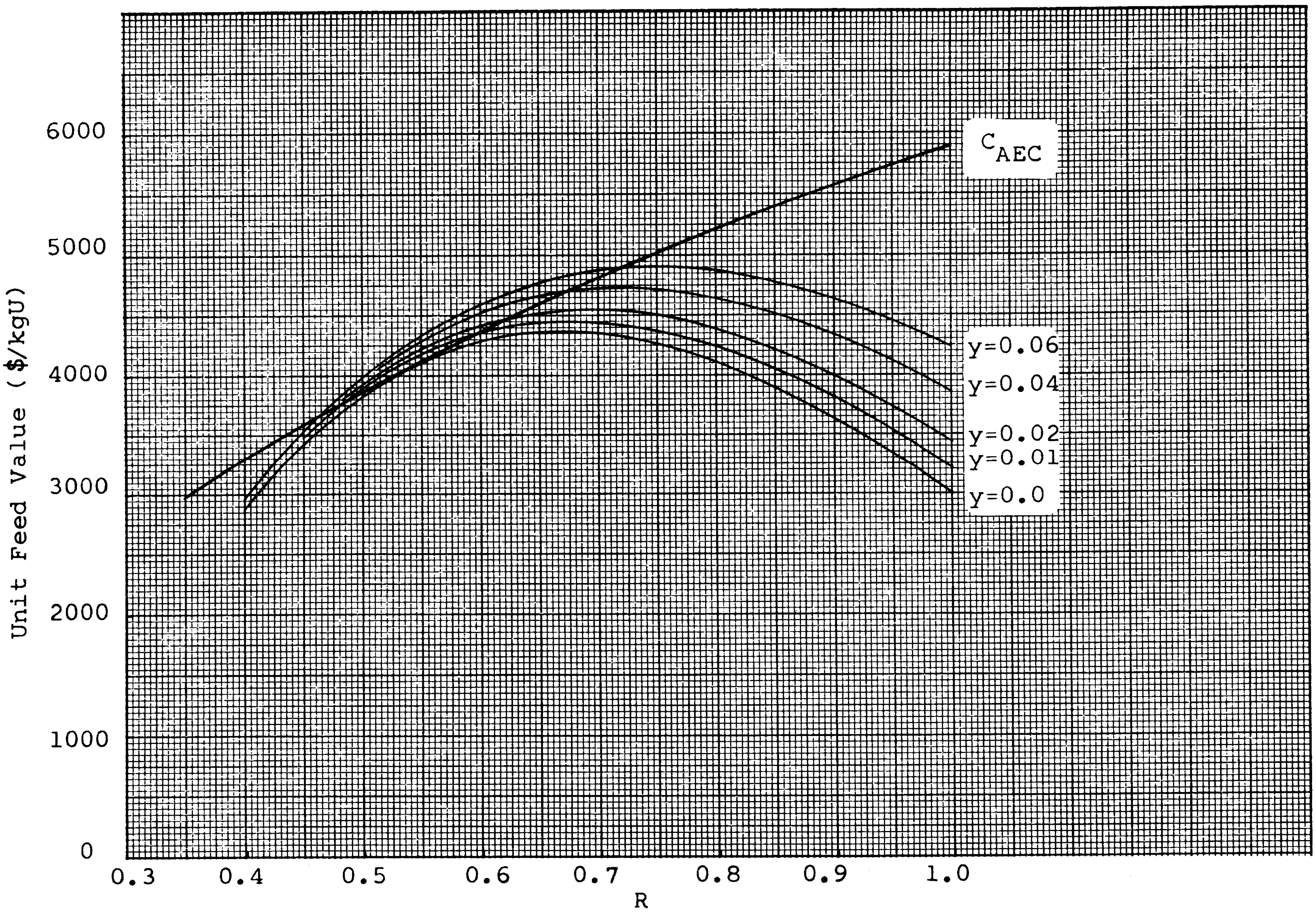


FIGURE II.3 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, C_N = $60/g, High Costs, L_F = 0.01

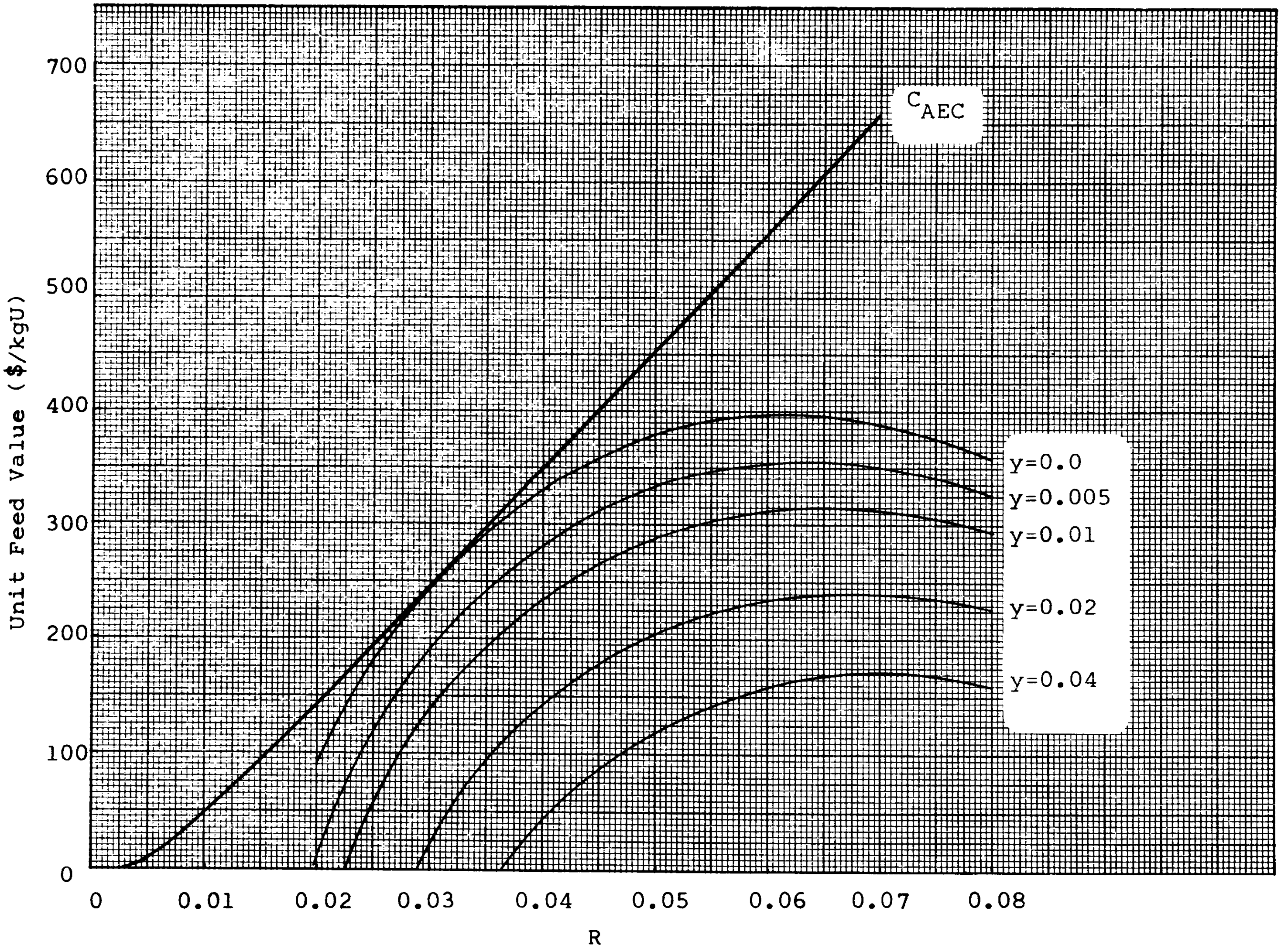


FIGURE II.4 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, C_N = $0/g, High Costs, L_F = 0.01

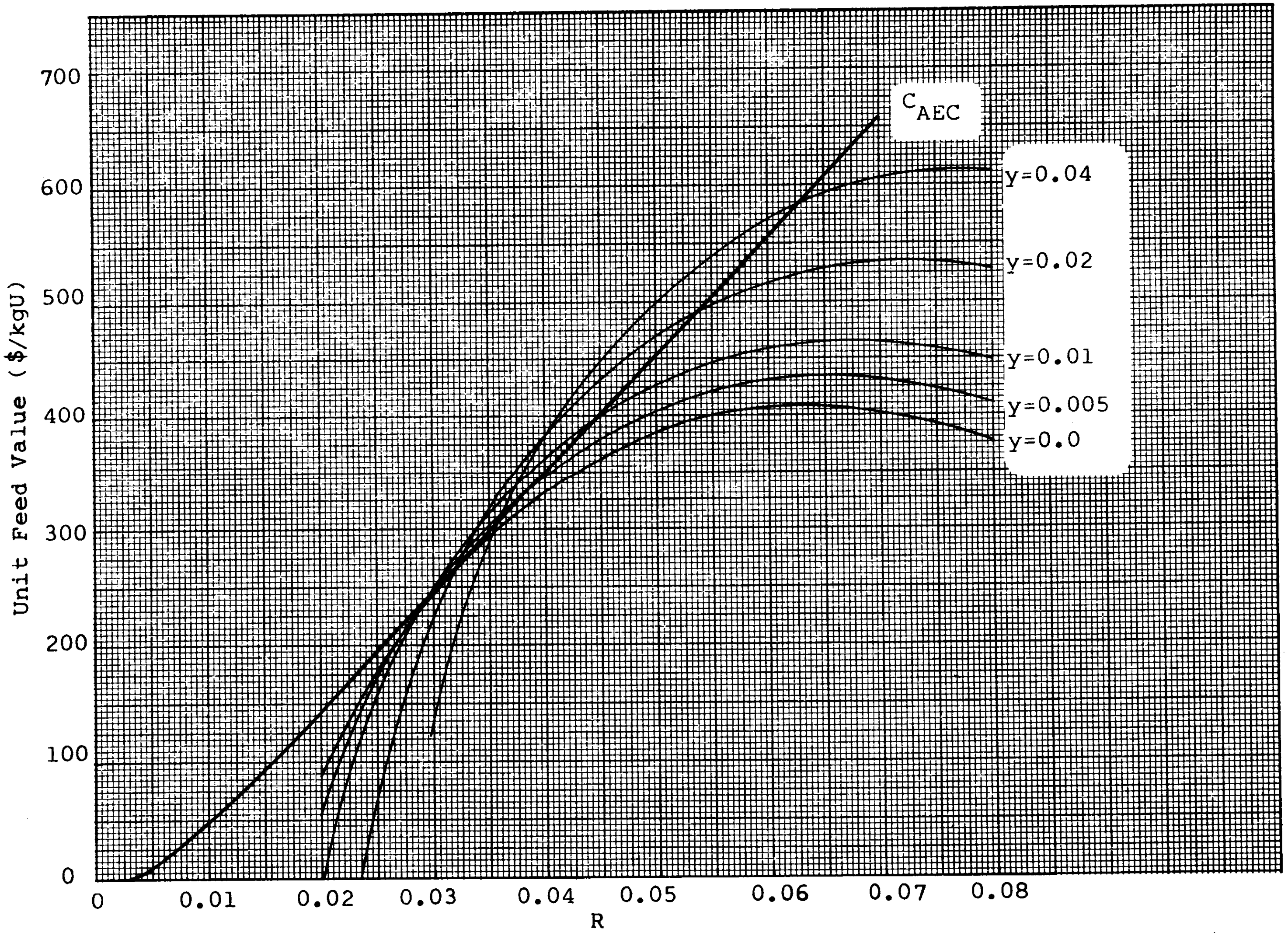


FIGURE II.5 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$60/g, High Costs, L_F = 0.01

in effect. For recycle to a diffusion plant, results for $C_N = \$60/g$ (Figure II.5) show an overlapping of the lines for certain values of y, indicating that the sale of Np-237 at this price is not sufficient to overcome the economic disadvantage of U-236 poisoning for all of the (R,y) points considered. However, for $R > 0.04$, the Np-237 production per unit of feed is sufficiently high that feed value increases with increasing y over the range of y values considered.

Some characteristics of the V(R,y) results can be explained very simply. First, M(R,y) is defined as the total fuel cycle cost exclusive of feed costs, in \$/day, when feed has composition R,y. When UF_6 feed free of U-236 and having U-235 to U-238 weight ratio R is purchased on the AEC price scale at a unit price equal to $C_{AEC}(R)$, then the equation for overall fuel cycle cost $C_E(R)$, in mills/kwhr, can be written as

$$24LPC_E(R) = FC_{AEC}(R) + M(R,0), \$/\text{day}. \qquad \text{(II.1)}$$

When feed of composition R,y is purchased as UO_3, the equation for the value of the feed stream, in \$/day, can be written as follows, by employing the definition of feed value given in Part B of Section I:

$$FV(R,y) = 24LPC_E^* - M(R,y). \qquad \text{(II.2)}$$

Here, C_E^* is the minimum value of $C_E(R)$, which occurs at $R=R^*$. By setting $y=0$ in Equation II.2, we can combine the resulting equation with Equation II.1 to get

$$F[C_{AEC}(R)-V(R,0)] = 24LP[C_E(R)-C_E^*]. \tag{II.3}$$

Since $C_E(R^*) = C_E^*$ and $C_E(R) > C_E^*$ for $R \neq R^*$, we see from Equation II.3 that

$$V(R^*,0) = C_{AEC}(R^*) \tag{II.4}$$

and $$V(R,0) < C_{AEC}(R), \quad R \neq R^*. \tag{II.5}$$

Thus, for any set of economic conditions and for either basic recycle scheme, a line representing V(R,0) is tangent to the AEC price scale line at R* and lies below the AEC scale for all other values of R.

Using Equation II.2, an equation for V(R,y) can be written as

$$V(R,y) = \frac{24LPC_E^* - M(R,y)}{F}. \tag{II.6}$$

The major components of M(R,y) are approximately proportional to F_R and N. For fixed R, the effect on the unit feed value which results from the presence of U-236 can be seen by comparing F, F_R/F, and N/F when y=0 and when y > 0. These quantities are given in Table II.2 for both y=0 and y=0.01 when R is near R*. Since F and F_R/F increase with an increase of y, V(R,y > 0) will be less than V(R,0) when no credit is taken for the sale of Np-237, i.e., when C_N = \$0/g. However, N/F also increases with increasing y and, if $C_N > 0$, this represents a positive effect of increasing y which, for a sufficiently high C_N, could lead to $V(R,y > 0)$ being larger than $V(R,0)$. In the latter case, the presence of U-236 would enhance the value of feed uranium.

The items listed in Table II.2 will naturally vary with both R and y, but values near R^* are of particular importance and indicate the general trends very well.

The $V(R,y)$ results given for the reference conditions are typical of all other cases considered. As R^* changes from one case to the next, the family of curves shifts appropriately to maintain the tangency of $V(R,0)$ with the AEC price scale at $R=R^*$, but the general appearance of the results is the same as in Figures II.2 through II.5.

The dropoff of the $V(R,y)$ curves as R approaches the upper and lower ends of the R-ranges in Figures II.2 through II.5 indicates that operation according to a basic recycle scheme becomes economically undesirable when R is far from R^*. This provides the major incentive for utilizing the modified modes of operation shown in Figure I.3. Using results for $V(R,y)$, the maximum unit values for feed having composition R,y were calculated for pre-enrichment by gaseous diffusion and for blending with natural uranium. These unit values are denoted by $V_D(R,y)$ and $V_B(R,y)$, respectively. Figure II.6 shows a superposition of results for $V_D(R,y)$,

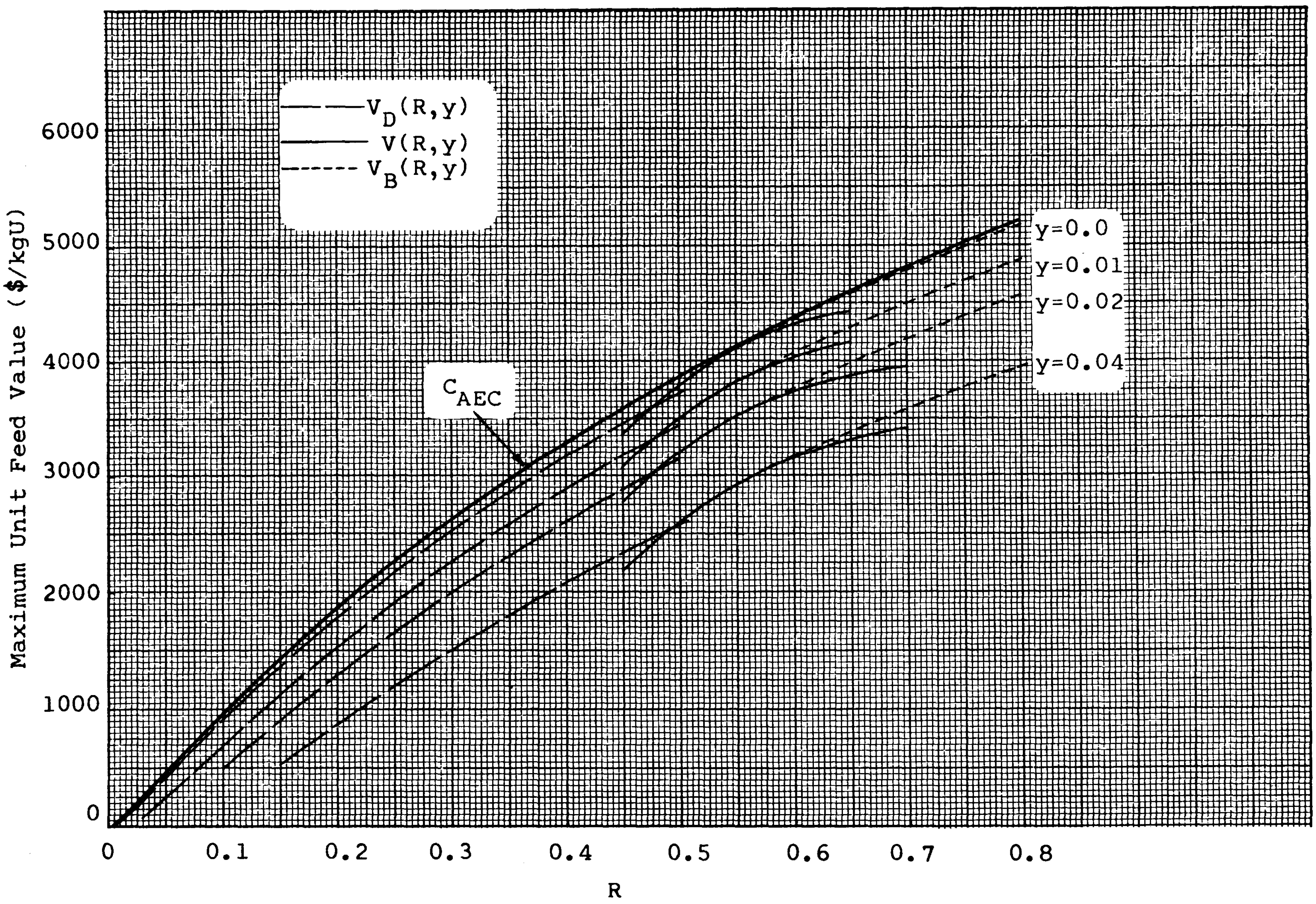


FIGURE II.6 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.01

$V(R,y)$, and $V_B(R,y)$ for recycle to fabrication when the reference conditions are used and when C_N = \$0/g. The mode of operation which gives the highest possible unit feed value depends upon the values of R and y being considered. At any (R,y) point, the largest of $V_D(R,y)$, $V(R,y)$, and $V_B(R,y)$ is defined as $V_m(R,y)$ and represents the maximum unit price the PWR operator could afford to pay for this feed without incurring a fuel cycle cost greater than C_E^*. The line representing $V_m(R,y)$ at constant y is made up of segments of the $V_D(R,y)$, $V(R,y)$, and $V_B(R,y)$ curves. Except for a rather narrow range of R in the vicinity of R^* over which $V_m(R,y) = V(R,y)$, the maximum unit feed value is obtained by either pre-enrichment or blending with natural uranium. For each y, $V_m(R,y)$ increases continuously with increasing R, in contrast to the behavior of $V(R,y)$ shown in Figure II.2. The values of R at which $V_D(R,y)$ and $V(R,y)$ are equal vary with y, as do the values of R at which $V(R,y)$ and $V_B(R,y)$ are equal. The line for $V_m(R,0)$ retains the characteristics of the $V(R,0)$ line of being tangent to the AEC price scale line at R^* and lying below the AEC price line for all other R values. Although optimum values of R_D and R_B were found to be very close to R^* when y=0, the cost of converting UO_3 to UF_6 and inventory charges during the toll enrichment period force $V_D(R,0)$ to be less than $C_{AEC}(R)$, while the loss of value incurred when mixing streams of different U-235 content results in $V_B(R,0)$ being less than $C_{AEC}(R)$.

When C_N is increased to \$60/g and to \$100/g, results for recycle to fabrication using the reference conditions are as shown in Figures II.7 and II.8. For C_N = \$60/g, the lines are so closely spaced around the AEC price scale that only the y=0 and y=0.04 lines are given, but the presence of U-236 now increases the maximum feed value over the entire range of R for the values of y considered. At C_N = \$100/g, feed value is increased to an even greater extent by the presence of U-236.

For the reference conditions, maximum unit feed values when recycling to a diffusion plant are given in Figures II.9, II.10, and II.11 for C_N = \$0, \$60, and \$100/g, respectively. Qualitative trends described for the recycle-to-fabrication case are also apparent for this recycle scheme. Due to the shift of R^* to lower values of R, the intersections among $V_D(R,y)$, $V(R,y)$ and $V_B(R,y)$ now occur much lower in the overall R-range. At \$60/g, the $V_m(R,y)$ lines for $y > 0$ lie above the y=0 line over the entire R-range, representing a drastic change from the intersecting $V(R,y)$ lines shown in Figure II.5.

At each (R,y) point examined, $V_m(R,y)$ varies linearly with C_N for both recycle schemes.

The trends described above for the $V_m(R,y)$ results are the same for all other cases considered, with

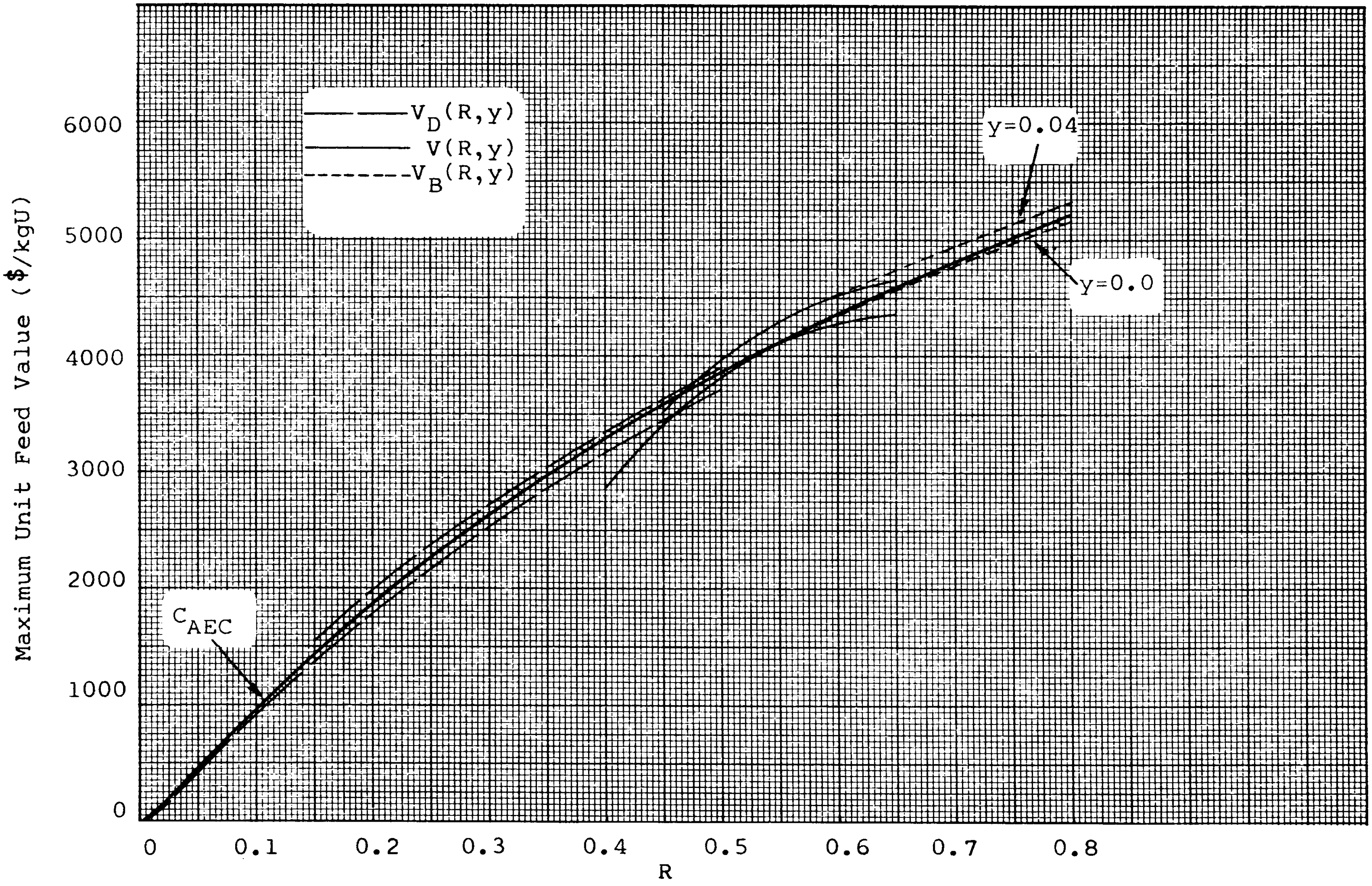


FIGURE II.7 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$60/g, High Costs, L_F = 0.01

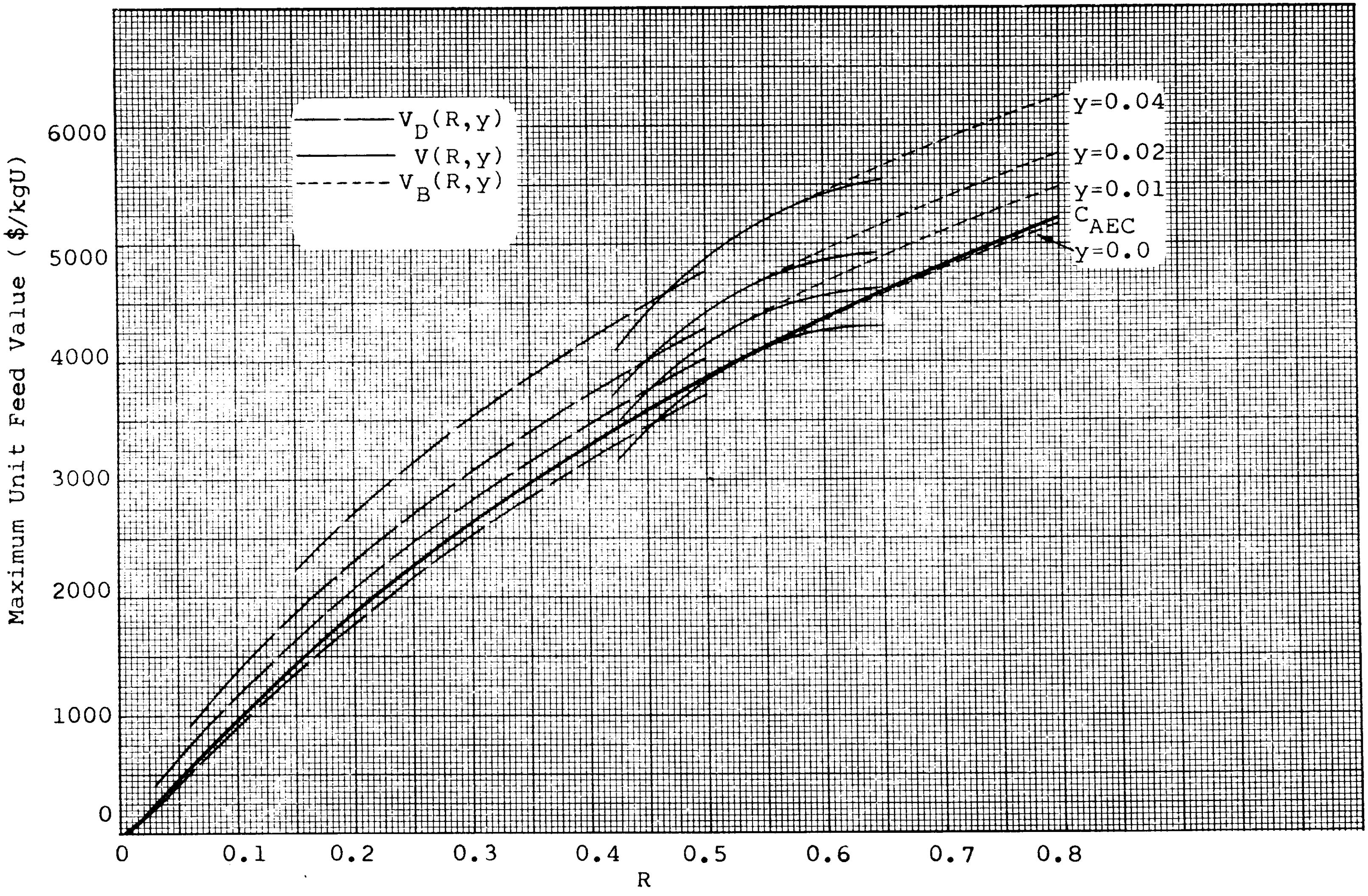


FIGURE II.8 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, C_N = $100/g, High Costs, L_F = 0.01

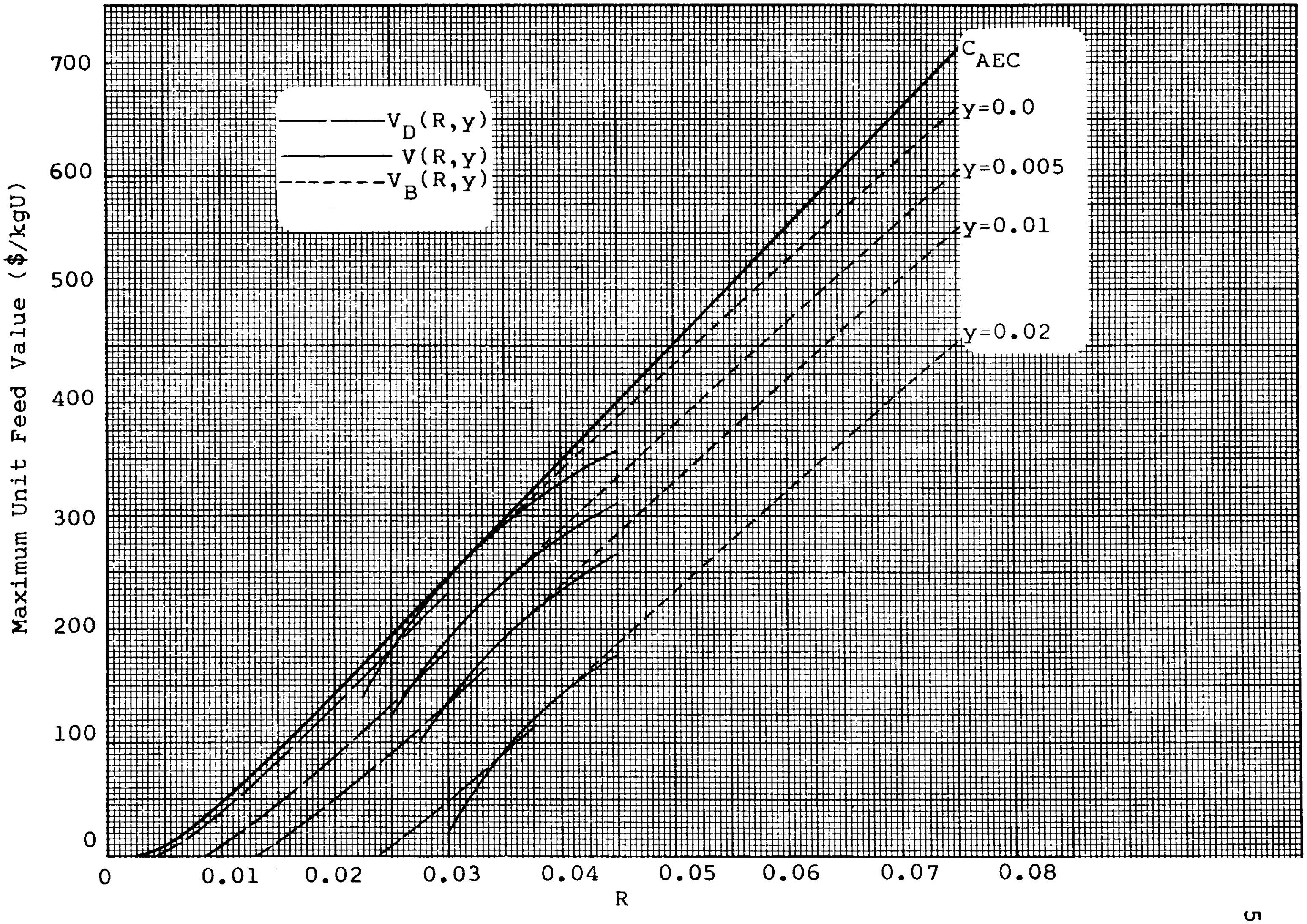


FIGURE II.9 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.01

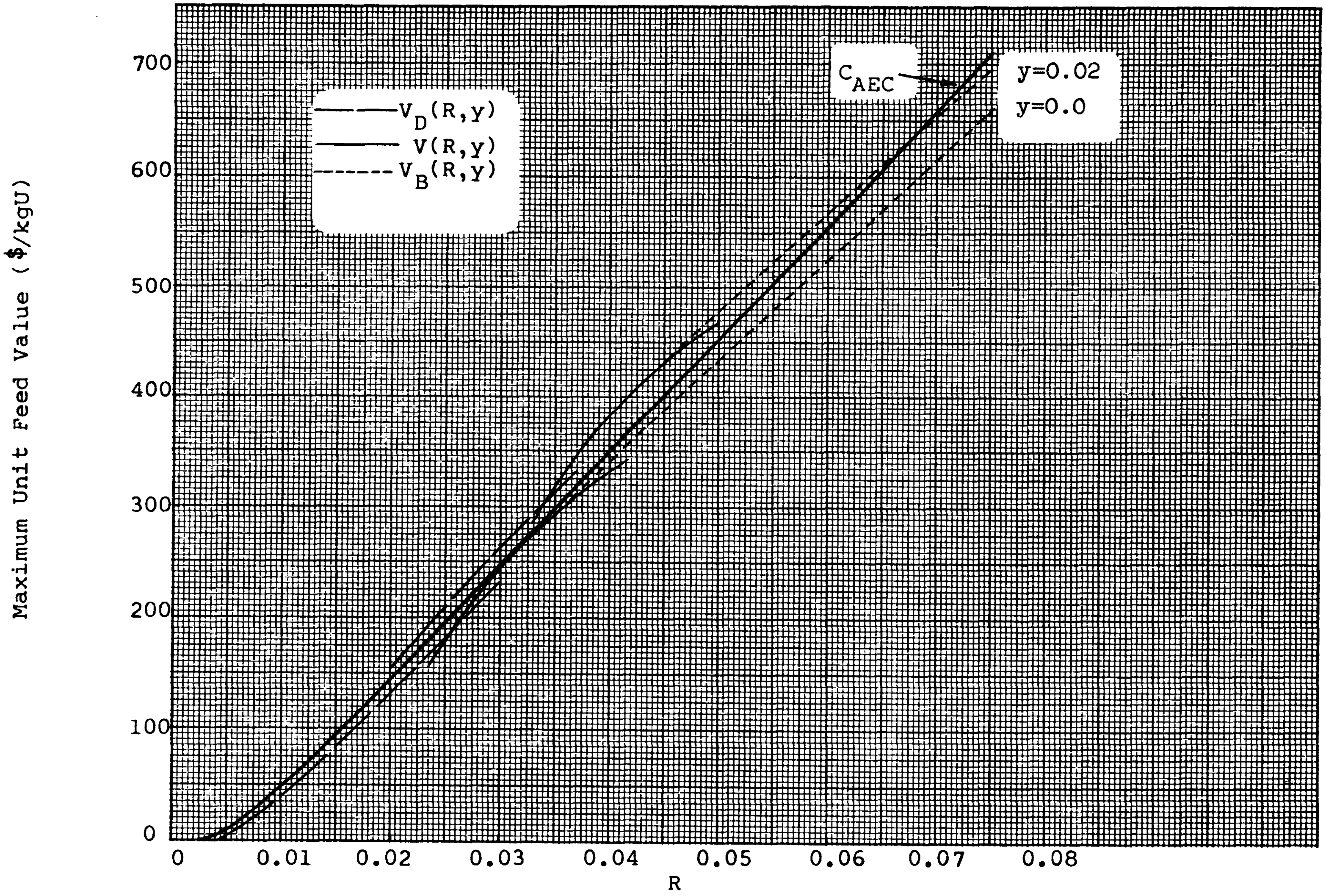


FIGURE II.10 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$60/g, High Costs, L_F = 0.01

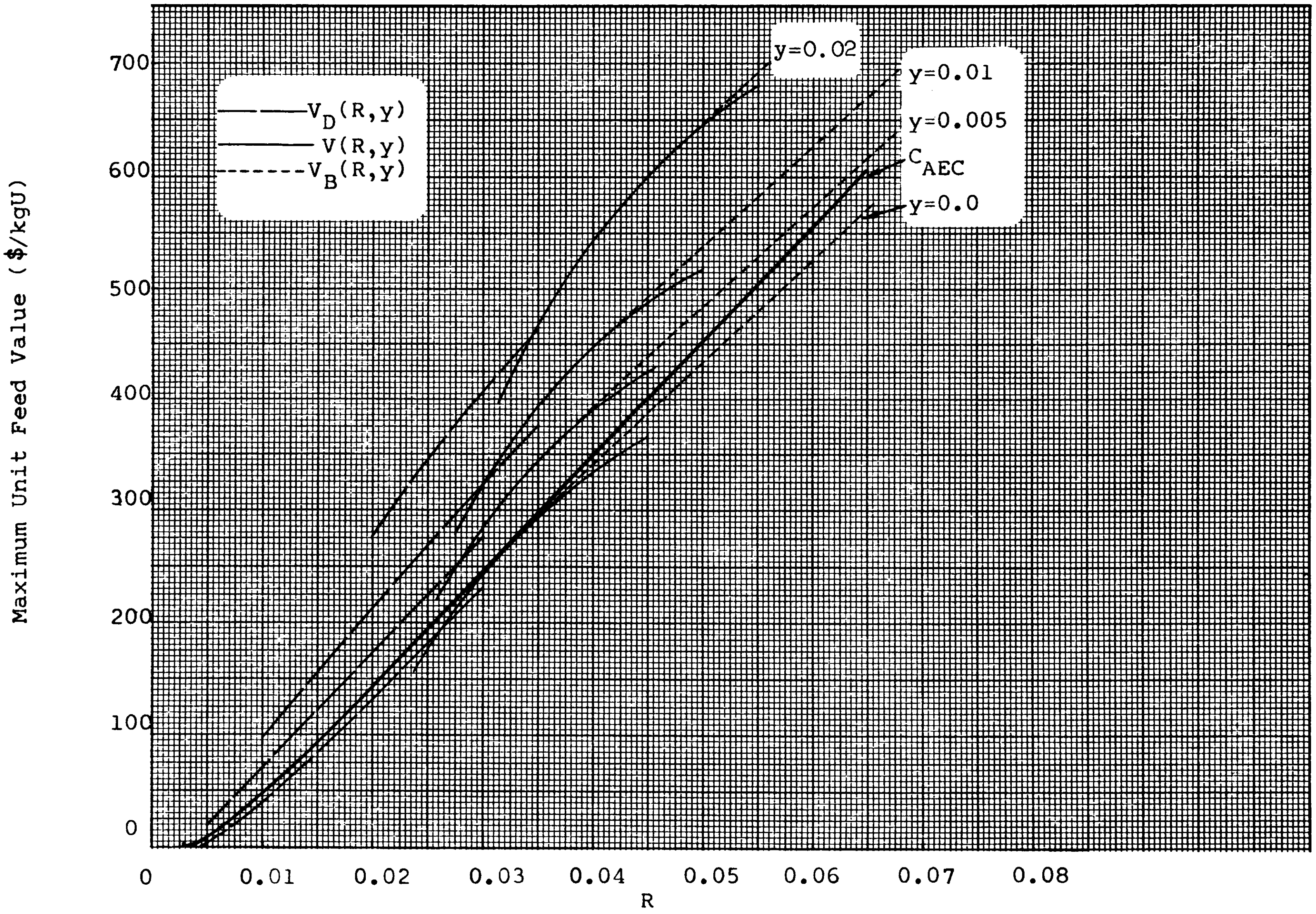


FIGURE II.11 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$100/g, High Costs, L_F = 0.01

differences being caused primarily by the changes in R*, as listed in Table II.1, and the corresponding shifts in V(R,y) results.

The U-236 penalty, denoted by $\delta(R,y)$, was defined in Section I as the reduction in total feed value per gram of U-236 when y kg of U-236 are added to (1-y) kg of U-235 + U-238 at a constant U-235 to U-238 weight ratio R. This definition can be expressed symbolically as

$$\delta(R,y) = \frac{(1-y)V_m(R,0) - V_m(R,y)}{1000\ y}\ ,\ \$/\text{g U-236}. \tag{II.7}$$

Results for $\delta(R,y)$ were calculated for various values of y and for a range of R from 0.005 to 15 (fully enriched). Figure II.12 shows $\delta(R,y)$ for recycle to fabrication when reference conditions are assumed and for C_N = \$0, \$60, and \$100/g. The corresponding $\delta(R,y)$ results for recycle to a diffusion plant are given in Figure II.13. For both recycle schemes, $\delta(R,y)$ for both C_N = \$60/g and \$100/g is shown to be negative over the entire range of R for all values of y considered. A negative penalty indicates that the presence of U-236 causes a mixture of (1-y) kg of U-235 plus U-238 and y kg of U-236 to have a higher total value than the (1-y) kg of U-235 plus U-238 alone. Penalty lines for y = 0.15 are shown at high R, since uranium having isotopic compositions in this range is often discharged

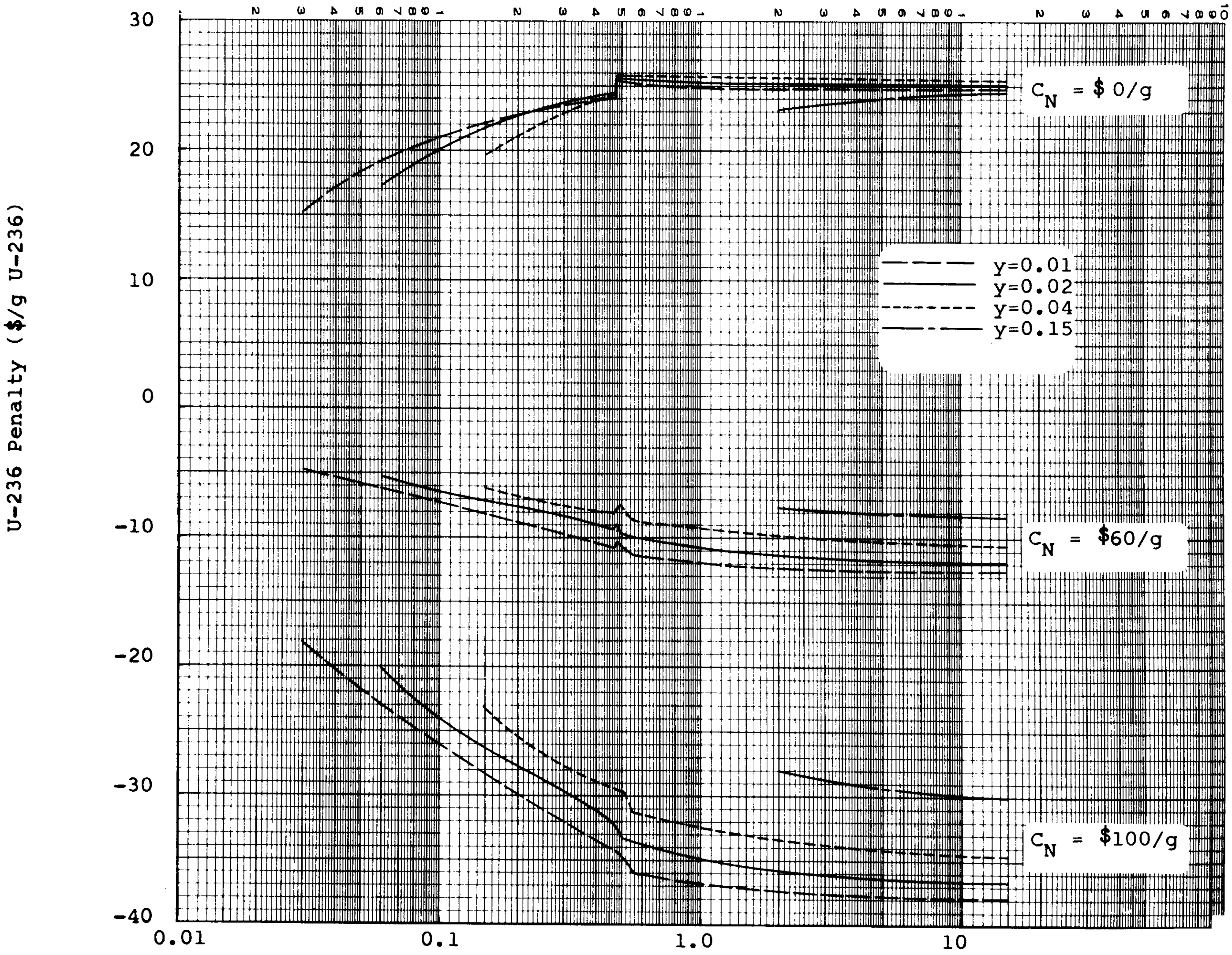


FIGURE II.12 U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

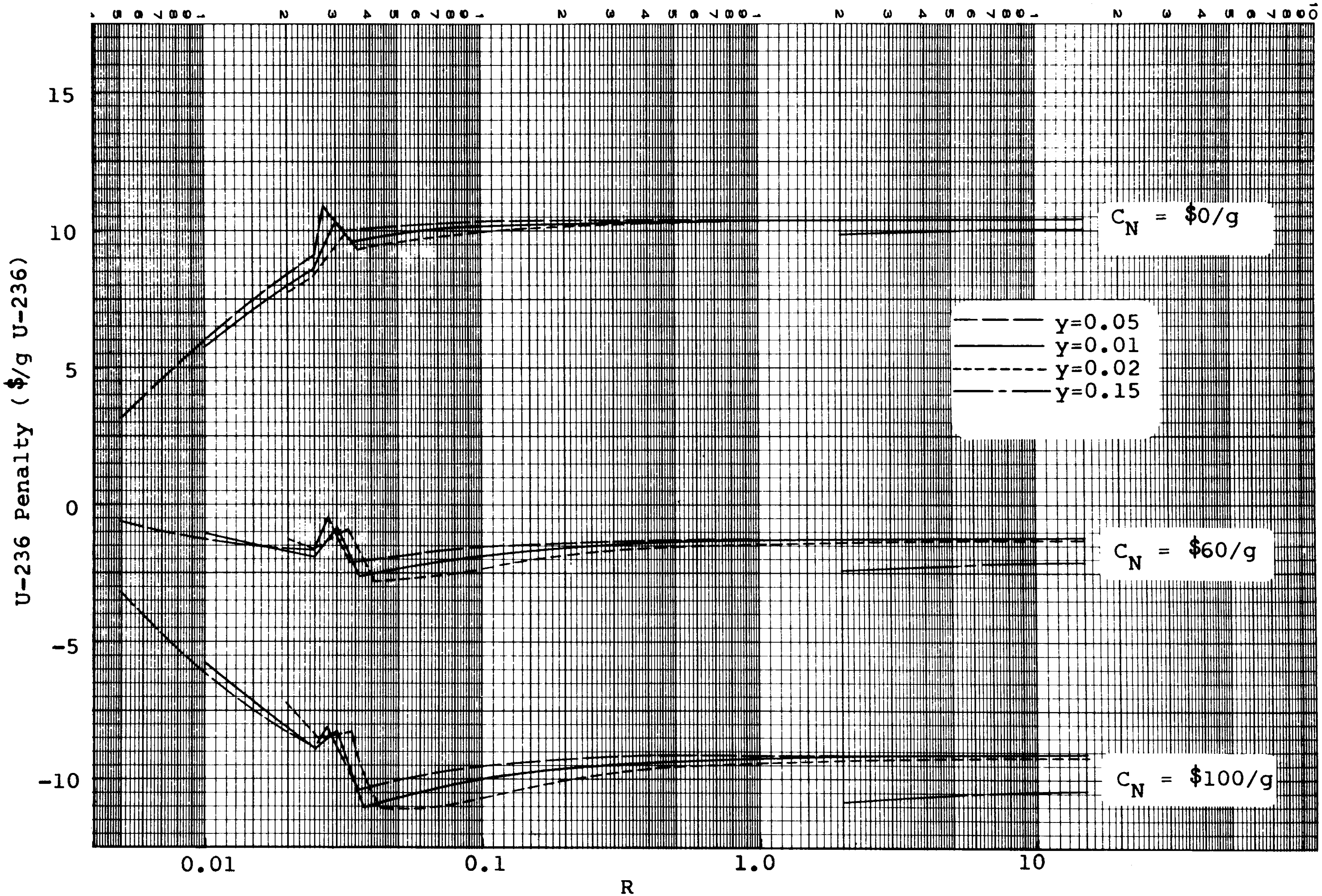


FIGURE II.13 U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

from research or test reactors and might be available for purchase as feed.

The reasons for the irregular variation of $\delta(R,y)$ with both R and y are numerous and complex; however, two major sources of irregularity exist. First, the use of $V_m(R,y)$ in Equation II.7 causes $\delta(R,y)$ for constant y to be calculated first using $V_D(R,y)$, then using $V(R,y)$, and finally using $V_B(R,y)$, as R is increased from low to high values. Second, over certain ranges of R, $V_m(R,0)$ is obtained by using a different mode of operation than is $V_m(R,y)$ for $y > 0$. These irregular variations are not serious, however, since the primary purpose for calculating $\delta(R,y)$ is to indicate the general level of the U-236 penalty for different economic conditions and for the two recycle schemes. Consequently, it is convenient to define a "penalty level" , $\bar{\delta}$, as the approximate penalty at R^*. For recycle to fabrication, the differences between $\delta(R^*,y)$ for various y-values are sufficiently great that $\bar{\delta}$ is arbitrarily based on $y = 0.02$. When so defined, $\bar{\delta}$ provides a useful approximate summary of a set of $\delta(R,y)$ results.

Table II.3 gives values of $\bar{\delta}$ obtained for the various conditions considered. The major effects which influence the variation of $\bar{\delta}$ can be determined by detailed analysis of the penalty near R^*. For R near R^*, we can assume that $V_m(R,y) = V(R,y)$ and then combine

TABLE II.3

U-236 Penalty Levels, $\bar{\delta}$, and Np-237 Indifference Prices, C_N^o.

Recycle To	Fab. Loss Fraction, L_F	Unit Costs	$C_{U_3O_8}$ (\$/lb)	$C_N^o(R,y)$ Range (\$/gNp-237)	C_N (\$/gNp-237)	R*	$\bar{\delta}$ (\$/gU-236)
Fabrication	0.01	High	6	37 - 43	0	0.571	24
					60	0.552	-11.5
			8	39 - 46	0	0.557	25.5
					60	0.539	-10
					100	0.528	-33.5
			10	42 - 50	0	0.545	27
					60	0.529	- 8.5
		Low	8	34 - 41	0	0.497	21.5
					60	0.480	-13.5
	0.002	High	8		0	0.694	30
Diffusion Plant	0.01	High	6	43 - 53	0	0.0318	9
					60	0.0325	- 2.5
			8	47 - 56	0	0.0309	10
					60	0.0315	- 1.5
					100	0.0319	- 9
			10	50 - 59	0	0.0300	11
					60	0.0307	- 0.5
		Low	8	41 - 49	0	0.0270	8.5
					60	0.0275	- 2.5

Equations II.6 and II.7 to get the following expression for $\delta_3(R,y)$, the penalty based on basic recycle operation alone:

$$\delta_3(R,y) = \frac{24LPC_E^*\beta + \eta}{1000y}\ , \qquad \text{(II.8)}$$

where

$$\beta = \frac{1-y}{F(R,0)} - \frac{1}{F(R,y)}\ , \qquad \text{(II.9)}$$

and

$$\eta = \frac{M(R,y)}{F(R,y)} - \frac{(1-y)M(R,0)}{F(R,0)}\ . \qquad \text{(II.10)}$$

F has been written to show dependence on R and y. β influences δ_3 through the increase in F which occurs with increasing y. η is a measure of the change in the total fuel cycle cost exclusive of feed costs, normalized to unit feed, when U-236 is introduced into the feed; hence, η is governed by the increases of quantities such as F_R/F (caused by reduced burnup) and N/F (caused by higher U-236 content in reactor feed) which occur when y is increased, as shown in Table II.2.

Table II.4 gives a representative sampling of results for β, $24LPC_E^*\beta$, η, and $\delta_3(R,y)$ when y=0.01 for R close to R^*. Results for β are governed predominantly by the feed rate level, with β increasing as the general level of F decreases. Thus, β is larger for recycle to fabrication than for recycle to a diffusion plant. Reduction of L_F for recycle to fabrication leads to

TABLE II.4

Items Which Govern U-236 Penalty Changes

Recycle to	L_F	Unit Costs	R	$C_{U_3O_8}$ (\$/lb)	ß	C_N (\$/gNp)	$24LPC_E^{*}\beta$ (\$/kgU)	η (\$/kgU)	$\delta_3(R,0.01)$ (\$/gU-236)
Fabrication	0.01	High	0.55	8	0.01003	0	167.94	88.16	25.61
						60	116.78	-222.37	-10.56
						100	82.50	-429.00	-34.65
				6	0.01003	0	154.28	86.40	24.07
		Low	0.50	8	0.00956	0	142.92	71.94	21.49
	0.002	High	0.70	8	0.01097	0	185.85	108.95	29.48
Diffusion Plant	0.01	High	0.03	8	0.00425	0	56.63	47.45	10.41
						60	50.14	-58.12	- 0.80
						100	45.80	-128.51	- 8.27
				6	0.00413	0	50.13	44.81	9.49
		Low	0.03	8	0.00425	0	49.73	31.54	8.13

lower feed rates and a higher β. Changes of β and C_E^* from case-to-case lead to differences in the $24LPC_E^*\beta$ contribution to the penalty.

At C_N = \$0/g, the η contribution is positive and important, but is smaller than $24LPC_E^*\beta$. As C_N becomes larger, the Np-237 credit increases faster for y=0.01 than for y=0, which leads to smaller η values. At C_N = \$60/g and \$100/g, η is strongly negative and provides the dominant contribution to the penalty. Since both C_E^* and η decrease with increasing C_N, the penalty also decreases as shown.

When C_N = \$0/g, higher β and C_E^* for recycle to fabrication provide about \$11/g of the \$15/g penalty differential between the two recycle schemes. The remaining \$4/g of the difference is caused by increased sensitivity of η to changes of y for the recycle-to-fabrication scheme. However, as C_N increases, the more rapid decrease of C_E^* (see Figure II.1) and the greater sensitivity of N/F to changes of y serve to reduce $24LPC_E^*\beta$, η, and $\delta_3(R,y)$ at a higher rate for recycle to fabrication.

For recycle to fabrication, reduction of L_F leads to increased η as well as higher β, as mentioned above, and to an increment of about \$4/g to the penalty. The increase in η results from a higher sensitivity of burnup to changes of y when R is near R^* for the lower L_F. Changes in L_F do not significantly affect the characteristics for recycle to a diffusion plant; hence, feed values and penalties were not recalculated for that case.

Detailed penalty results for all cases studied retain the same general appearance as those in Figures II.12 and II.13, except for shifts in $\bar{\delta}$. For any (R,y) point, $\delta(R,y)$ varies linearly with C_N; however, the variation of $\delta(R,y)$ with $C_{U_3O_8}$ is non-linear, although the rather crudely-chosen values for $\bar{\delta}$ in Table II.3 suggest linearity.

The penalty level has been seen to exhibit the following general characteristics:

a. $\bar{\delta}$ increases as the feed rate requirement decreases;

b. $\bar{\delta}$ decreases as C_E^* decreases; and

c. $\bar{\delta}$ decreases as C_N increases.

The "indifference price" of Np-237, $C_N^o(R,y)$, is the value of C_N at which $\delta(R,y) = 0$. At this neptunium price the value of uranium feed containing a given amount of U-235 and U-238 is the same whether or not the uranium contains U-236; therefore, it is a matter of indifference in purchasing uranium containing U-235 and U-238 at a given price whether the uranium contains U-236 or not. Results calculated for $C_N^o(R,y)$ fall within the approximate ranges indicated in Table II.3.

For all sets of economic conditions considered, the range of $C_N^o(R,y)$ is lower for recycle to fabrication. The rate at which $\delta(R,y)$ decreases with increasing C_N is sufficiently greater for recycle to fabrication that $\delta(R,y)$ becomes zero at a lower C_N, despite the fact that $\delta(R,y)$ is substantially higher at $C_N = \$0/g$ than it is for recycle to a diffusion plant. It is noteworthy that the Np-237 indifference prices are all between \$34/g and \$59/g. Consequently, it appears safe to generalize that the U-236 penalty, as defined above, will be positive for $C_N < \$30/g$ and negative for $C_N > \$60/g$. Between $C_N = \$30/g$ and $C_N = \$60/g$, one has to consider the effects of economic conditions and recycle scheme before U-236 can be judged as economically beneficial or as economically undesirable.

Figures II.12 and II.13 indicate a substantial decrease in the absolute magnitude of the penalty at constant y as R decreases toward the low end of the R-range. In this portion of the R-range, $V_m(R,y)$ is generally attained by pre-enriching feed in a gaseous diffusion plant. During pre-enrichment, only a fraction α of the U-236 in the feed is retained in the product stream, the remainder being discharged in the tails or lost during conversion of UO_3 to UF_6. As R decreases, a higher fraction of the feed U-236 appears in the tails and α becomes smaller. The penalty variation at low R is related to α. Thus, the absolute magnitude of the penalty decreases as R decreases in the range in which pre-enrichment is used. In an attempt to remove part of the dependence of the U-236 penalty on R, it is logical to define an "adjusted" penalty as

$$\delta_{ADJ}(R,y) = \frac{1}{\alpha}\delta(R,y), \qquad \text{(II.11)}$$

which has units of \$/g of U-236 reaching fabrication, rather than \$/g of U-236 in feed. Since there is no loss of feed U-236 when using the basic recycle scheme or when blending with natural uranium, then whenever $V_m(R,y)$ is equal to either $V(R,y)$ or $V_B(R,y)$, α is effectively equal to one and $\delta_{ADJ}(R,y) = \delta(R,y)$.

$\delta_{ADJ}(R,y)$ is plotted against R at constant y in Figures II.14 and II.15. By comparing $\delta_{ADJ}(R,y)$ in these figures with $\delta(R,y)$ in Figures II.12 and II.13, it can be seen that variation of δ_{ADJ} with R at low R is much less than the variation of δ with R. In fact, the values of $\bar{\delta}$ given in Table II.3 may be considered as approximately representative of δ_{ADJ} over the entire range of R, provided the units of $\bar{\delta}$ are taken to be \$/g of U-236 reaching fabrication. These values of $\bar{\delta}$ may be used in rough estimates of the effect of U-236 on the value of uranium feed for pressurized water reactors.

The results of this study clearly indicate that the operators of PWR systems must be prepared to account for the effect of U-236 on their fuel cycle economics when

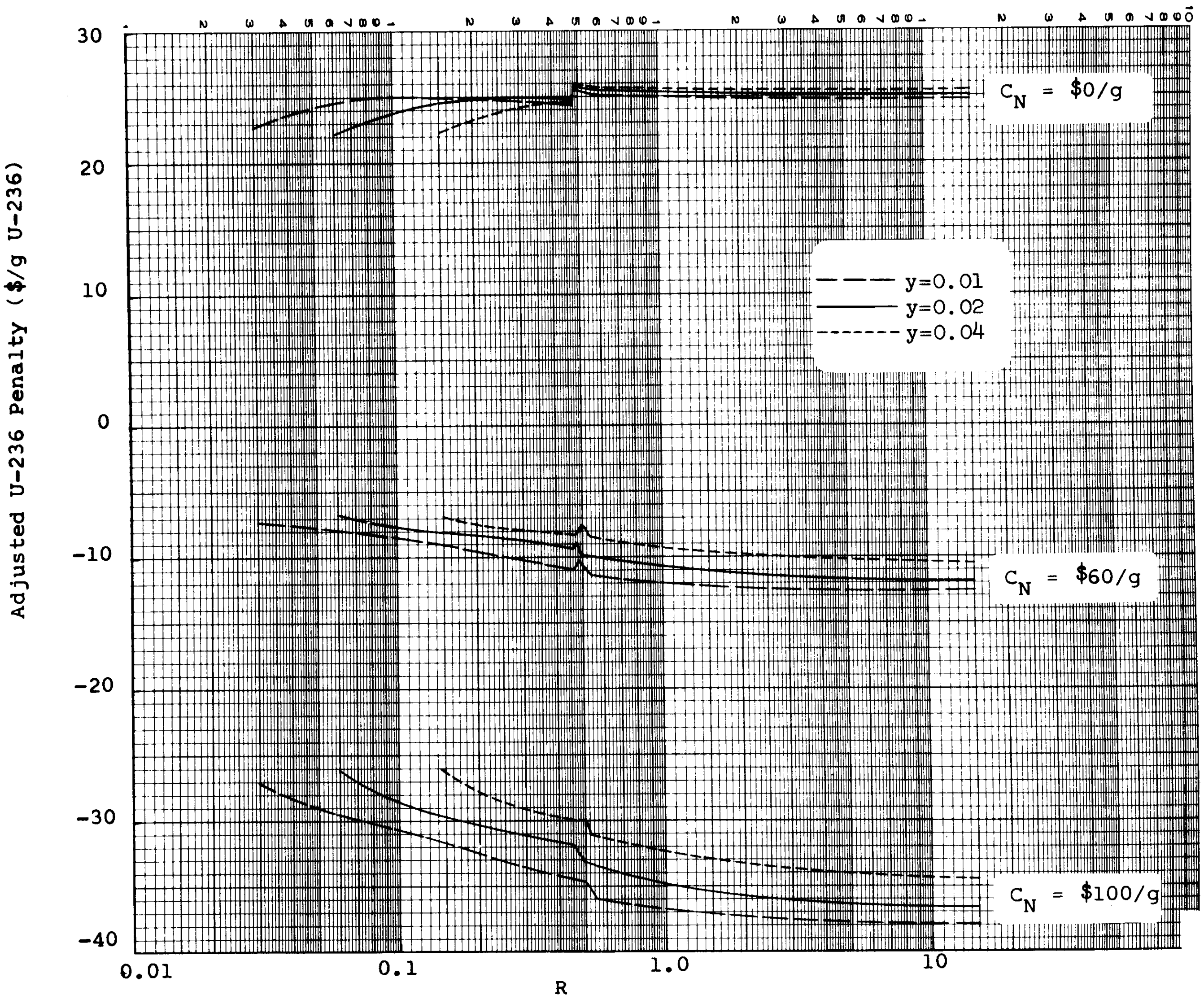


FIGURE II.14 Adjusted U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

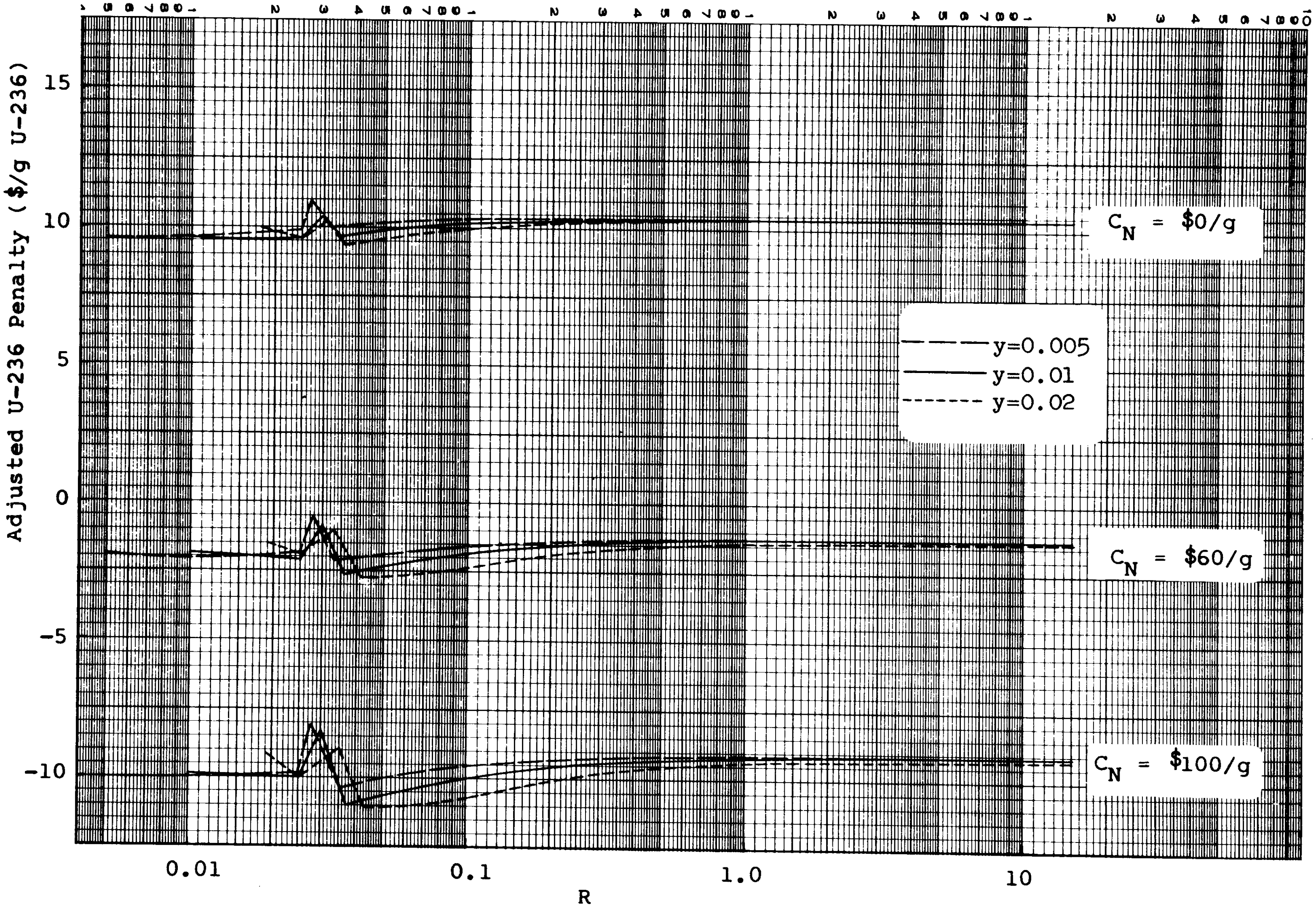


FIGURE II.15 Adjusted U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $ 8/lb, High Costs, L_F = 0.01

they become involved in the purchase of previously-irradiated uranium. Operators of other reactor types would find it advantageous to carry out studies similar to the present one when considering the use of uranium feed containing U-236, before deciding on the price they could afford to pay for such uranium.

It has also been shown that the price at which byproduct Np-237 is sold can strongly influence the cost of power, the value of uranium containing U-236, and the selection of an overall fuel-flow scheme. As a result, considerable effort should be expended in an attempt to forecast the market price for Np-237 before specifying a fuel cycle scheme and before establishing limits on the price which can be afforded for feed uranium.

III. REFERENCE REACTOR - SAN ONOFRE PWR

A. Reactor Description

The reference reactor chosen for the study is that of the San Onofre Nuclear Generating Station, which will be jointly owned by the Southern California Edison Company and the San Diego Gas and Electric Company. The plant is expected to attain full power operation early in 1968.(16) The closed-cycle, pressurized light water moderated and cooled reactor was designed by Westinghouse and will generate 1346 MW(t), leading to a net electrical output of 430 MW(e) from the plant.(10)

The core is made up of 157 fuel elements, each composed of 196 metallic tubes positioned in a square lattice by grid assemblies of an "egg-crate" configuration. Of the 196 tubes, 180 contain uranium dioxide and 16 may either contain the individual neutron absorbing rods of a rod cluster control element or be left vacant. Rod cluster control elements are placed in 45 of the fuel elements, and since there are no follower elements, water replaces the absorber rods as the control cluster is withdrawn from the core. The core is arranged to form a unit that is roughly cylindrical in shape, with an active length of 10 ft. and an equivalent diameter of 9.2 ft.

Although the initial loading of the fuel will be clad with Type 304 stainless steel, it is expected that

Zircaloy-4 will be the cladding material used for subsequent loadings. Since this study is based on steady-state recycle operation of the reactor and its fuel cycle, it was decided that Zircaloy-4 cladding would be used here. The core loading is approximately 53,000 kg of uranium.

Reactivity control is provided both by the rod cluster control absorbers and by boric acid dissolved in the light water coolant. The boric acid concentration is varied to compensate for reactivity effects due to xenon and samarium, fuel depletion and fission product buildup, and change of the primary coolant temperature from shutdown to hot-operating conditions at zero power. The control rod clusters provide control for shutdown margin, Doppler broadening effects, and reactivity changes associated with the programmed increase in the average coolant temperature in the core above the hot, zero power condition.

A detailed listing of reactor characteristics is given in Appendix A. Since a major part of the overall study is to examine the effect of varying uranium feed isotopic composition on the unit feed value, the content of U-235, U-236, and U-238 in uranium charged to the reactor is not unique but will vary from one feed composition to another. Likewise, the steady-state average discharge burnup will depend on the feed isotopic composition being considered. The variation of the steady-state reactor feed composition and average discharge burnup with the isotopic composition of feed uranium is discussed in detail in Section IV, Part A.

B. Refueling Scheme

The San Onofre Reactor design will utilize a modified out-in fuel shuffling scheme. For a core of this size, use of normal out-in movement of fuel leads to poor power sharing by the heavily depleted inner region and excessive maximum-to-average power ratios for the equilibrium core. In order to improve the power distribution, Westinghouse(10) has specified that several slightly-depleted fuel assemblies be placed near the center of the core while some of the more highly depleted assemblies are moved towards the outside of the core, the net effect being a more uniformly reactive core. It is difficult to simulate such a refueling procedure without resorting to extremely complex and time-consuming computer codes.

A more-easily simulated refueling scheme and one also being considered for cores of this size(17) is a modified version of the multibatch scatter refueling scheme devised by Westinghouse for very large (1,000 MWe) reactors(11). This scheme, which was selected for use in this study, differs from complete scatter refueling in that fresh fuel is first loaded into an outer annular ring, from which it is then used as partially-depleted feed for the remainder of the core, which is fueled according to the scatter procedure. In effect, there is a region refueled scatter-wise, surrounded radially by an annular region which feeds the central region with assemblies that have been irradiated for the period of time between reloadings. This modification tends to provide a flatter power distribution than does complete scatter refueling for the reference design core size(17), since the outer core power production is increased by the fresh fuel located there.

A 4-batch refueling scheme was selected for the study, as this yields about a one-year refueling interval, preferred by most utility companies, for near-optimum equilibrium refueling operation. As a result, the outer ring occupies one-fourth of the total core volume while the inner scatter region occupies the remaining three-quarters of the core.

C. Reactivity and Depletion Calculation Model

All fuel depletion calculations and predictions of reactor characteristics at the steady-state refueling condition were carried out using CELLMOVE, which is a modified version of FUELMOVE, a fuel management program written at MIT(14). Two space dimensions (R-Z geometry) are utilized in the diffusion theory calculation and energy dependence is described by a modified two-group model. A Wigner-Wilkins spectrum is calculated below the thermal cutoff energy.

Two separate codes - CELL(13) and MOVE - are actually involved. First, CELL is used to calculate the fuel isotopic composition and the unit cell characteristics as functions of thermal flux-time for the uranium which is charged to the reactor. The MOVE code then performs the flux distribution calculations throughout core lifetime, using the results from CELL to calculate the flux-time-dependent characteristics at each mesh point in the reactor, and predicts the reactivity lifetime of the core and average discharge burnup. The original version of MOVE(14) provides a variety of fuel management options for discharging, charging, and shuffling fuel between cycles and also for repeating the refueling scheme a sufficient number of times to reach steady-state operation. For the present study, a version of MOVE was written which simulates the 4-batch modified scatter refueling scheme described above and which automates the approach to steady-state refueling for a fixed <u>reactor</u> feed composition, R_R and y_R. Once steady-state refueling has been reached for specified values of R_R and y_R, the revised MOVE will calculate all other steady-state flow rates and uranium isotopic compositions throughout the recycle flowsheets of Figures I.1 and I.2. The scatter refueling version of MOVE is discussed in more detail in Appendix C.

The original FUEL(14) code could not be used to accurately predict the time-dependent characteristics of pressurized water reactors.(18) The need to perform a large number of steady-state refueling calculations made it mandatory that a relatively simple and fast, yet reasonably accurate, fuel management program be used. As a result, a number of modifications were made to FUEL by Beaudreau(13) and the CELL code evolved. The agreement of CELLMOVE predictions with both experimental data for the Yankee Reactor and Westinghouse calculations for the San Onofre Reactor was sufficiently close to justify the use of CELLMOVE as the major computational tool for the study. A summary description of the CELL code is given in Reference 41. A modification which was made to CELL in order to correctly represent the buildup of Np-237 is described in Appendix B.

D. Procedure for Obtaining Steady-State Recycle Characteristics

Determination of the steady-state fuel flow rates and isotopic compositions which correspond to a specified feed isotopic composition (R and y) is a major part of the analysis for the basic fuel cycle flowsheets shown in Figures I.1 and I.2. Steady-state operation of a fuel cycle is reached only when flow rates and compositions at every point in the cycle become invariant with time. Such an operating condition insures that steady-state refueling of the reactor is in effect, i.e., the fuel fed to the reactor and the fuel discharged both have isotopic compositions which do not vary from one irradiation cycle to the next.

Since only the variation of steady-state flowsheet characteristics with R and y is required for the economic analysis in this study, there is no need to examine the transient cycle characteristics in detail. For both Figures I.1 and I.2, the "direct" procedure would be to maintain a fixed feed composition R,y and to follow successive batches of fuel through the reactor, during recycle, and in the re-enrichment (by gaseous diffusion and/or mixing with feed uranium) step, until the transient period terminates and all fuel batches possess identical histories through the fuel cycle. Such a procedure would permit determination of all steady-state characteristics as functions of R and y directly. However, the reactor feed composition, described by R_R and y_R, then changes from one transient cycle to the next and a separate CELL run would be required for each reactor feed composition, resulting in excessive computer time and data handling requirements for each (R,y) point considered.

An alternative method of predicting steady-state characteristics which utilizes the CELL code more efficiently has been chosen for the study. For both recycle schemes, this "indirect" procedure begins with the assumption of R_R and y_R values. Using CELLMOVE and keeping this reactor feed composition fixed, the refueling scheme is brought to a steady-state condition. Since R_R and y_R are the same for all transient cycles, it is necessary to perform the CELL calculation only once for each approach to steady-state refueling as performed by MOVE. For the steady-state cycle, MOVE calculates the time-averaged reactor feed rate and spent fuel flow rate and then utilizes material balance considerations to determine all other flow rates and uranium compositions throughout both basic recycle flowsheets; hence, the values of R and y which correspond to a fixed reactor feed composition R_R, y_R can be determined for both recycle schemes. The disadvantage of this simple procedure is the lack of direct control over the (R,y) points for which the corresponding steady-state flowsheet characteristics are known; however, procedures have been developed for transferring the direct dependence of flowsheet characteristics from R_R and y_R to R and y. This is discussed further in Section IV, Part A.

A major advantage of the "indirect" procedure is that a set of flowsheet characteristics for both basic recycle schemes can be obtained from a single CELLMOVE calculation for fixed values of R_R and y_R. In contrast, the "direct" procedure would necessitate a complete set of CELLMOVE calculations for each recycle scheme, thereby increasing the overall computer time required for the study even more.

IV. MODES OF OPERATION

A. Basic Recycle Schemes

The two basic schemes considered for recycling spent uranium are described in detail in this section. The two schemes differ in the method utilized for re-enriching the spent uranium prior to its use as feed to the reactor. In the first scheme described, feed uranium is purchased and blended with recycled uranium to form the reactor feed, while the second scheme involves re-enrichment of recycled uranium in a gaseous diffusion plant with subsequent mixing of the requisite feed with the diffusion plant heads stream to form the reactor feed. The two schemes require significantly different feed isotopic compositions to maintain reasonable reactor operation under steady-state recycle conditions. The relative economic advantages and disadvantages of the two schemes depend strongly upon the economic climate and will be discussed in Section VI.

1. Recycle to Fabrication

The flowsheet for this recycle scheme is shown in Figure IV.1. Flow rates indicated at various points in the cycle are steady-state, time-averaged values, based on plant operation at a load factor L and at a net electrical power output of P MW. Note that throughout this study such flow rates are used instead of discrete batch sizes. The reader should not interpret

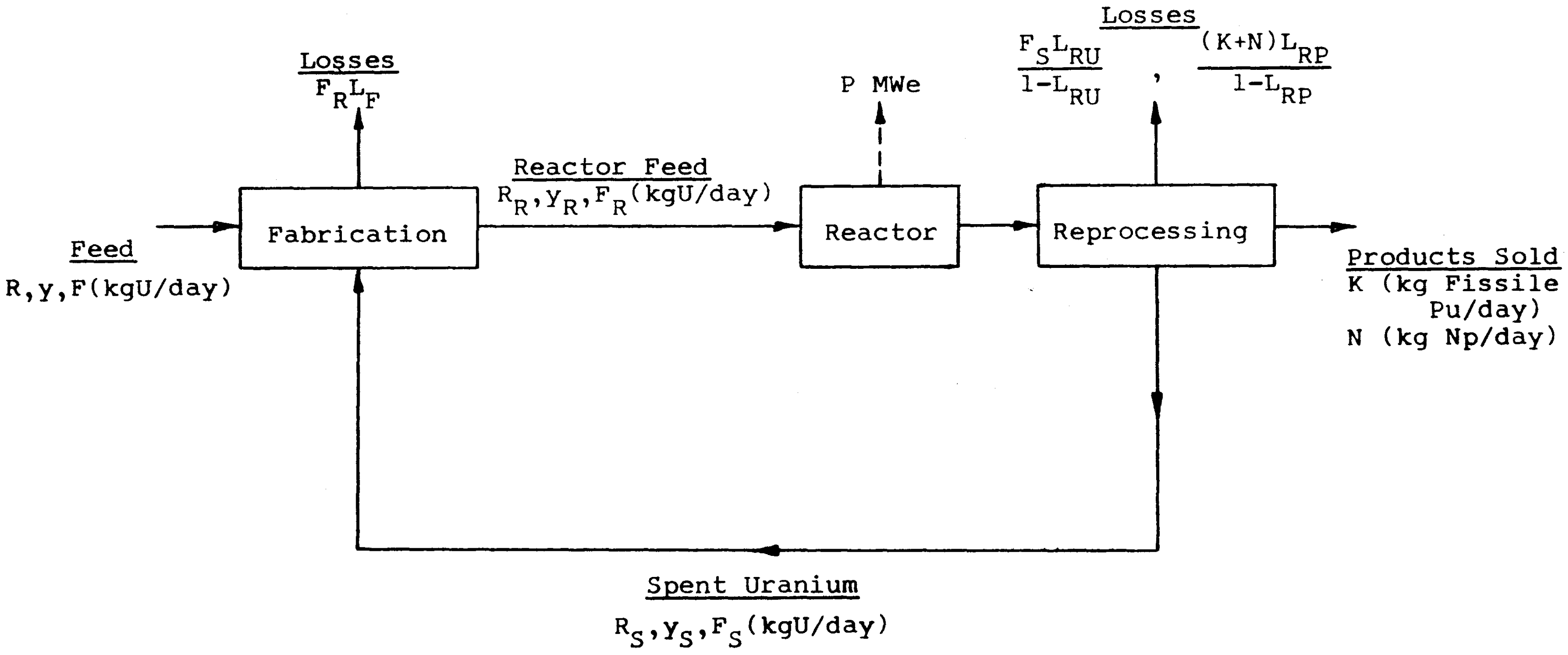


FIGURE IV.1 Flowsheet for Recycle of Uranium to Fabrication this is an indication of reactor operation with steady, on-line refueling, but rather as a convenience in expressing the uranium requirements of the steady-state flowsheet. The isotopic composition of uranium at various points is described by the U-235 to U-238 weight ratio (R_i) and the weight fraction of U-236 in total uranium (y_i).

Uranium of composition R_R, y_R is fed to the reactor at the flowrate F_R, is irradiated, discharged, and shipped to a reprocessing plant where plutonium, neptunium, and spent uranium are recovered. Fissile plutonium and Np-237 are sold in nitrate form immediately after their recovery at rates K and N, respectively. Spent uranium of composition R_S, y_S is assumed to be converted from UNH to UO_3 (a form suitable for shipping) at the reprocessing site, and is recycled as UO_3 at flowrate F_S back to the fabrication plant. Losses of uranium (L_{RU}), plutonium (L_{RP}), and neptunium (L_{RP}) occur during reprocessing, as indicated on the flowsheet. Note that R_S, y_S is also the composition of uranium in the immediate reactor discharge stream.

In this scheme, the only means available for re-enriching the recycled uranium is by blending it with more-highly-enriched feed uranium to form the reactor feed stream. Feed uranium is assumed to be purchased as either UO_3 or UF_6 at rate F and with composition R,y. Feed purchased as UF_6 would be purchased on the

AEC price scale and would contain no U-236 (y=0). Blending, conversion to UO_2, and fuel fabrication are carried out with an accompanying uranium loss rate of $F_R L_F$. Reactor feed uranium is sent from fabrication to the reactor to complete the fuel cycle.

Since we are considering only the steady-state flowsheet, the uranium product from blending feed with recycled spent uranium must have composition R_R, y_R and must be obtained at rate $F_R(1+L_F)$. The uranium purchased as feed must balance the amounts of U-235, U-236, and U-238 in the three uranium "sinks" - depletion during irradiation, reprocessing losses, and fabrication losses.

In order to carry out the fuel cycle economics calculations described later, it is necessary to determine all flowsheet characteristics over a range of feed isotopic compositions, i.e., for various combinations of R and y. As discussed in Section III-D, it is advantageous to specify R_R and y_R and to proceed through the flowsheet to calculate the corresponding values of R and y. This procedure is discussed in detail below.

For a specified R_R, y_R combination, the 4-batch scatter refueling scheme is brought to steady-state using the CELLMOVE code, and the values for F_R, R_S, y_S, $F_S/(1-L_{RU})$, $K/(1-L_{RP})$ and $N/(1-L_{RP})$ can be calculated for the discharged fuel. Results for F_S, K, and N are simply obtained from:

$$F_S = (1-L_{RU})(\frac{F_S}{1-L_{RU}}), \tag{IV.1}$$

$$K = (1-L_{RP})(\frac{K}{1-L_{RP}}), \tag{IV.2}$$

and $$N = (1-L_{RP})(\frac{N}{1-L_{RP}}). \tag{IV.3}$$

The feed characteristics can be determined by total uranium, U-236, and U-235 mass balance relations for the fabrication plant.

$$F = (1+L_F)F_R-F_S \tag{IV.4}$$

$$yF = (1+L_F)y_RF_R - y_SF_S \tag{IV.5}$$

$$(\frac{R}{1+R})(1-y)F = (1+L_F)(\frac{R_R}{1+R_R})(1-y_R)F_R - (\frac{R_S}{1+R_S})(1-y_S)F_S \tag{IV.6}$$

Thus, from the arbitrary choice of R_R and y_R, complete steady-state flowsheet characteristics can be determined which correspond to the calculated R and y values.

Since the purpose of the study is to determine the value of feed having composition R,y, it is inconvenient to have knowledge of flowsheet characteristics only at scattered points in the R - y plane. By calculating characteristics at a series of (R_R,y_R) points spaced regularly over an R_R - y_R grid, a procedure can be developed for transferring the functional dependence of flowsheet characteristics from R_R and y_R to R and y. The steps are described below.

a. Select a value of y for which characteristics are desired.

b. Specify a value for R_R (not necessarily a value in the $R_R - y_R$ grid).

c. Specify a value for y_R and use double Lagrangian interpolation over tables of $1/F_R$, R_S, y_S, $(1-L_{RU})/F_S$, $K/(1-L_{RP})$, and $N/(1-L_{RP})$ vs. R_R and y_R to determine discharged fuel composition. Interpolation was performed on the reciprocals of F_R and $F_S/(1-L_{RU})$ to avoid difficulty at points of very low burnup, i.e., for very large F_R and $F_S/(1-L_{RU})$.

d. Use Equations IV.1 through IV.6 to calculate R, y, and F.

e. Repeat steps c and d until a value for y_R is obtained which gives the desired y. Since y increases with increasing y_R (as discussed later in this section), the iteration is not difficult.

f. Repeat steps c, d, and e for a series of R_R values.

g. Flowsheet characteristics are now known for a series of irregularly spaced values of R and the specified y. Using Lagrangian interpolation, this data can then be used to calculate flowsheet characteristics at each of a series of regularly-spaced R values.

h. Repeat steps b through f for other values of y.

The iterations involved can be carried out with little difficulty on the computer, so that the use of the "indirect" method of obtaining steady-state characteristics results in only minor inconvenience.

2. Recycle to Diffusion Plant

The second scheme for recycling spent uranium is shown in Figure IV.2. This flowsheet differs from the one described in the preceding section only in that re-enrichment of the recycled uranium is now performed in a gaseous diffusion plant.

Spent uranium of composition R_S, y_S leaves the reprocessing plant as UO_3 at rate F_S and is then converted to UF_6 preparatory to being fed to the diffusion plant. During conversion, a fraction L_C of the converted uranium is lost. The remainder of the UF_6 is fed to the diffusion plant where it is separated into a heads stream having composition R_P, y_P and flowrate F_P and a tails stream having composition R_W, y_W and flowrate F_W. Feed uranium having composition R, y is purchased at rate F in the form of either UO_3 or UF_6. At the fabrication plant, the feed and re-enriched heads streams are mixed, converted to UO_2, and fabricated, with an overall loss rate of $F_R L_R$. Shipment of fabricated elements to the reactor completes the cycle.

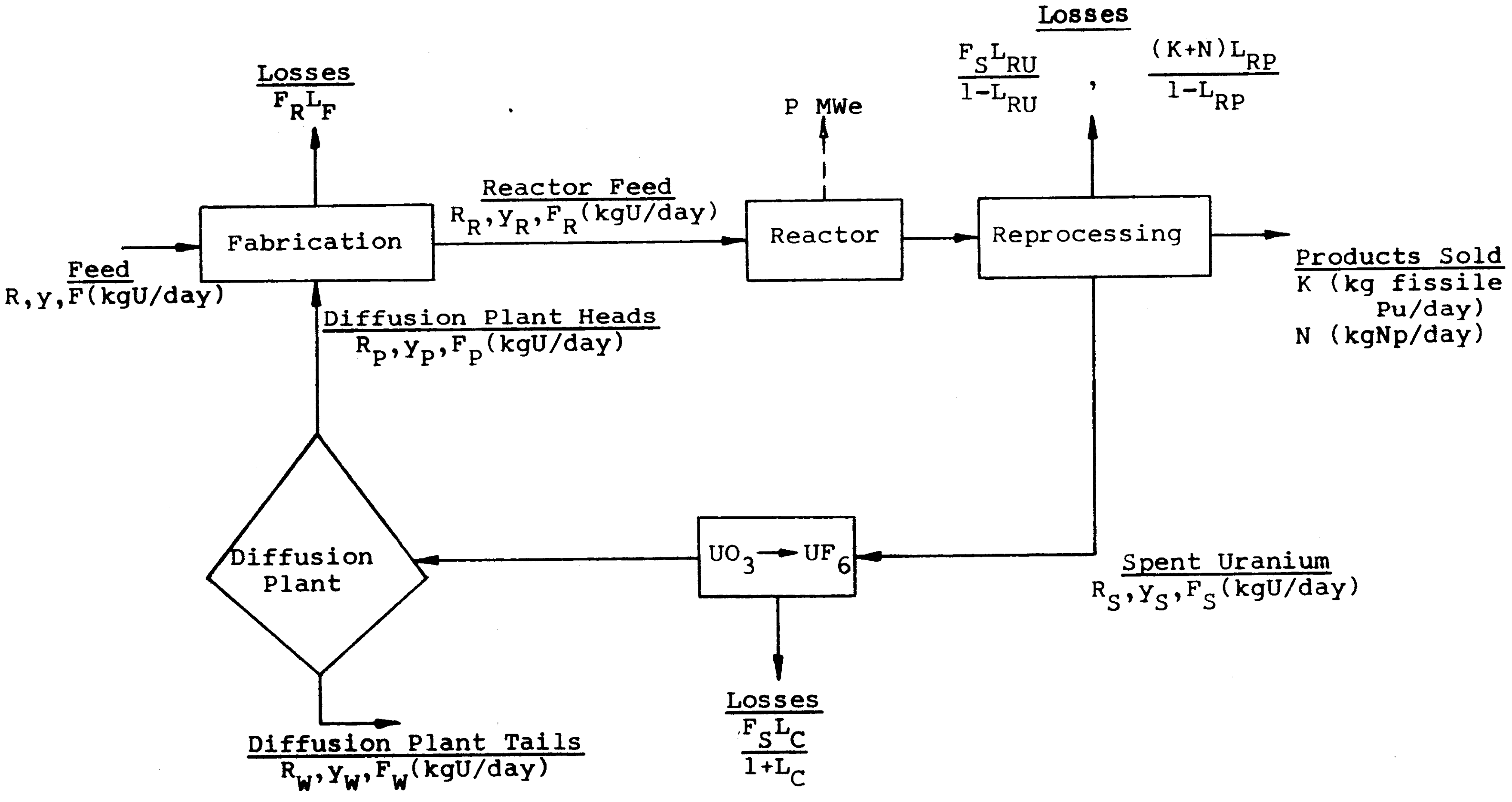


FIGURE IV.2 Flowsheet for Recycle of Uranium to Gaseous Diffusion Plant

In this steady-state flowsheet, the uranium purchased as feed must balance not only the uranium lost due to depletion, reprocessing, and fabrication, but also the amounts of U-235, U-236, and U-238 lost during conversion of UO_3 to UF_6 and the amounts discharged in the diffusion plant tails stream. Later it will be shown that the tails stream represents a uranium sink which causes drastic differences in the feed stream characteristics required to insure near-optimum reactor operation for the two basic recycle schemes.

The diffusion plant is assumed to be so operated that, at each point where two streams are mixed, both streams have the same U-235 to U-238 weight ratio. De la Garza, Garrett, and Murphy(12) call a diffusion cascade operated in this way a "matched-R cascade". Analysis of fuel cycle performance is much simpler with matched-R operation of the diffusion plant than with more complex methods which in principle might lead to lower expenditures of separative work, but which for the cases of practical importance in the present work do not reduce separative work significantly below the matched-R results. In Appendix K it is shown that, for the cases dealt with in this study, the use of matched-R operation yields separative work requirements in close agreement with those resulting from a method of cascade operation which is more efficient but far more complex from an analytical standpoint.

A basic assumption which is unavoidable in performing the study is that, in every diffusion plant operation considered, the only feed, product, and tails streams are those in the fuel cycle being examined; no other material is fed to or taken from the diffusion plant. In actual toll enrichment transactions(19), uranium of known composition is presented to the AEC (e.g., natural uranium or uranium discharged from a reactor) and product having a higher U-235 content is requested. Instead of using the supplied feed material to produce the desired product, the AEC may actually furnish product which was enriched from a different feed material. Thus, lack of control over the U-236 content in the product uranium could result, since the composition of feed streams and other product streams of the diffusion plant will be relatively unpredictable. Due to the impossibility of predicting the composition of all possible feed and product streams of the diffusion plant at some future date, it is necessary to make the above assumption.

The matched-R cascade operates with a "zero-value" tails stream, with the optimum R_W determined in the same way(15) as for the "ideal cascade" mode of operation used presently in the AEC enrichment facilities. When the optimum R_W is used, the tails stream has zero value regardless of its U-236 content.$^{(12)}$ The assumption is made that the tails stream always has the optimum R_W corresponding to the price paid for natural uranium and the current unit cost of separative work charged by the AEC. If the market price for natural uranium is reasonably stable, this is a realistic assumption.

The calculation of steady-state characteristics for this flowsheet is identical to that described for the recycle-to-fabrication scheme through the calculation of R_S, y_S, and F_S, i.e., values for R_R and y_R are specified and CELLMOVE is used together with Equations IV.1, IV.2, and IV.3 to calculate F_R, R_S, y_S, K, N, and F_S.

The distribution of U-236 in the external streams of a matched-R cascade is governed by$^{(12)}$

$$\frac{y_P F_P}{(R_P)^{1/3}} + \frac{y_W F_W}{(R_W)^{1/3}} = \frac{y_S F_S}{(1+L_C)(R_S)^{1/3}} \quad . \qquad \text{(IV.7)}$$

Mass balance relations for the diffusion plant are given next for the total uranium, U-236, and U-235.

$$F_P + F_W = \frac{F_S}{1 + L_C} \qquad \text{(IV.8)}$$

$$y_P F_P + y_W F_W = \frac{y_S F_S}{1 + L_C} \qquad \text{(IV.9)}$$

$$\left(\frac{R_P}{1+R_P}\right)(1-y_P)F_P + \left(\frac{R_W}{1+R_W}\right)(1-y_W)F_W =$$

$$\left(\frac{R_S}{1+R_S}\right)(1-y_S)\frac{F_S}{1 + L_C} \qquad \text{(IV.10)}$$

The matched-R condition which governs the diffusion plant operation is also applied at the point where the feed and diffusion plant heads streams are mixed to form reactor feed, i.e.,

$$R = R_P = R_R, \tag{IV.11}$$

so that R and R_P are known once R_R is specified. Mass balance relations for total uranium and for U-236 can be written for the fabrication plant, as follows:

$$F = (1+L_F)F_R - F_P \tag{IV.12}$$

$$yF = (1+L_F)y_R F_R - y_P F_P \quad . \tag{IV.13}$$

As discussed above, R_W is known once the unit cost of separative work and the price of natural uranium have been specified. The remaining unknowns - y_W, F_W, y_P, F_P, y, and F - can be determined from Equations IV.7, IV.8, IV.9, IV.10, IV.12, and IV.13. Manipulation of these six equations leads to the following:

$$y_W = \frac{A}{1 + A} ,$$

$$\text{where } A = \frac{y_S(R_W-R_P)(1+R_S)}{(1-y_S)(R_S-R_P)(1+R_W)} \left[\frac{\left(\frac{R_P}{R_S}\right)^{1/3} - 1}{\left(\frac{R_P}{R_W}\right)^{1/3} - 1} \right] , \tag{IV.14}$$

$$\text{and } F_W = \frac{F_S(1-y_S)(R_S-R_P)(1+R_W)}{(1+L_C)(1-y_W)(R_W-R_P)(1+R_S)} \ . \tag{IV.15}$$

Knowing y_W and F_W, Equations IV.8, IV.9, IV.12, and IV.13 can be used to calculate F_P, y_P, F, and y, respectively.

Thus, from an arbitrary specification of R_R and y_R, all steady-state flowsheet characteristics can be determined which correspond to the calculated value of y and the specified $R = R_R$ value.

Determination of cycle characteristics for points spaced regularly in the R - y plane is simpler here than for the recycle-to-fabrication scheme, because one has direct control over the values of R examined, as indicated by Equation IV.11. The procedure described in the preceding section applies to the present case with the exception of step g, which can be omitted. By selecting values of R_R which adequately cover the range desired for R, there is no need to interpolate flowsheet characteristics to regularly-spaced R values.

This emphasis on obtaining characteristics over a regular R - y grid is justified by the convenience this provides when examining results and, more important, by the need to interpolate some characteristics at non-tabular (R,y) points, as described in later sections.

3. Operating Parameters

In order to determine flowsheet characteristics, values for a number of parameters were assumed, with an attempt made to choose values which might be typical of reactor operation in the mid-to-late 1970's. Table IV.1 summarizes the values used in the flowsheet analyses.

TABLE IV.1

Summary of Operating Parameters

Net electrical power output (MW), P	430
Full-power thermal output (MW)	1346
Average load factor, L	0.8
Fractional loss during fabrication, L_F	0.01, 0.002
Fractional losses during reprocessing:	
Uranium, L_{RU}	0.01
Plutonium and Neptunium, L_{RP}	0.01
Fractional loss during conversion of UO_3 to UF_6, L_C	0.003
Unit cost of separative work (\$/kgU), C_Δ	30
Optimum ratio of U-235 to U-238 in tails, R_W:	
\$6/lb U_3O_8	0.0028195
\$8/lb U_3O_8	0.0025372
\$10/lb U_3O_8	0.0023173

It was mentioned in Section III that the San Onofre reactor will operate with a net electrical power output, P, of 430 MW. In lieu of detailed load vs. time predictions for this reactor, it was considered reasonable to assume a steady-state average load factor, L, equal to 0.8.

Fuel losses of 1% during fabrication and 1% during reprocessing were assumed; in addition, it was decided that 0.2% , a figure often used by ORNL(20) in their studies, should be considered as an alternative loss during fabrication. A loss of 0.3% was assumed to occur during the conversion of UO_3 to UF_6.

A major part of this study is to examine the effect on the fuel value results when $C_{U_3O_8}$, the price of natural uranium as U_3O_8, is varied. A change in $C_{U_3O_8}$ affects the characteristics of the recycle-to-diffusion plant flowsheet for each (R,y) point, since the optimum tails weight ratio also changes.

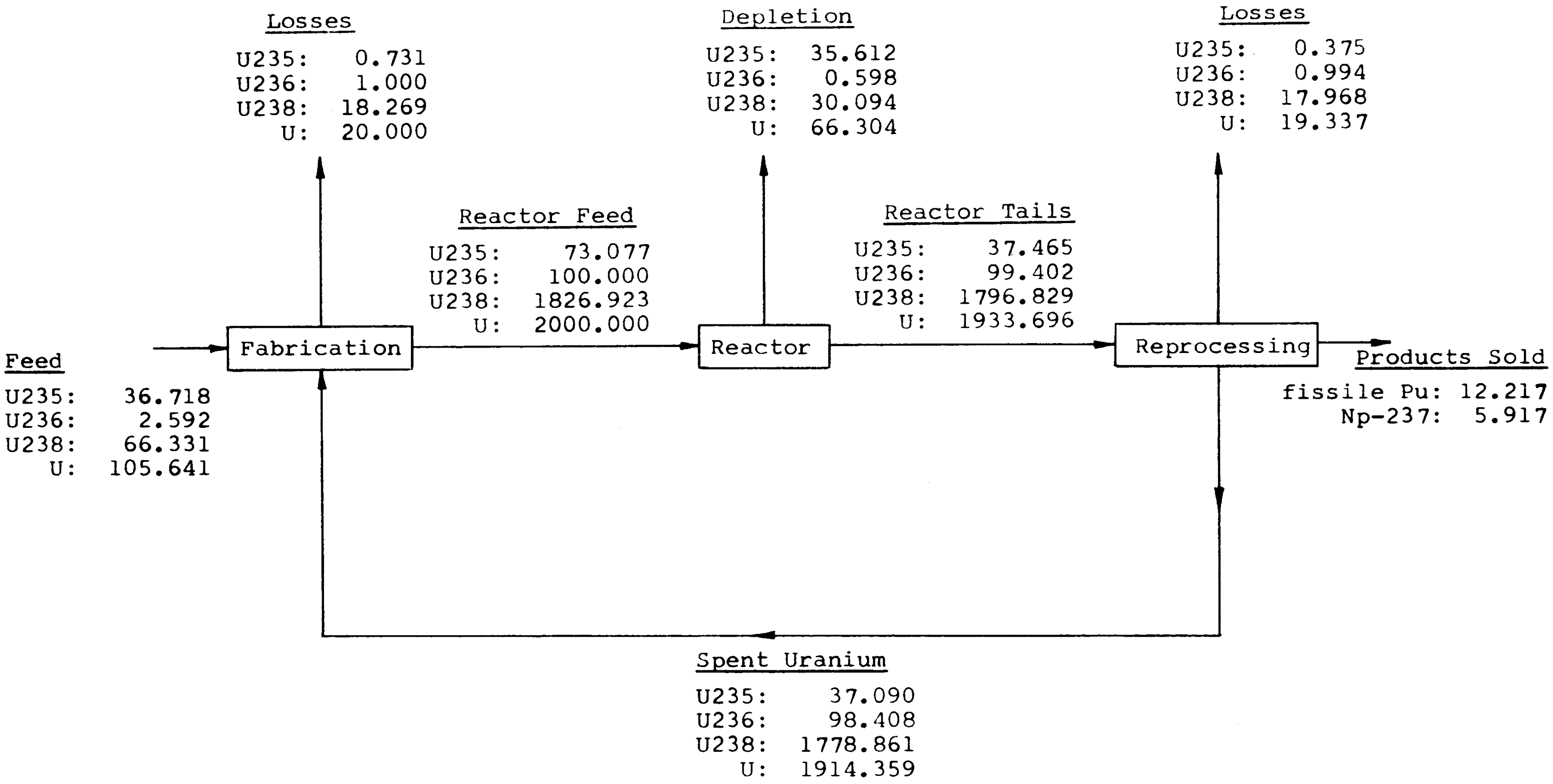
Calculation of optimum R_W for the three U_3O_8 prices is described in Appendix F. The results were based on a unit cost of separative work, C_Δ, of $30/kgU.

4. Flowsheet Characteristics

The effects of U_3O_8 price, fabrication losses, and U-236 feed content on major flowsheet characteristics will be described for the two basic recycle schemes, and major differences between the recycle schemes will be pointed out. A detailed presentation of reactor and flowsheet characteristics, as calculated by CELLMOVE, is given in Appendix L for each R_R,y_R combination considered. In addition, major flowsheet characteristics are presented as functions of feed composition, R and y, in Appendix E.

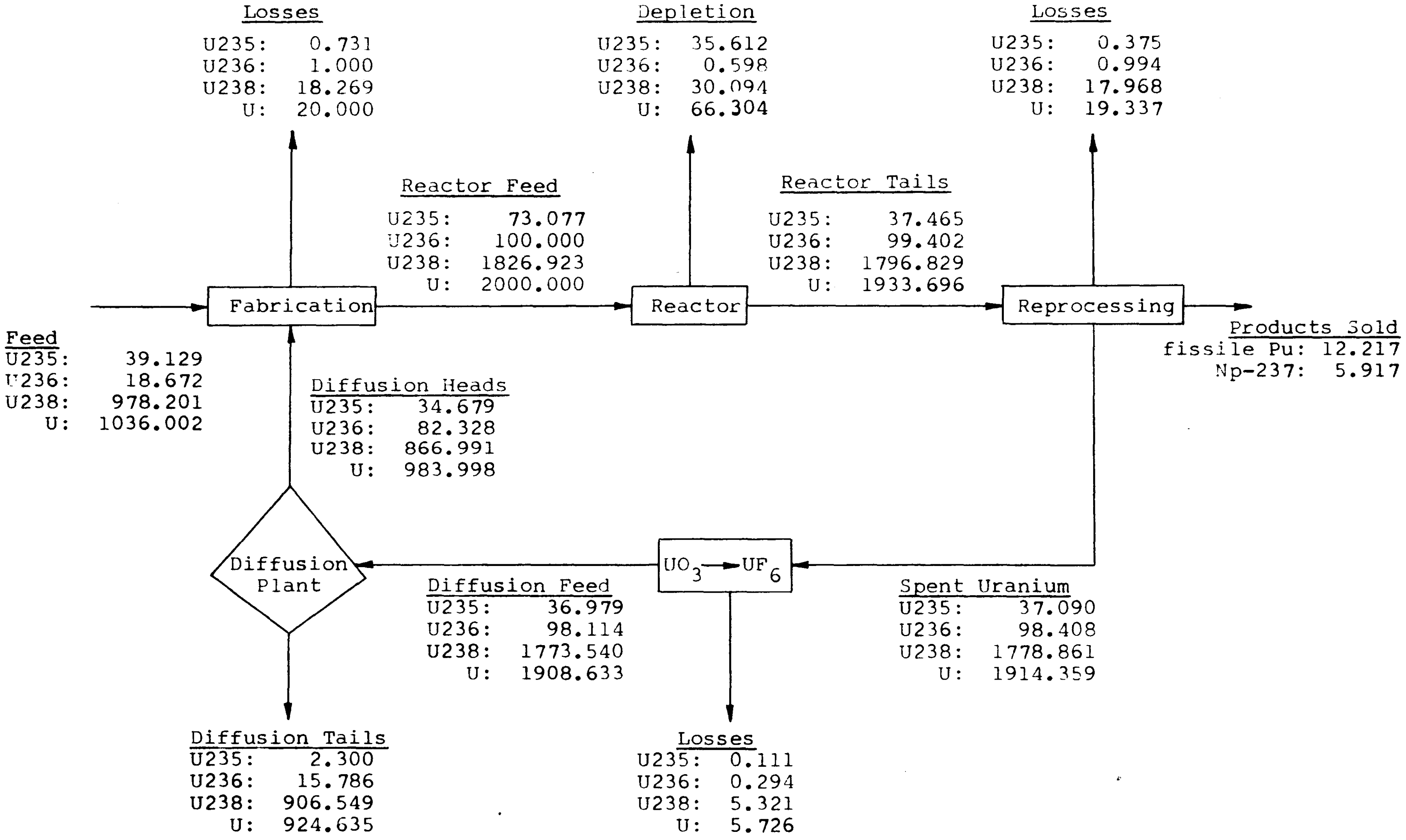
The most basic difference between the two recycle schemes is in the feed characteristics required to maintain reactor operation. This is best seen by comparing isotopic masses throughout both recycle schemes, when the reactor feed is the same in each case. Figures IV.3 and IV.4 show mass balances for recycle to fabrication and to a diffusion plant, respectively, with masses normalized to 100 units of U-236 in the reactor feed, when $R_R = 0.04$ and $y_R = 0.05$. The discharge burnup for this case is 20,600 MWD/MT. Fabrication losses were taken as 1% and diffusion plant operation is based on a U_3O_8 price of $8/lb. Comparison of these mass balances indicates a number of key points.

a. Due to the large amount of uranium discharged in the tails stream, it is necessary that almost an order of magnitude more feed be purchased when reenrichment is by gaseous diffusion.



Note. All masses normalized to 100 units of U-236 in reactor feed; numbers result from specifying $R_R = 0.04$ and $y_R = 0.05$, with 1% loss during fabrication.

FIGURE IV.3 Typical Mass Balance - Recycle to Fabrication



Note. All masses normalized to 100 units of U-236 in reactor feed; numbers result from specifying R_R = 0.04 and y_R = 0.05, with \$8/lb U_3O_8 and 1% loss during fabrication.

FIGURE IV.4 Typical Mass Balance - Recycle to Diffusion Plant

b. The relatively small discharge of U-235 in the tails stream leads to about the same U-235 feed requirements for both flowsheets; however, the lack of a strong U-238 sink in the recycle-to-fabrication scheme leads to much higher R values (R = 0.554 in Figure IV.3) than when a diffusion plant is used.

c. Although U-236 tends to be separated more from U-238 than from U-235 during gaseous diffusion, the diffusion plant offers the only strong U-236 sink and its presence in a recycle scheme leads to a significantly lower ratio of U-236 mass entering the reactor to U-236 mass in the feed than for recycle to fabrication.

d. The loss streams provide a significant uranium sink in Figure IV.3 and, due to their appearance in streams of low U-235 to U-238 ratio, appreciably reduce R below the U-235 to U-238 ratio of above unity in the depletion pseudo-stream. However, the tails stream so dominates the uranium discharged from the other flowsheet that loss streams are a very minor consideration.

e. The amount of Np-237 sold per unit of feed purchased is much greater when blending is used for re-enrichment of spent uranium (Figure IV.3) than when the diffusion plant is used (Figure IV.4).

The importance of loss streams in the recycle-to-fabrication scheme can be clearly seen by noting the effect of reducing the fabrication loss fraction L_F from 0.01 to 0.002:

L_F	0.01	0.002
Fabrication losses		
U-235	0.731	0.146
U-236	1.000	0.200
U-238	18.269	3.654
U	20.000	4.000
Feed		
U-235	36.718	36.133
U-236	2.592	1.792
U-238	66.331	51.716
U	105.641	89.641
R	0.554	0.699

Most noteworthy is the lower U-238 feed requirement and the associated increase in R from 0.554 to 0.699.

The effect of U_3O_8 price on the mass balance of Figure IV.4 is seen by comparing tails and feed stream compositions given below for $6/lb and $10/lb with those for $8/lb on the flowsheet.

	Tails		Feed	
	$6/lb	$10/lb	$6/lb	$10/lb
U-235	2.575	2.088	39.404	38.917
U-236	16.749	15.020	19.635	17.906
U-238	913.433	901.259	985.085	972.911
U	932.757	918.367	1044.124	1029.734

As $C_{U_3O_8}$ increases, R_W decreases, and the recycled uranium enters the cascade further from the tails end, so that less uranium is discharged in the tails.

In particular, as R_W decreases, the U-236 in the tails decreases since U-236 tends to "follow" U-235 rather than U-238 in the cascade.

It is interesting to examine the variation of a few principal characteristics with R and y. The variation of y_R, R_R, F, N, and average burnup (B) will be illustrated and discussed briefly. When they are significant, the effects of $C_{U_3O_8}$ and L_F will be indicated.

Figure IV.5 shows the variation of R_R with R, for three values of y and for both L_F values, when recycling to fabrication. Values for R_R increase as L_F increases since losses occur in streams having high U-238 content. As y increases at fixed R, we see that R_R tends to increase somewhat, since the discharge burnup decreases (due to greater U-236 poisoning) leading to higher reactor throughput rates and correspondingly higher loss rates. As R becomes larger, this y effect disappears because the resulting high burnups result in low loss rates.

Figure IV.6 shows the effect of R and y on y_R for both recycle schemes. For both schemes, an increase in R also increases R_R ($R = R_R$ in the diffusion plant case), which leads to greater U-236 production during irradiation and thus to a higher concentration of U-236 in reactor feed. Generally, y_R increases more rapidly with increasing y when the diffusion plant is used

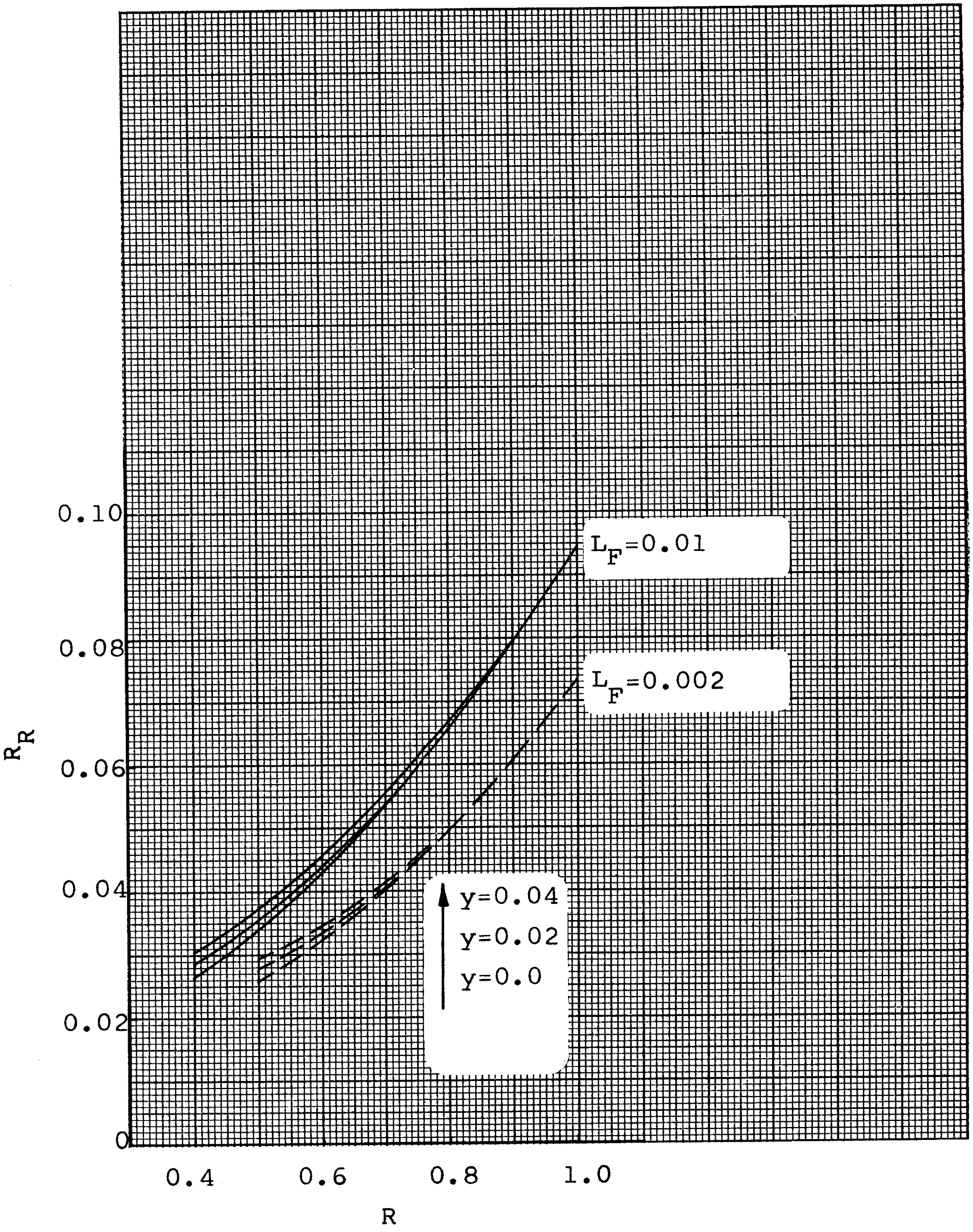


FIGURE IV.5 Variation of R_R with R and y - Recycle to Fabrication

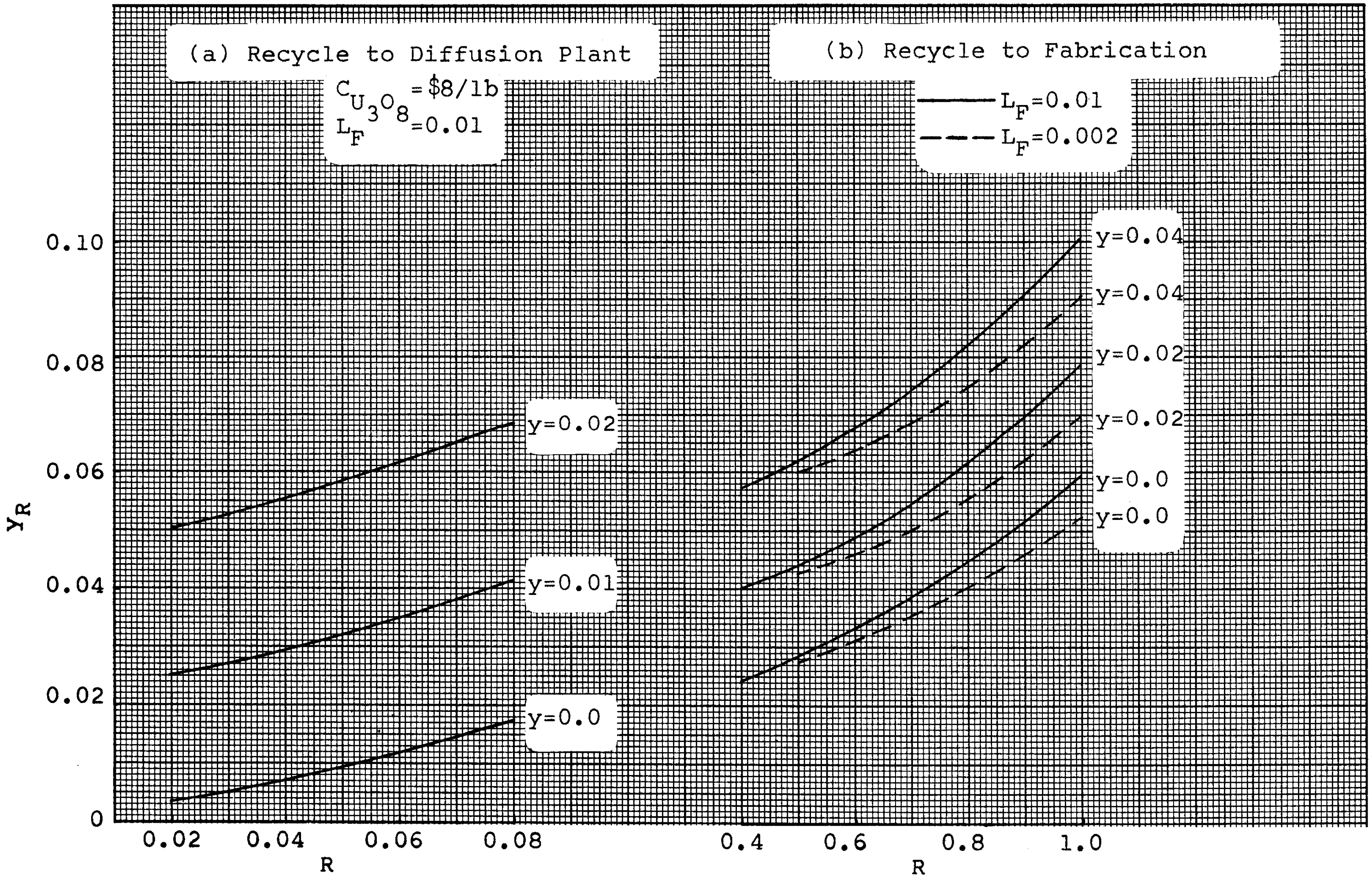


FIGURE IV.6 Variation of y_R with R and y since the U-236 content in the discharged tail increases with y at a rate which is less than linear. Reduction of L_F leads to lower R_R, lower U-236 production, and lower y_R for the same (R,y) point, when recycling to fabrication. The loss effect is not significant for the diffusion plant case.

In Figure IV.7 we see expected increases of average discharge burnup (B) with increasing R and, due to U-236 poisoning, decreases of B with increasing y. Since a decrease of L_F leads to lower R_R in the recycle-to-fabrication case, and since an increase in $C_{U_3O_8}$ leads to higher y_R in the diffusion plant case, both conditions would result in reduced B. The results for B give information on F_R since a simple inverse proportionality exists between the two quantities:

$$F_R(\text{kgU/day}) = \frac{1000}{B}(\text{thermal power, MW})(\text{load factor}) \tag{IV.16}$$

Thus, as B increases, F_R decreases and effects a decrease in all non-depletion streams. This is reflected by the general variation of feed rate, F, illustrated in Figure IV.8.

Figure IV.9 illustrates a general increase in the net production rate of Np-237, N, as y increases. When no U-236 is present in the feed purchased, N increases monotonically with R, with significantly higher Np-237 production for the recycle-to-fabrication

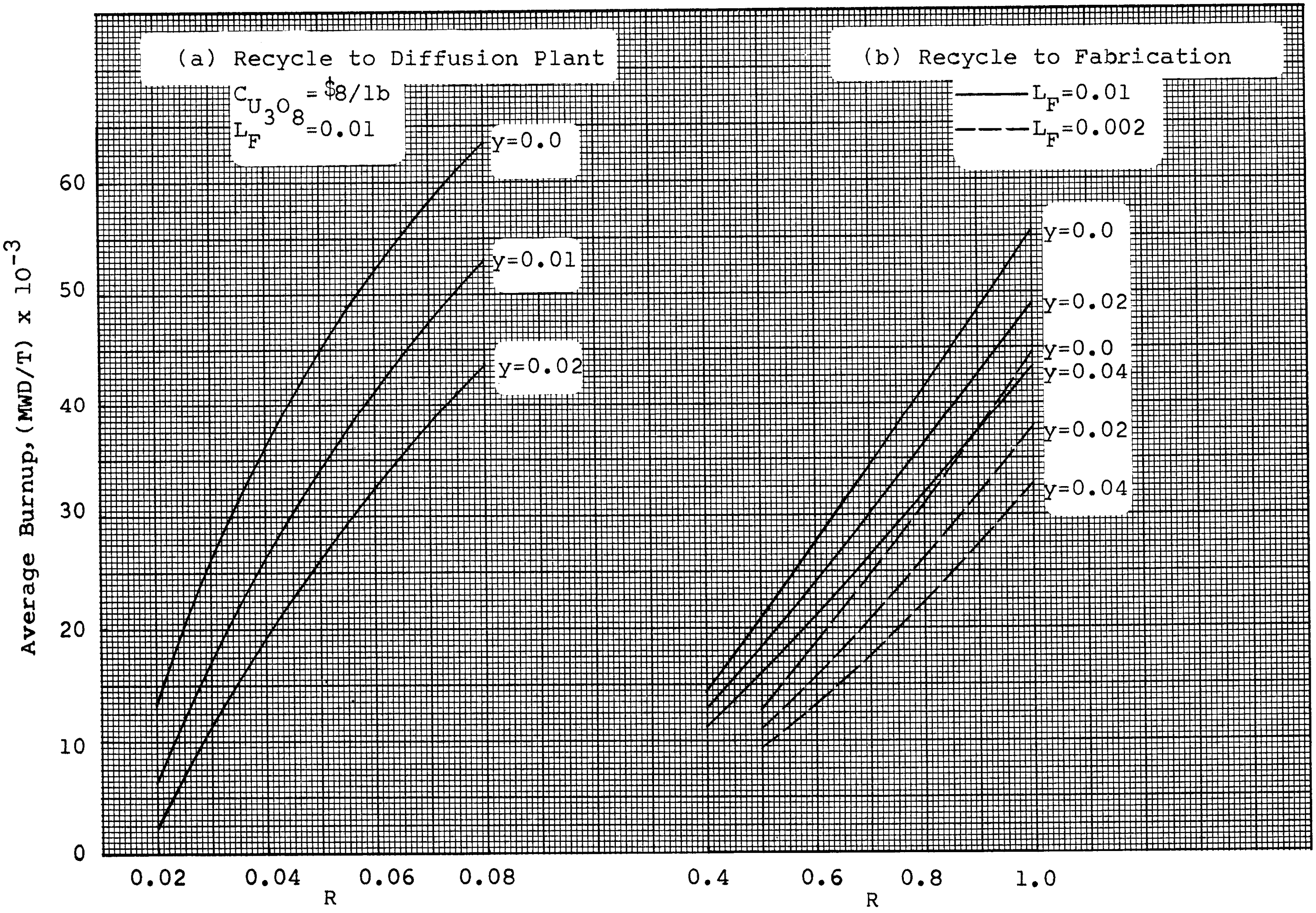


FIGURE IV.7 Variation of Burnup with R and y

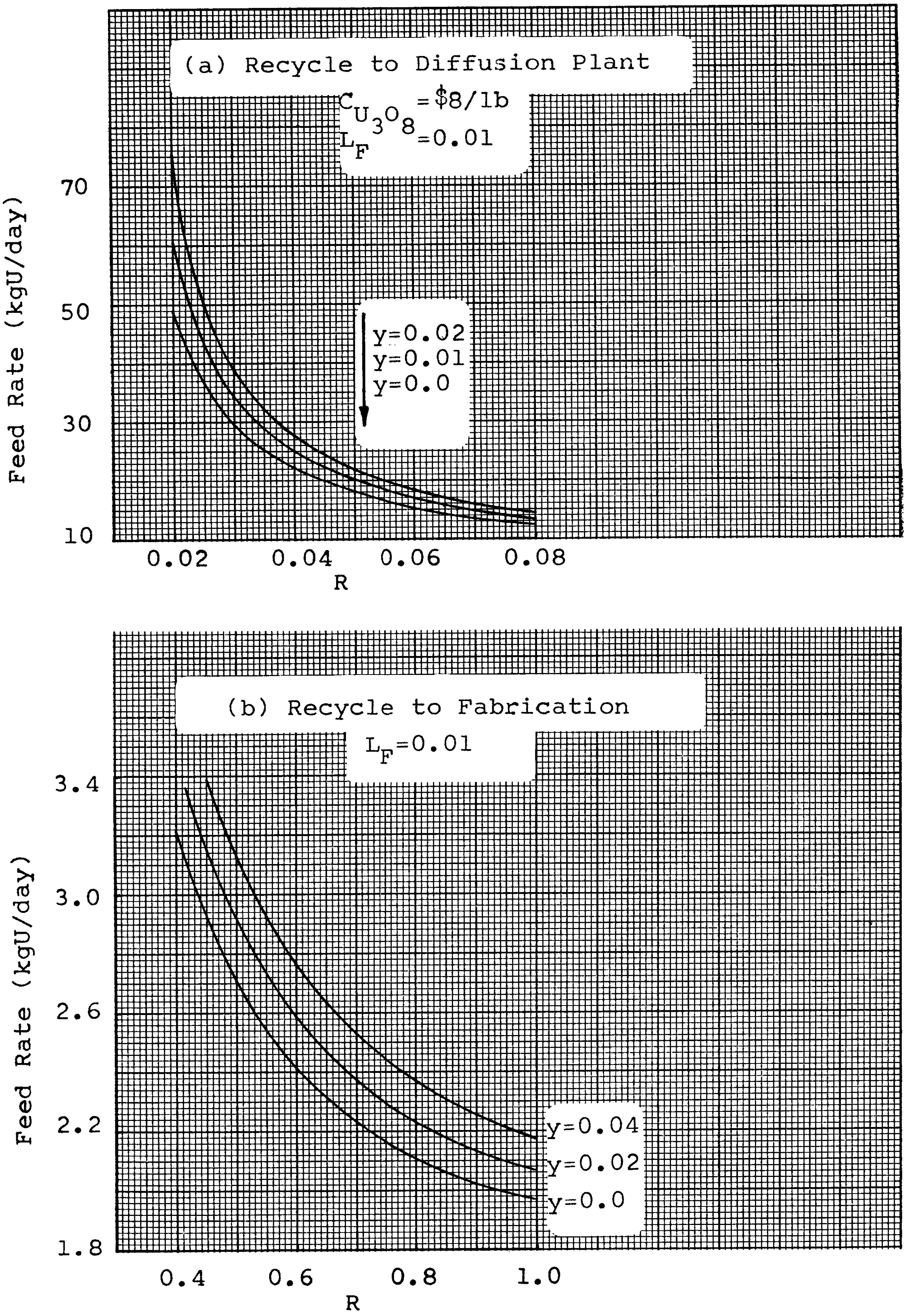


FIGURE IV.8 Variation of Feed Rate with R and y

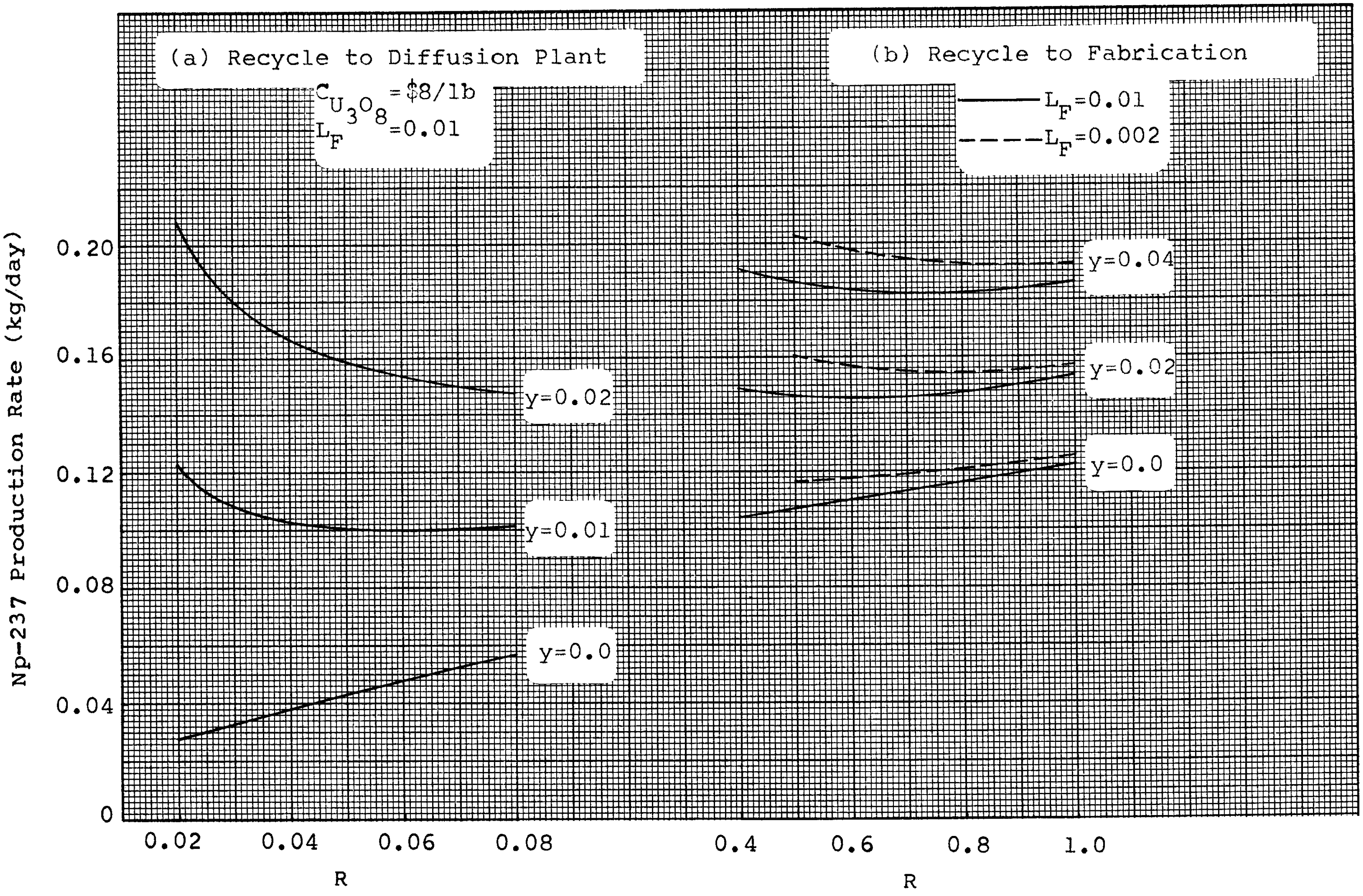


FIGURE IV.9 Variation of Np-237 Production Rate with R and y case. This point is of great importance in an economic comparison of the recycle schemes, as will be seen in Section VI. For higher y values, N first decreases with increasing R (hence, increasing burnup) since the effect of Np-237 absorptions during irradiation becomes larger; however, at sufficiently high R, the absorption rate in U-236 becomes so large that the net Np-237 production rate increases with a further increase of R. When L_F is decreased, N increases due to a decrease in burnup and reduction of the absorptions in Np-237 produced during irradiation. As $C_{U_3O_8}$ increases, N will increase slightly due to an increase in y_R.

Of particular importance in studying the effect of U-236 on the unit value of feed uranium is the change in various flowsheet characteristics with increasing y. Since unit feed value is to be examined, the effect of y on items normalized to a unit of feed is of most interest. Table IV.2 gives such information when y is increased from 0 to 0.01 for R = 0.03 in the diffusion plant scheme and for R = 0.55 for recycle to fabrication. These values of R are close to those which give minimum fuel cycle cost for each flowsheet (as determined in Section VI) when $C_{U_3O_8}$ = \$8/lb and L_F = 0.01.

One can see the marked increase in the amount of U-236 entering the reactor per unit of feed ($F_R y_R/F$),

TABLE IV.2

Effect of y on Fuel Cycle Characteristics
Normalized to Unit Feed
($C_{U_3O_8}$ = \$8/lb; L_F = 0.01)

	y=0	y=0.01	Change with increase in y
Recycle to Fabrication, R = 0.55:			
$F_R y_R/F$	0.539	0.688	0.149
N/F	0.0428	0.0483	0.0055
F_R/F	17.56	18.11	0.55
K/F	0.1165	0.1152	-0.0013
Recycle to Diffusion Plant, R = 0.03:			
$F_R y_R/F$	0.0070	0.0486	0.0416
N/F	0.0011	0.0031	0.0020
F_R/F	1.395	1.806	0.411
K/F	0.0089	0.0098	0.0009
Δ/F	0.933	1.122	0.189
F_P/F	0.408	0.824	0.416

when y is increased from 0 to 0.01. The increase is more than three times greater for the recycle-to-fabrication case, which results in an increase of N/F which is almost three times greater than for the diffusion plant case and leads to increased sensitivity of the unit value of uranium containing U-236 to Np-237 price changes.

The decrease in burnup as y increases effects an increase in F_R/F. The normalized production of fissile plutonium changes only slightly with increasing y, decreasing because of increased R_R (see Figure IV.5) for the recycle-to-fabrication case, and increasing because of reduced burnup, hence reduced plutonium depletion, for the diffusion plant case. For the diffusion plant case, the normalized separative work requirement (Δ/F) and heads stream flow rate (F_P/F) both increase with y, primarily because of the increase of F_R/F. The increase in Δ/F is partially due to the presence of higher U-236 levels in the cascade.

B. Modified Modes of Operation

In Figure IV.7 it is apparent that the values for R which result in reasonable burnups fall within a narrow range for both basic recycle schemes. Also, the R-values near the upper and lower ends of both ranges give burnups too high or too low for favorable fuel cycle economics. In order to extend the range of R over which uranium values can be obtained and to provide alternative means for utilizing uranium feed suitable for basic recycle operation, two schemes have been developed for modifying the isotopic composition of feed uranium before it is fed to a basic flowsheet. Both modifications can be used in connection with either basic recycle scheme. Taken together, these schemes permit calculation of feed value for uranium of any isotopic composition.

1. Pre-Enrichment by Gaseous Diffusion

As shown in Figure IV.10, UO_3 feed having composition R,y is purchased at a rate F_D. The UO_3 is first converted to UF_6 and is then fed to a diffusion plant for upgrading. The product stream has composition R_D, y_D (of course, $R_D > R$) and is fed as UF_6 to the fabrication plant at rate F. The flowsheet can be completed, as indicated, by considering operation according to either basic recycle scheme. Tails having composition R_T, y_T are discharged from the cascade at rate F_T. Since the diffusion plant is operated as a matched-R cascade, R_T will have the optimum value corresponding to the values of $C_{U_3O_8}$ and C_Δ being considered.

When this modified scheme is used with the recycle-to-diffusion plant scheme, one matched-R cascade could be used to upgrade both the feed and spent uranium streams; however, the overall study is carried out in a

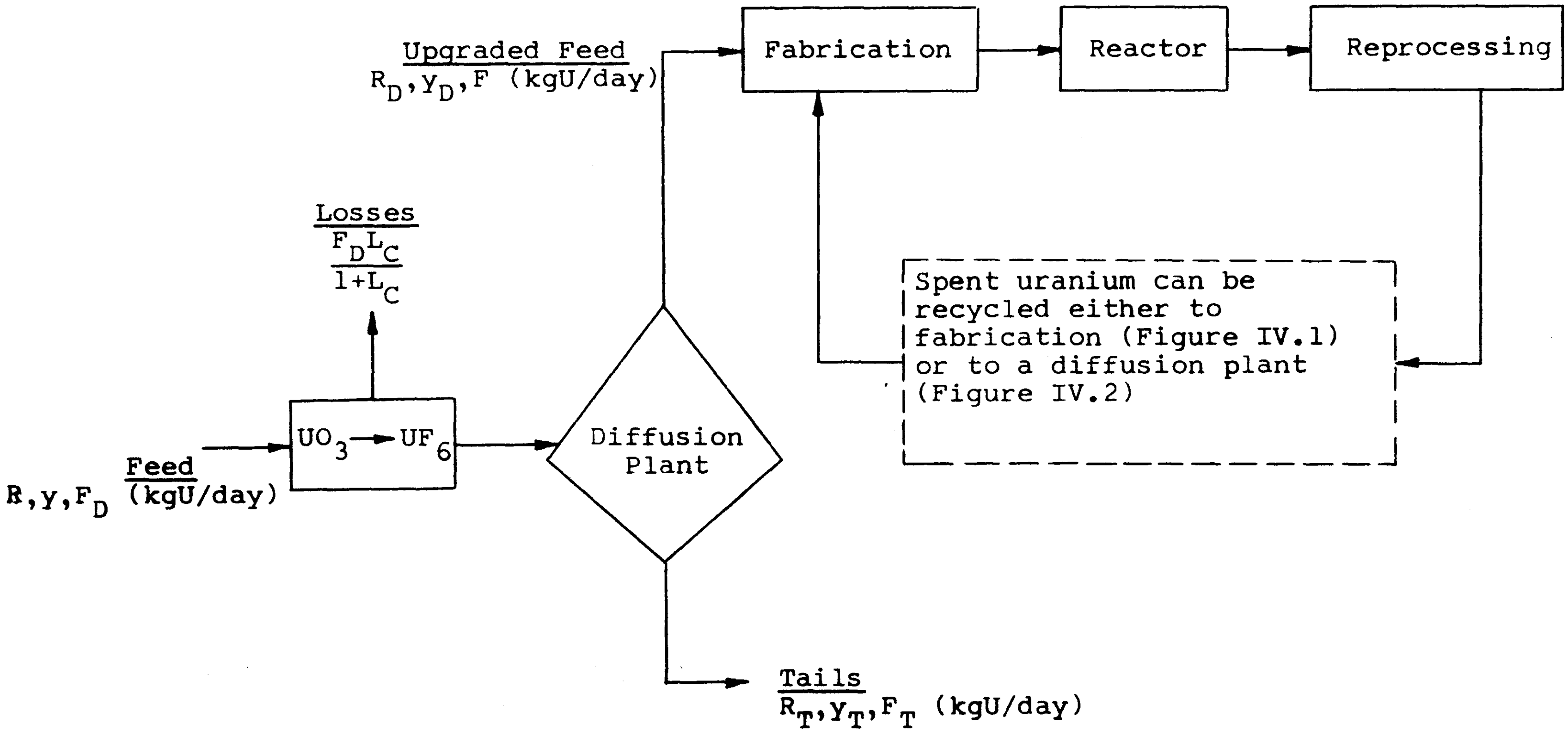


FIGURE IV.10 Flowsheet for Pre-Enrichment of Feed by Gaseous Diffusion more consistent manner when the basic recycle scheme and the modified modes are analyzed separately, since the basic recycle-to-fabrication scheme excludes diffusion plant operations.

In solving for flowsheet characteristics, four equations are available - cascade mass balances for total uranium, U-236, and U-235, and the U-236 distribution equation.(12) These are

$$F + F_T = \frac{F_D}{1 + L_C}, \tag{IV.17}$$

$$y_D F + y_T F_T = \frac{yF_D}{1 + L_C}, \tag{IV.18}$$

$$\left(\frac{R_D}{1+R_D}\right)(1-y_D)F + \left(\frac{R_T}{1+R_T}\right)(1-y_T)F_T = \left(\frac{R}{1+R}\right)(1-y)\frac{F_D}{1+L_C}, \tag{IV.19}$$

and

$$\frac{y_D F}{(R_D)^{1/3}} + \frac{y_T F_T}{(R_T)^{1/3}} = \frac{yF_D}{(1+L_C)(R)^{1/3}}. \tag{IV.20}$$

A fifth restraint is that F can be calculated, using the results of the basic recycle scheme study, once values for R_D and y_D are determined. Eight unknowns are present so there is freedom to choose three quantities arbitrarily. It is desirable to specify values for R and y so that direct control over the feed composition is retained. The presence of R_D to the 1/3 power in Equation IV.20 makes it convenient to select R_D as the third arbitrary quantity. The five remaining unknowns - F_D, F, y_D, y_T, and F_T - can be calculated from the four equations and knowledge of $F(R_D, y_D)$.

The fact that R_D and y_D are not both specified seems to imply an iterative solution; however, iteration can be avoided by dividing Equations IV.17 through IV.20 by F and then solving them for F_T/F, F_D/F, y_D, and y_T. The result for y_D is

$$y_D = \frac{X}{1 + X} ,$$

$$\text{where } X = \frac{y(R_D - R_T)(1+R)}{(1-y)(R-R_T)(1+R_D)} \left[\frac{1 - \left(\frac{R_T}{R}\right)^{1/3}}{1 - \left(\frac{R_T}{R_D}\right)^{1/3}} \right] . \qquad \text{(IV.21)}$$

Knowing R_D and y_D, F can be calculated from the basic recycle flowsheet results described in the preceding section. Next, F_T is determined from

$$F_T = F\left[\frac{(1-y_D)(R_D-R_T)(1+R)}{(1-y)(R-R_T)(1+R_D)} - 1\right] . \qquad \text{(IV.22)}$$

Finally, F_D and y_T can be found using Equations IV.17 and IV.18.

Note that for specified values of R and y, R_D can be used as a parameter for optimizing flowsheet operation with respect to some desired economic criterion. Further mention of this is made in Section V.

2. Blending with Natural Uranium

In this scheme, shown in Figure IV.11, UO_3 having composition R,y is purchased at flowrate F_B and is

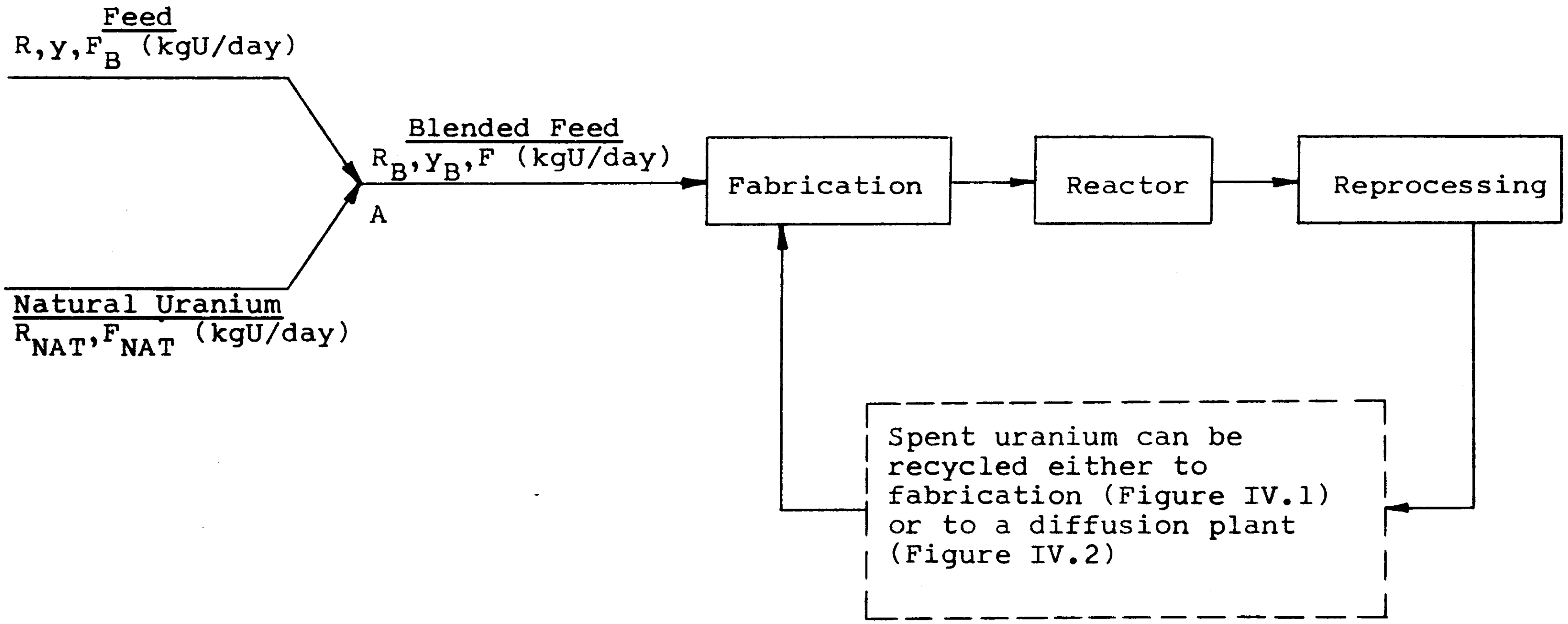


FIGURE IV.11 Flowsheet for Blending of Feed with Natural Uranium blended with natural uranium (R_{NAT} = 0.007161) purchased at rate F_{NAT}. The natural uranium stream could be purchased as U_3O_8 or UF_6, with blending actually performed after conversion to some suitable chemical form at the fabrication plant (this is discussed further in Section V, Part E). The blended stream has composition R_B, y_B and flowrate F and becomes the feed stream to either of the basic recycle schemes.

Unlike the other modified operating mode, which serves to increase the ratio of U-235 to U-238 in the feed, blending with natural uranium results in R_B being lower than R and, since natural uranium contains no U-236, causes y_B to be less than y.

If ϵ is defined as the fraction of blended feed consisting of natural uranium,

$$\epsilon = \frac{F_{NAT}}{F} , \tag{IV.23}$$

then equations for y_B and R_B can be written as

$$y_B = (1-\epsilon)y \tag{IV.24}$$

and $$R_B = \left[\frac{1-y+\epsilon y}{\frac{\epsilon R_{NAT}}{1+R_{NAT}} + \frac{(1-\epsilon)R}{1+R}(1-y)} - 1\right]^{-1} , \tag{IV.25}$$

after taking U-235 and U-236 mass balances at point A and using the following mass balance for total uranium:

$$F = F_{NAT} + F_B . \tag{IV.26}$$

For selected values of R and y, ϵ can be specified and y_B and R_B calculated from Equations IV.24 and IV.25. Using the results of the basic recycle scheme study, F can be determined at the known (R_B, y_B) point. Equations IV.23 and IV.26 can then be used to calculate F_{NAT} and F_B.

In addition to the freedom of specifying feed composition R and y, an additional degree of freedom is available and is used by specifying ϵ . Thus, for a given (R,y) point, ϵ can be optimized with respect to a desired economic condition. This is discussed further in Section V.

V. PROCEDURE FOR CALCULATING URANIUM VALUE

A. Basic Principle

The principle to be followed in determining the value of uranium of a given composition R,y when it is used as feed in a specified fuel flow model is that the overall fuel cycle cost with feed uranium of this composition shall equal the lowest fuel cycle cost which can be obtained for the same fuel cycle when feed uranium contains no U-236 and is priced on the AEC scale. If the price of uranium is equal to the value determined in this way, it will be a matter of indifference to the reactor operator whether the fuel cycle is fed with uranium of optimum enrichment, containing no U-236, priced on the AEC scale, or with uranium of some other composition priced according to this principle.

Four basic assumptions have been made in the application of this value principle.

a. Value will be determined for feed uranium as UO_3, which is a convenient form for shipping processed uranium.

b. Two kinds of diffusion plants are assumed to be operating. One accepts uranium streams containing U-236 and performs toll enrichment taking into account U-236 effects in the cascade. The second accepts natural uranium feed only and provides the enriched UF_6 product, free of U-236, which is purchased as feed for the basic recycle flowsheets at a price consistent with the AEC scale.

c. In the economic analysis, it is assumed that UF_6 of any enrichment can be purchased from the AEC without actually supplying natural uranium for toll enrichment; hence, the delay in receiving enriched product from toll enrichment(19) is not incurred for this feed uranium.

d. When more than one unit value can be obtained for uranium having specified composition and used as feed in a particular fuel cycle, the maximum unit value will be used as the criterion for optimizing fuel cycle operation.

B. Fuel Cycle Cost Equations

The equations used to determine minimum fuel cycle costs for the two methods of recycling uranium correspond to the basic recycle schemes shown in Figures IV.1 and IV.2 when feed containing no U-236 is purchased as UF_6 on the AEC scale. Operation according to either of the modified flowsheets of Figures IV.10 and IV.11 would lead to higher fuel cycle costs than for the basic recycle scheme alone since 1) pre-enrichment by gaseous diffusion requires a delay between the delivery of diffusion plant feed and the receipt of enriched product, resulting in an additional inventory charge, and 2) blending with natural uranium involves the mixing of streams having different U-235 content and causes a net loss of value which would effect an increase in fuel cycle cost.

1. Recycle to Fabrication

Using the nomenclature given in Section IV, Part 1 (or see Appendix M), the equation for $C_E(R)$, the overall fuel cycle cost in mills/kwhr when UF_6 feed having a U-235 to U-238 weight ratio of R and containing no U-236 is purchased on the AEC price scale, is given by:

$24PLC_E(R) =$	cost of electricity (\$/day)
$FC_{AEC}(R)$	cost of feed
$+ F_RC_F$	cost of fabrication
$+ (\frac{F_S}{1-L_{RU}} + \frac{N+K}{1-L_{RP}})(C_A+C_{SH})$	cost of reprocessing and shipping
$- 1000\ KC_K$	credit for plutonium
$- 1000\ NC_N$	credit for neptunium
$+ it_F(\frac{C_R}{1-L_F} + C_F)F_R$	interest on inventory during fabrication
$+ \frac{iI}{2x365}[\frac{C_R}{1-L_F} + C_F + \frac{1000(KC_K+NC_N)+F_S(C_S-C_C)}{F_R} - (\frac{F_S}{1-L_{RU}} + \frac{N+K}{1-L_{RP}})\frac{(C_A+C_{SH})}{F_R}]$	interest on mean value of reactor inventory

(Equation continued on p. 120)

$$+ \; it_{RU}F_S[C_S - C_C - \frac{(C_A + C_{SH})}{1 - L_{RU}}]$$

interest on uranium inventory during reprocessing

$$+ \; it_{RP}[1000(KC_K + NC_N) - \frac{(N+K)}{1-L_{RP}}(C_A + C_{SH})]$$

interest on Pu + Np inventory during reprocessing

(V.1)

In this equation,

C_F is the unit fabrication cost per kg of uranium leaving fabrication and includes the cost of converting UO_3 or UF_6 to UO_2 and the cost of pre-irradiation shipping;

$C_{AEC}(R)$ is the price of UF_6 having U-235 to U-238 ratio R, based on the AEC scale, in \$/kgU;

C_A is the unit cost of reprocessing per kg of fuel fed to the plant and includes a charge for converting UNH to UO_3;

C_{SH} is the unit cost of post-irradiation shipping;

C_K and C_N are the prices received for fissile plutonium and Np-237, respectively, in \$/g;

i is the annual fixed charge rate on working capital;

t_F is the average pre-irradiation holdup time for uranium, in years, including the time required for shipping feed or recycled uranium to the fabrication plant;

t_{RU} and t_{RP} are the average post-irradiation holdup times, in years, for uranium and for Pu + Np, respectively;

I is the total initial uranium loading of the reactor in kg; and

C_C is the unit cost of converting UO_3 to UF_6.

In addition, unit prices of reactor feed, C_R, and spent uranium, C_S, are needed to compute inventory charges. For this purpose, as a reasonable approximation, these are assigned the same price they would have as UF_6 on the AEC price scale, with U-236 treated as U-238. Thus, for inventory charges:

a) the value of reactor fuel prior to irradiation is that of fuel elements fabricated from UF_6 of unit price C_R; and b) the value of spent uranium is C_S minus the costs of shipping, reprocessing, and conversion to UF_6. This accounts for the presence of C_C in Equation V.1.

The above definition of C_F implies that the cost of converting UO_3 to UO_2, per kg of uranium, is taken to be the same as the cost of converting UF_6 to UO_2. Slight differences which might actually exist do not warrant the inclusion of numerous additional items in the cost equations, particularly since this is not a major contributor to the overall fuel cycle cost. In many situations throughout the study, the fabricator receives streams of UF_6 and UO_3 for conversion to UO_2 and subsequent fabrication, and it is convenient to assign a single, overall cost of fabrication (including conversion) for each kg of uranium shipped to the reactor. In order to secure a homogeneous mixture of any two streams, regardless of their chemical form, it is likely that they would both be put into solution for mixing, after which the homogeneous solution would be converted to UO_2. Thus, since neither stream would be converted directly to UO_2, the assumption of a single cost of conversion per kg of reactor feed is not unreasonable.

By using Equation V.1 to calculate $C_E(R)$ for a sufficient numberof feed R values, the minimum fuel cycle cost C_E^* and the corresponding optimum U-235 to U-238 weight ratio R^* can be determined for a particular set of economic conditions.

2. Recycle to Diffusion Plant

For this scheme, illustrated in Figure IV.2, the equation for $C_E(R)$ is identical to Equation V.1, except that the following cost items must now be included on the right side of the equation: the separative work charge, ΔC_Δ; the cost of converting recycled UO_3 to UF_6, $F_S C_C$; and the inventory charge on the product from toll enrichment, $it_E F_P C_D$.

C_Δ is the unit cost of separative work, in \$/kgU, and Δ is the time-averaged separative work expended in the matched-R cascade, in kgU/day. This is calculated from(12)

$$\Delta = F_P \phi_P + F_W \phi_W - \frac{F_S}{1 + L_C} \phi_S \ , \qquad (V.2)$$

where ϕ_i, the separation potential of stream i, is

$$\phi_i = [2(1-y_i)\frac{R_i}{1 + R_i} + 4y_i - 1] \ln R_i . \qquad (V.3)$$

The time interval, in years, between the delivery of uranium to the AEC for toll enrichment and the receipt of product uranium is given by t_E. C_D, the price of the product from toll enrichment, is needed only for the inventory term and is approximated by the price on the AEC scale which the product would have if U-236 were taken as U-238.

The various assumptions made and nomenclature used for Equation V.1 also apply to this case. The minimum fuel cycle cost, C_E^*, can be determined by varying R until the optimum value, R^*, is reached.

C. Uranium Value Equations

When the feed uranium is purchased as UO_3, and may contain U-236, its unit value is determined from the condition that the net fuel cycle cost which results from its use is equal to the minimum fuel cycle cost, C_E^*, for the recycle scheme being examined. The equations developed below permit the calculation of unit value for uranium of any composition R,y when it is used as feed for either recycle scheme.

It was assumed in the preceding section that the unit cost of fabrication, C_F, includes conversion of either UO_3 or UF_6 to UO_2. Thus, the fact that feed is now purchased as UO_3 rather than as UF_6 does not necessitate any adjustment to the fuel cycle cost model.

1. Recycle to Fabrication - Basic Scheme

The unit value, $V(R,y)$, of UO_3 feed having specified R and y can be evaluated from Equation V.1 by setting $C_E(R) = C_E^*$, replacing $C_{AEC}(R)$ with $V(R,y)$, and solving for $V(R,y)$. Note that all steady-state characteristics now correspond to the specified (R,y) point. $V(R,y)$, in \$/kgU, is found to be:

$$\begin{aligned} V(R,y) = \frac{1}{F}\Big\{ & 24PLC_E^* - F_R C_F - \left(\frac{F_S}{1-L_{RU}} + \frac{N+K}{1-L_{RP}}\right)(C_A+C_{SH}) \\ & + 1000(KC_K+NC_N) - it_F\left(\frac{C_R}{1-L_F} + C_F\right)F_R \\ & - \frac{iI}{730}\Big[\frac{C_R}{1-L_F} + C_F + \frac{1000(KC_K+NC_N)+F_S(C_S-C_C)}{F_R} \\ & \qquad - \left(\frac{F_S}{1-L_{RU}} + \frac{N+K}{1-L_{RP}}\right)\frac{(C_A+C_{SH})}{F_R}\Big] \\ & - it_{RU}F_S\left[C_S-C_C-\frac{(C_A+C_{SH})}{1-L_{RU}}\right] - it_{RP}\Big[1000(KC_K+NC_N) \\ & \qquad - \frac{(N+K)}{1-L_{RP}}(C_A+C_{SH})\Big]\Big\} \end{aligned} \tag{V.4}$$

2. Recycle to Diffusion Plant - Basic Scheme

Knowing C_E^* for operation according to this recycle procedure, the unit value, $V(R,y)$, of feed can be written by including the diffusion plant cost items in

Equation V.4.

$$
\begin{aligned}
V(R,y) = \frac{1}{F}\Big\{ & 24LPC_E^{*} - F_R C_F - \left(\frac{F_S}{1-L_{RU}} + \frac{N+K}{1-L_{RP}}\right)(C_A+C_{SH}) \\
& - \Delta C_{\Delta} - F_S C_C \\
& + 1000(KC_K+NC_N) - it_F\left(\frac{C_R}{1-L_F} + C_F\right)F_R - it_E F_P C_D \\
& - \frac{iI}{730}\Big[\frac{C_R}{1-L_F} + C_F + \frac{1000(KC_K+NC_N)+F_S(C_S-C_C)}{F_R} \\
& - \left(\frac{F_S}{1-L_{RU}} + \frac{N+K}{1-L_{RP}}\right)\frac{(C_A+C_{SH})}{F_R}\Big] \\
& - it_{RU}F_S\Big[C_S-C_C-\frac{(C_A+C_{SH})}{1-L_{RU}}\Big] + it_{RP}\Big[1000(KC_K+NC_N) \\
& - \frac{(N+K)}{1-L_{RP}}(C_A+C_{SH})\Big]\Big\} \qquad (V.5)
\end{aligned}
$$

3. Pre-Enrichment by Gaseous Diffusion

In the analysis of Figure IV.10, it was pointed out that, once the composition R_D, y_D of the upgraded feed stream is known, the flowrate of upgraded feed, F, can be determined from the results of the basic recycle scheme analysis discussed in Part A of Section IV. Similarl unit value of the upgraded feed stream $V(R_D, y_D)$ determined from the results of the basic heme feed value analysis just described, sinc d feed stream serves as the feed stream for le scheme being considered. The defin. permits the use of V(R,y) results for feed in the form of either UF_6 or UO_3.

By performing a value and cost balance for Figure IV.10, we get the following equation:

$$FV(R_D,y_D) = (1+it_C)F_DV_D(R,y,R_D) + F_DC_{CT} + \Delta_DC_\Delta + it_EFV(R_D,y_D) \qquad (V.6)$$

where $V_D(R,y,R_D)$ is the unit value of UO_3 feed having composition R,y when upgraded to R_D;

t_C is the time interval between the purchase of UO_3 and delivery of UF_6 for toll enrichment;

C_{CT} includes all unit costs incurred during t_C; and Δ_D is the daily separative work expenditure required for pre-enrichment, as calculated from

$$\Delta_D = F\varnothing_D + F_T\varnothing_T - \frac{F_D\varnothing}{1 + L_C}, \qquad (V.7)$$

with $\varnothing_i$, the separation potential of the stream having composition R_i,y_i, calculated from Equation V.3.

Equation V.6 can be solved for $V_D(R,y,R_D)$ in the form:

$$V_D(R,y,R_D) = \frac{1}{(1+it_C)F_D}[(1-it_E)FV(R_D,y_D) - F_DC_{CT} - \Delta_DC_\Delta] \qquad (V.8)$$

For a specified R and y, flowsheet characteristics and unit feed value can be changed by varying R_D, as discussed in Part B of Section IV. The maximum $V_D(R,y,R_D)$ which can be obtained by varying R_D is of principal interest and is defined as $V_D(R,y)$.

4. Blending with Natural Uranium

In Figure IV.11, the unit value of the blended feed stream is $V(R_B, y_B)$ and is known from results of the basic recycle scheme feed value analysis. Using $\epsilon = F_{NAT}/F$, a dollar-flow balance for the blending process leads to the following equation:

$$V_B(R, y, \epsilon) = \frac{V(R_B, y_B) - \epsilon C_{NAT}}{1 - \epsilon}, \qquad (V.9)$$

where $V_B(R, y, \epsilon)$ is the unit value of UO_3 having composition R,y when a fraction ϵ of the blended stream is made up of natural uranium, and C_{NAT} is the unit price of natural uranium as UF_6.

By varying ϵ at constant R and y, R_B and y_B will change according to Equations IV.24 and IV.25, and the effect of ϵ on $V(R_B, y_B)$ and $V_B(R, y, \epsilon)$ can be determined. At the optimum ϵ, $V_B(R, y, \epsilon)$ will be a maximum, defined as $V_B(R, y)$. Obviously, the restriction on ϵ is that $0 \leqslant \epsilon < 1.0$.

Although C_{NAT} is based on UF_6, the natural uranium could be purchased as U_3O_8 instead of UF_6. It is assumed that the cost of converting U_3O_8 to UO_2 is equal to the cost of converting U_3O_8 to UF_6 plus the cost of converting UF_6 to UO_2. Since the fabrication cost C_F includes conversion of either UF_6 or UO_3 to UO_2, and since C_{NAT} equals $C_{U_3O_8}$ plus the cost of converting U_3O_8 to UF_6, we can assign the price C_{NAT} to the natural uranium and still retain a consistent economics model.

D. Choice of Economic Parameters

In selecting values for the economic parameters required for the feed value calculations, an attempt was made to reflect a large-scale expansion of fabrication and reprocessing activity during the 1970's. For some items, more than one value was selected to avoid the choice of a single overly pessimistic or optimistic number.

A complete summary of all items which appear in the feed value equations is given in Table V.1. Pertinent operating parameters listed previously in Table IV.1 are given again for completeness.

As discussed in Section IV, Part A, three prices for U_3O_8 are considered in the study - \$6, \$8, and \$10/lb. Variation of $C_{U_3O_8}$ not only necessitates adjustment of diffusion plant optimum tails composition, thereby changing flowsheet characteristics, but directly affects all economic parameters which are dependent upon the AEC price scale. Development of the AEC scale for each $C_{U_3O_8}$ price, based on a unit cost of separative work of \$30/kgU, is described in Appendix F. The AEC scale is given below as a function of x, the weight fraction of U-235, but can be rewritten as $C_{AEC}(R)$ by replacing x with R/(1+R).

$$C_{AEC}(x) = 30[(2x-1)\ln\frac{x}{1-x} + A_1x - A_2], \qquad (V.10)$$

TABLE V.1

Summary of Economic Parameters

Reactor inventory (kgU), I	53,000
Net electrical power output (MW), P	430
Load factor, L	0.8
Np-237 price ($/g), C_N	variable between 0 and 100
U_3O_8 price ($/lb), $C_{U_3O_8}$	6,8,10
Fissile Pu price ($/g), C_K:	
$C_{U_3O_8} = 6$	9.01
$= 8$	10.00
$= 10$	10.94
Natural UF_6 price ($/kgU), C_{NAT}:	
$C_{U_3O_8} = 6$	18.17
$= 8$	23.46
$= 10$	28.75
Cost of separative work ($/kgU), C_Δ	30
Fixed charge rate on inventory (yr^{-1}), i	0.10
Fabrication cost ($/kg), C_F	60,40
Reprocessing cost ($/kg), C_A	40,25
Post-irradiation shipping cost ($/kg), C_{SH}:	
Recycle to fabrication	6,3
Recycle to diffusion plant	7,4
Cost of converting UO_3 to UF_6 ($/kgU), C_C	4
Cost incurred between purchase of UO_3 and conversion to UF_6 ($/kgU), C_{CT}	5

TABLE V.1

(Continued)

Fractional losses:	
Fabrication, L_F	0.01,0.002
Reprocessing, uranium, L_{RU}	0.01
Reprocessing, Pu + Np, L_{RP}	0.01
Conversion of UO_3 to UF_6, L_C	0.003
Pre-irradiation holdup time (yr), t_F	0.356
Post-irradiation uranium holdup time (yr), t_{RU}:	
Recycle to fabrication	0.603
Recycle to diffusion plant	0.685
Post-irradiation Pu + Np holdup time (yr), t_{RP}	0.548
Holdup during toll enrichment (yr), t_E	0.247
Holdup between purchase of UO_3 and conversion to UF_6 (yr), t_C	0.0822

where:

$C_{U_3O_8}$	A_1	A_2
\$6/lb	366.409	6.86840
8	406.083	6.97415
10	443.677	7.06505

The choice of plutonium nitrate price, C_K, was governed by current AEC policy$^{(21)}$, which is based on the fuel value of plutonium when substituted for U-235 in thermal reactor fuel. The AEC is currently allowing a credit of \$10 per gram for fissile plutonium as nitrate, which is 10/12 of the AEC price in \$/g for U-235 in 90% enriched uranium, with natural uranium priced at \$8/lb U_3O_8 and separative work at \$30/kgU. At natural uranium prices of \$6/lb or \$10/lb, the price for fissile plutonium is still set at 10/12 of the price of U-235 contained in 90% enriched uranium. This calculation, described in more detail in Appendix F, results in the values for C_K shown in Table V.1. Although the price of plutonium in the mid-1970's could be influenced by the higher value of plutonium when used in fast reactors, the above assumption was considered adequate for a study of U-236 and Np-237 effects on uranium value.

The price of natural uranium as UF_6 was calculated for the three U_3O_8 prices using an equation developed in Appendix F.

$$C_{NAT} = (1+L_C')[(2.2046)(\frac{842}{714})(1+it_c)C_{U_3O_8} + C_{CT}'], \tag{V.11}$$

where C'_{CT} = \$2.26/kgU and includes unit costs incurred between the purchase of U_3O_8 and the conversion of U_3O_8 to UF_6. L'_C is the fraction of uranium lost during the conversion of U_3O_8 to UF_6.

The price received for Np-237, C_N, is of great importance in the study. Since Np-237 derives its value from its use as a target material for producing Pu-238, the size and stability of the Pu-238 market will strongly affect the Np-237 price. Note that the economics equations do not include any additional cost for recovering Np-237, so that C_N represents the net credit to the reactor operator from selling Np-237 after payment is made for the costs of its recovery. Both the future price of Pu-238 and the processing and irradiation costs involved in producing Pu-238 from Np-237 are unknown and have been treated as parameters(9) in studies of Np-237 value. For this reason and since the Np-237 price is likely to vary considerably before stabilizing at some future date, it was decided that a range of C_N values should be considered. The range chosen for C_N is from \$0/g to \$100/g and, as will become evident in Sections VI and VII, is sufficiently broad to indicate all important effects of Np-237 price on PWR fuel cycle economics.

For fabricating UO_2 fuel elements under conditions predicted for the early 1970's, General Electric(22) has established a warranted price of about \$85/kgU. This price will probably be reduced by the mid-to-late 1970's due to the anticipated growth of the industry; hence, \$60/kgU was selected as a reasonable estimate for C_F. A more optimistic unit cost of \$40/kgU was selected as an alternative value for C_F. This lower cost is consistent with predictions of about \$43/kgU made by Battelle-Northwest(23) for a fabrication plant capable of handling 1.0 MT of uranium per day.

A cost of \$40/kgU was used for fuel reprocessing, based on predictions made by ORNL.(20) A second value for C_A of \$25/kgU was selected by slightly reducing the General Electric(22) warranted price of near \$30/kgU (where the listed price has been reduced to exclude shipping costs) to account for industry growth.

A post-irradiation shipping cost of \$6/kg(24) was chosen for recycle to fabrication. For recycle to a diffusion plant, the additional shipment of fuel from the reprocessing plant to the diffusion plant is accounted for by specifying C_{SH} as \$7/kg. Alternative, more optimistic values of C_{SH} are also considered; these are \$3/kg for recycle to fabrication and \$4/kg for recycle to a diffusion plant.

The unit cost of converting UO_3 to UF_6, C_C, was specified as \$4/kgU, or slightly less than the standard(25) charge of \$5.60/kgU for converting UNH to UF_6. A \$1/kgU cost of shipping UO_3 from its point of purchase to the conversion site therefore resulted in C_{CT} being taken as \$5/kgU.

The fixed charge rate on working capital was set at 10% per year, a rate commonly used in fuel cycle studies.(24)

In estimating fuel holdup times, any difference between the refueling interval and the time required to obtain refabricated fuel from reactor discharge was neglected. The pre-irradiation holdup of 130 days ($t_F = 0.356$ yr) and the interval of 200 days ($t_{RP} = 0.548$ yr) between reactor discharge and recovery of nitrates both are consistent with ORNL estimates.(20) By allowing 20 days for the UNH-to-UO_3 conversion step and an additional 30 days for shipping and conversion of UO_3 to UF_6, the values for t_{RU} of 0.603 yr and 0.685 yr were obtained for recycle to fabrication and recycle to a diffusion plant, respectively.

The time required for toll enrichment was set at 90 days ($t_E = 0.247$ yr).(19) Shipping of purchased UO_3 and conversion to UF_6 was assumed to require 30 days ($t_c = 0.0822$ yr).

In calculating feed values for various economic conditions, the effect of changing the unit costs C_F, C_A, and C_{SH} is determined by varying all three at once, rather than individually. Thus, a "high unit cost" case refers to C_F = \$60/kg, C_A = \$40/kg, and C_{SH} = \$6 or \$7/kg, while a "low unit cost" case refers to C_F = \$40/kg, C_A = \$25/kg, and C_{SH} = \$3 or \$4/kg. The "high unit cost" condition will be used for most calculations, while the "low unit cost" condition will be used to indicate the effect on unit feed value of a more favorable economic climate.

In summary, the effect on unit feed value is determined when changes in the following items are made:

a. feed uranium isotopic composition (R and y)
b. fuel cycle flowsheet
c. fabrication losses (L_F)
d. U_3O_8 price ($C_{U_3O_8}$)
e. Np-237 price (C_N)
f. unit cost condition.

Items a through d affect the feed value results not only through the economics equations in this section, but also through their effects on the fuel cycle operating characteristics, as described in Section IV.

E. Description of Calculational Procedures

For a specified set of L_F, $C_{U_3O_8}$, and C_N values, and for a designated unit cost condition and recycle scheme, the procedure for calculating uranium feed values is briefly outlined below.

a. Consider the basic recycle flowsheet. Specify a value for R_R and vary y_R until $y = 0$, using the procedures developed in Section IV. Calculate the fuel cycle cost for the resulting flowsheet conditions. Repeat this procedure for other R_R values until the minimum fuel cycle cost, C_E^*, is obtained. The corresponding value for R is the optimum, R^*. ($R=R_R$ for the recycle - to - diffusion plant scheme).

b. Consider the basic recycle flowsheet. Uranium value results for distinct (R,y) points are obtained using the stepwise procedure outlined in Part A of Section IV for obtaining flowsheet characteristics as functions of R and y, with the insertion of a single step - the calculation of V(R,y) once flowsheet characteristics for a specified (R_R,y) point are known.

c. V(R,y) and F(R,y) are known in tabular form suitable for the interpolations required to calculate $V_B(R,y)$ and $V_D(R,y)$. For each (R,y) point to be examined using pre-enrichment by gaseous diffusion (generally $R < R^*$), R_D is varied until the maximum $V_D(R,y,R_D)$ is obtained. When blending with natural uranium is considered, ϵ is varied for each (R,y) point examined (generally $R > R^*$) until the maximum $V_B(R,y,\epsilon)$ is determined.

VI. RESULTS

A. Minimum Fuel Cycle Costs

Results obtained for C_E^* and the corresponding optimum conditions are given in detail in Appendix G.

Figure VI.1 shows the variation of C_E^* with C_N for three U_3O_8 prices and for both recycle schemes, when $L_F = 0.01$ and when high unit costs are used. For a given U_3O_8 price, two major characteristics are apparent:

a. at C_N = \$0/g (no credit for Np-237), C_E^* is about 0.4 mills/kwhr higher when uranium is recycled to fabrication rather than to a diffusion plant; and,

b. as C_N is increased from \$0 to \$100/g, C_E^* decreases significantly for both recycle schemes but with a steeper slope for recycle to fabrication, resulting in an eventual intersection of the lines for the two recycle schemes.

These two characteristics can be explained as follows. In Figure IV.6, the level of U-236 buildup in the reactor feed when y=0 is substantially greater when recycle is to fabrication; consequently, it is necessary that more U-235 be present in the reactor feed to offset U-236 poisoning when recycle is to fabrication, in order to attain similar burnup levels as for the other recycle scheme. The need to purchase more U-235 in the feed when recycling to fabrication

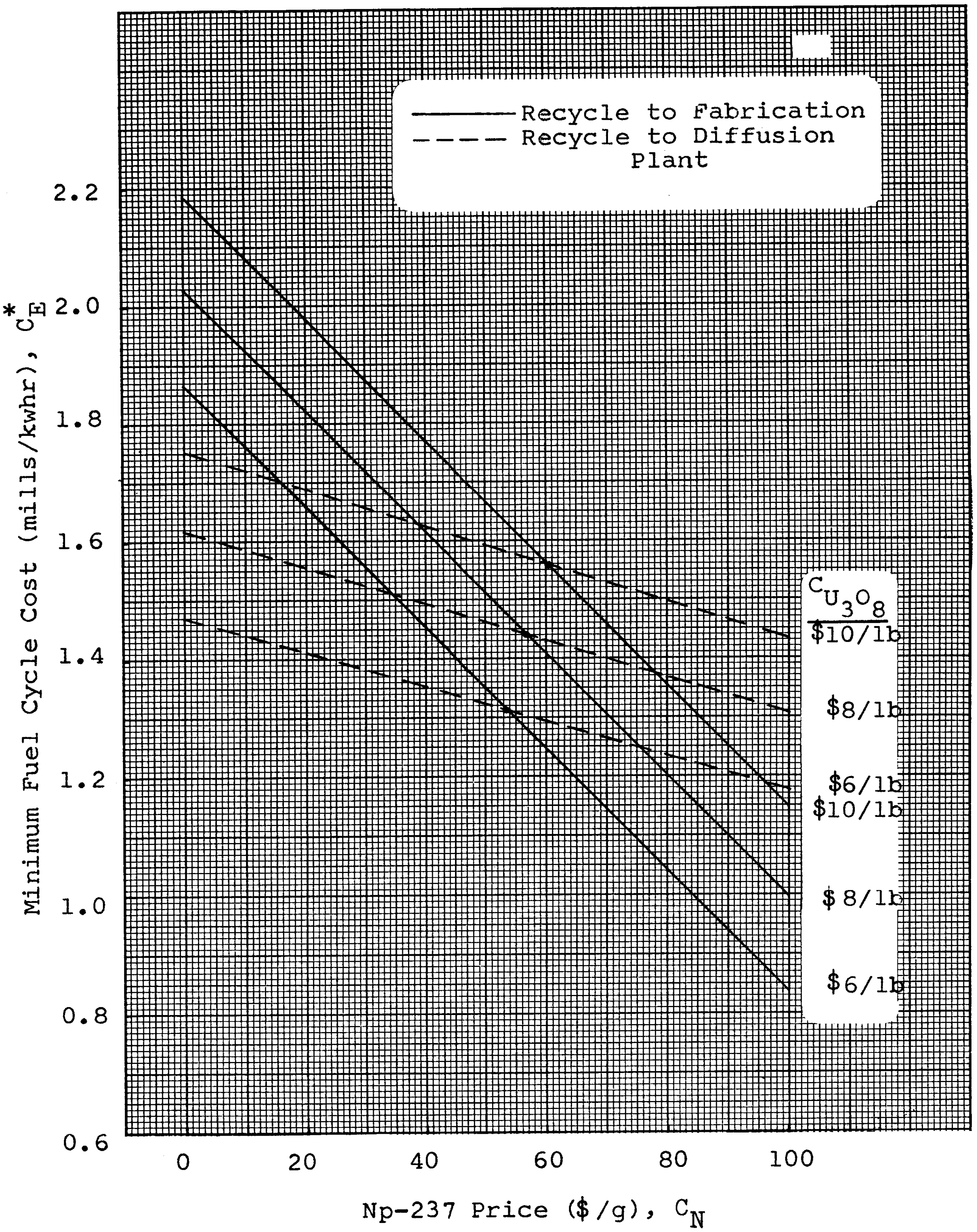


FIGURE VI.1 Effect of Np-237 Price on Minimum Fuel Cycle Cost: High Costs, $L_F = 0.01$

contributes about 0.15 mills/kwhr of the 0.4 mills/kwhr differential mentioned above. An additional 0.25 mills/kwhr is incurred when recycling to fabrication because of the loss in overall uranium value which occurs when mixing streams (feed and recycled uranium) having different U-235 weight fraction.

On the other hand, we have seen in Figure IV.10 that the higher buildup of U-236 in reactor feed leads to a higher Np-237 production rate when recycle is to fabrication and when feed contains no U-236. This fact is responsible for the difference in the slopes of C_E^* vs C_N for the two recycle schemes, and thus causes the intersection mentioned above. The value of C_N at which the lines intersect, C_N^I, represents the Np-237 price at which it is a matter of indifference which recycle scheme is used. For C_N less than C_N^I, it is more economical to recycle uranium to a diffusion plant and permit the discharge of some U-236 with the tails stream, while for C_N greater than C_N^I, it becomes more economical to retain U-236 in the fuel cycle as much as possible by recycling to fabrication.

Due to the strong effect of $C_{U_3O_8}$ on the AEC price scale and, therefore, on the cost of feed, C_E^* for recycle to fabrication will decrease more per unit change in U_3O_8 price than for the other scheme.

This brings about a decrease in C_N^I from roughly \$60/g to \$57/g to \$54/g as $C_{U_3O_8}$ decreases from \$10/lb to \$8/lb to \$6/lb, as shown in Figure VI.1.

The variation of C_E^* with C_N is shown in Figure VI.2 when $C_{U_3O_8}$ = \$8/lb for two other cases - low unit costs with $L_F = 0.01$ and high unit costs with $L_F = 0.002$. By comparing Figures VI.1 and VI.2, we see that reducing L_F from 0.01 to 0.002 results in an insignificant decrease in C_E^* when recycling to a diffusion plant. For the recycle to fabrication case, it was shown in Figure IV.9 that reducing L_F leads to generally higher Np-237 production rates; hence, C_E^* decreases somewhat faster with increasing C_N for $L_F = 0.002$ than for $L_F = 0.01$, although C_E^* results at C_N = \$0/g are very close for both L_F values. This steeper slope reduces C_N^I from \$54/g to about \$52/g when L_F is reduced.

As expected, use of lower unit costs decreases C_E^* significantly - by about 0.2 mills/kwhr. The decrease in C_E^* is somewhat greater for the recycle-to-fabrication case, which has relatively low optimum burnup levels, and leads to a C_N^I of about \$52/g compared with \$57/g for the high unit cost case.

A summary of C_E^* values and optimum conditions is given in Table VI.1 for representative cases. It is important to note that R^* increases with increasing C_N for recycle to a diffusion plant but decreases as C_N

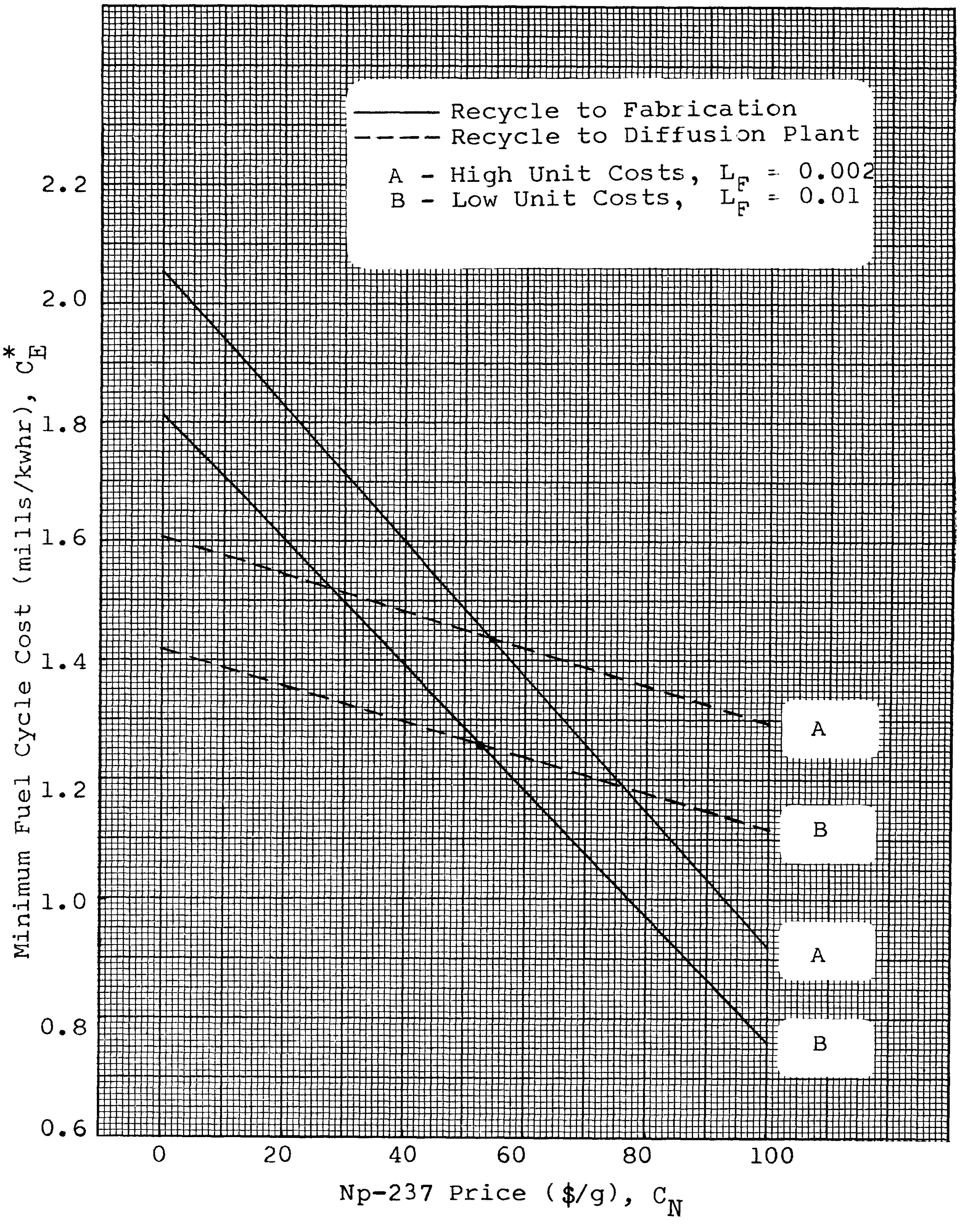


FIGURE VI.2 Effect of Np-237 Price, Unit Costs, and Fabrication Losses on Minimum Fuel Cycle Costs: $C_{U_3O_8} = \$8/\text{lb}$

TABLE VI.1

Summary of Minimum Fuel Cycle Cost Results

					Recycle to Fabrication			Recycle to Diffusion Plant		
L_F	Unit Costs	$C_{U_3O_8}$ ($/lb)	C_N^I ($/gNp-237)	C_N	C_E^* (m/kwhr)	R*	B (MWD/T)	C_E^* (m/kwhr)	R*	B (MWD/T)
0.01	high	6	54.01	0	1.863	0.571	25682	1.470	0.0318	28232
				60	1.248	0.552	24281	1.292	0.0325	28975
		8	57.41	0	2.028	0.557	24692	1.614	0.0309	26976
				20	1.823	0.551	24250	1.552	0.0311	27191
				60	1.410	0.539	23400	1.429	0.0315	27665
				100	0.996	0.528	22615	1.305	0.0319	28132
		10	60.53	0	2.183	0.545	23851	1.750	0.0300	25855
				60	1.563	0.529	22662	1.559	0.0307	26618
	low	8	52.58	0	1.812	0.497	20481	1.417	0.0270	22599
				60	1.181	0.480	19331	1.237	0.0275	23235
0.002	high	8	54.94	0	2.052	0.694	24360	1.604	0.0307	26742
				60	1.375	0.669	22715	1.417	0.0316	27667

increases for recycle to fabrication. This is due to a combination of the following:

a. the Np-237 production rate, hence the Np credit, increases more rapidly with increasing R for y=0 when recycle is to a diffusion plant, as seen in Figure IV.9, and

b. at y=0, the level of Np-237 production is greater by a factor of three for recycle to fabrication, resulting in greater sensitivity of Np carrying charges to increases in R than for recycle to a diffusion plant.

The net effect is that, when recycling to a diffusion plant, Np credit increases faster than Np carrying charges as R increases, while the reverse is true for the recycle-to-fabrication scheme.

The decrease in R* as $C_{U_3O_8}$ increases results from the accompanying increase in the AEC price scale. The sensitivity of inventory charges to changes in R is increased, while the effect of a change in R on direct costs - fabrication, reprocessing, etc. - remains the same. Hence, the inventory charge effect makes it more economical as $C_{U_3O_8}$ increases to select feed with somewhat lower U-235 content.

The decrease in R* when one shifts from the high to low unit cost condition is due to the reduced incentive to maintain high burnup. Since the reduction of direct charges with increasing R is now smaller, it becomes advantageous to reduce R and save on inventory charges.

One should not infer that the C_E^* results of this section represent the lowest possible fuel cycle costs for this reactor. They are the minima for the two recycle schemes considered in this study; however, lower C_E^* could possibly result from the sale of spent uranium to anotherreactor operator, rather than recycling it. T. Golden(4) has determined C_E^* and uranium feed values for this PWR when spent uranium is credited at the value it would have as feed for a heavy-water moderated, organic cooled reactor.

B. Uranium Values for Basic Recycle Schemes

Results for V(R,y) are given in detailed tabular form in Appendix H. For both recycle schemes, the following cases were examined: all combinations of $C_{U_3O_8}$ = \$6, \$8, \$10/lb and C_N = \$0, \$20, \$60, \$100/g for $L_F = 0.01$ and high unit costs; $C_{U_3O_8}$ = \$8/lb and C_N = \$0, \$60/g for $L_F = 0.01$ and low unit costs; $C_{U_3O_8}$ = \$8/lb and C_N = \$0, \$60/g for $L_F = 0.002$ and high unit costs. The discussion below includes only those cases which indicate an important trend in the results.

A major feature of the V(R,y) results for any set of economic conditions is that the line for y=0 is tangent to the AEC price scale at $R = R^*$ and lies below the AEC scale for all other R values. This is a direct result of the principle used in calculating uranium value and can be explained as follows, where the analysis applies to either basic recycle scheme. First, $M(R,y)$ is defined as the total fuel cycle cost exclusive of feed charges, when feed has composition R,y. The units of $M(R,y)$ are \$/day. Next, the equation for the UO_3 feed stream value, in \$/day, can be written (using either Equation V.4 or V.5) as

$$FV(R,y) = 24LPC_E^* - M(R,y) \; . \qquad \text{(VI.1)}$$

Equation V.1 for $C_E(R)$ can be rewritten as follows:

$$24LPC_E(R) = FC_{AEC}(R) + M(R,0) \; . \qquad \text{(VI.2)}$$

If we set $y=0$ in Equation VI.1 to get the value of a feed stream containing no U-236, we can use the resulting equation to eliminate $M(R,0)$ in Equation VI.2. This gives

$$F[C_{AEC}(R)-V(R,0)] = 24LP[C_E(R)-C_E^*]. \qquad \text{(VI.3)}$$

Since $C_E(R^*) = C_E^*$ and $C_E(R) > C_E^*$ for $R \neq R^*$, we see from Equation VI.3 that

$$V(R^*,0) = C_{AEC}(R^*) \qquad \text{(VI.4)}$$

and $$V(R,0) < C_{AEC}(R), \; R \neq R^* \; . \qquad \text{(VI.5)}$$

Note that the elimination of $M(R,0)$ between Equations VI.1 and VI.2 is possible only because of our assumption that the unit cost of converting UF_6 to UO_2 is the same as the unit cost of converting UO_3 to UO_2.

Since M(R,0) contains inventory charges as well as direct charges, it not only increases as R decreases below R* but also begins to increase at some point as R becomes greater than R*; hence, values of R will eventually be reached in both directions at which M(R,0) equals $24PLC_E^*$ and, from Equation VI.1, feed value becomes zero.

1. Recycle to Fabrication

In addition to the characteristics of the V(R,0) results just described, other generalities can be pointed out which aid in interpreting graphs showing V(R,y). Equation V.4 can be re-written in the following approximate form:

$$V(R,y) \approx \frac{b_1}{F} - b_2\frac{F_R}{F} - b_3\frac{F_S}{F} + b_4\frac{KC_K}{F} + b_5\frac{NC_N}{F} \; , \qquad \text{(VI.6)}$$

where the b's are constants. For a fixed R, as y increases F will become larger, as was shown in Figure IV.8; also, F_R/F increases, K/F decreases, and N/F increases with increasing y, as was indicated in Table IV.2. The ratio F_S/F varies in the same way as F_R/F, i.e., increases with y. When C_N = \$0/g, all the above effects tend to reduce unit feed value as the U-236 content increases. If $C_N > 0$, the increase of N/F is a positive effect of increasing y, and for sufficiently high C_N, could result in an increase of unit value as the U-236 content of the feed increases; however, this does not mean that unit value would then continue to increase indefinitely with increasing y. At some y value, the poisoning effect of U-236 will have sufficiently reduced the burnup level so that the unit value would decrease with any additional increase in y, regardless of how high a Np-237 price is in effect.

The relative magnitude of the effects described above will vary with R, but the qualitative trends hold for any R.

Figures VI.3, VI.4, and VI.5 show V(R,y) for $C_{U_3O_8}$ = \$8/lb, L_F = 0.01, and high unit costs, when C_N = \$0, \$20, and \$60/g, respectively. [Note: the line for $C_{AEC}(R)$ which corresponds to the indicated U_3O_8 price is given for comparison purposes on these and all other figures of this section.] In Figure VI.3, where U-236 has effect only as a neutron poison, the reduction of feed value due to the presence of U-236 is greatest at the lower end of the R-range, since the poisoning effect becomes relatively smaller as R increases; of course, as y increases, the feed value is reduced for all R. As C_N increases, the uranium value increases for any point with non-zero U-236 content; however, for y=0, the value decreases with

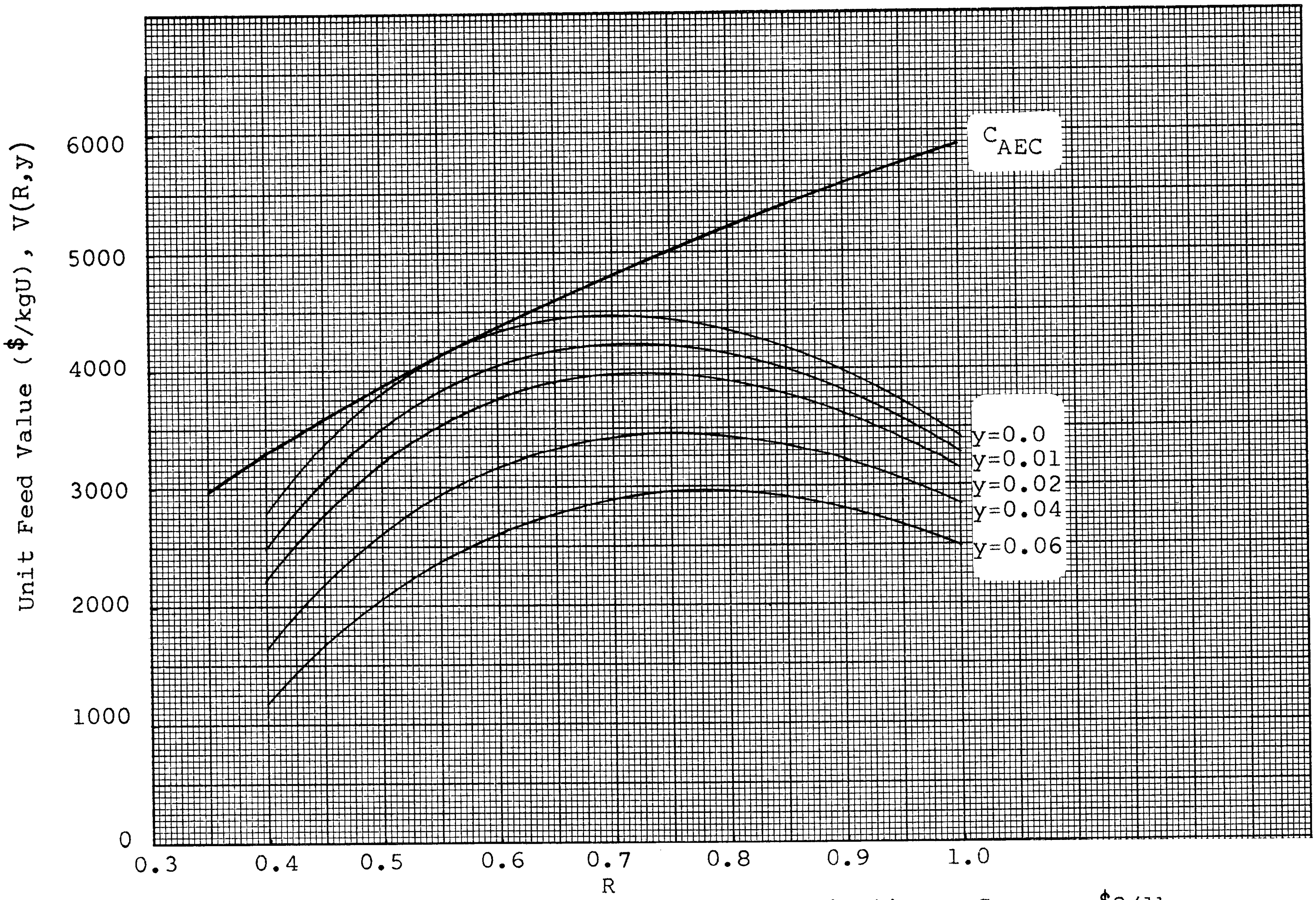


FIGURE VI.3 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8} = \$8/lb$, $C_N = \$0/g$, High Costs, $L_F = 0.01$

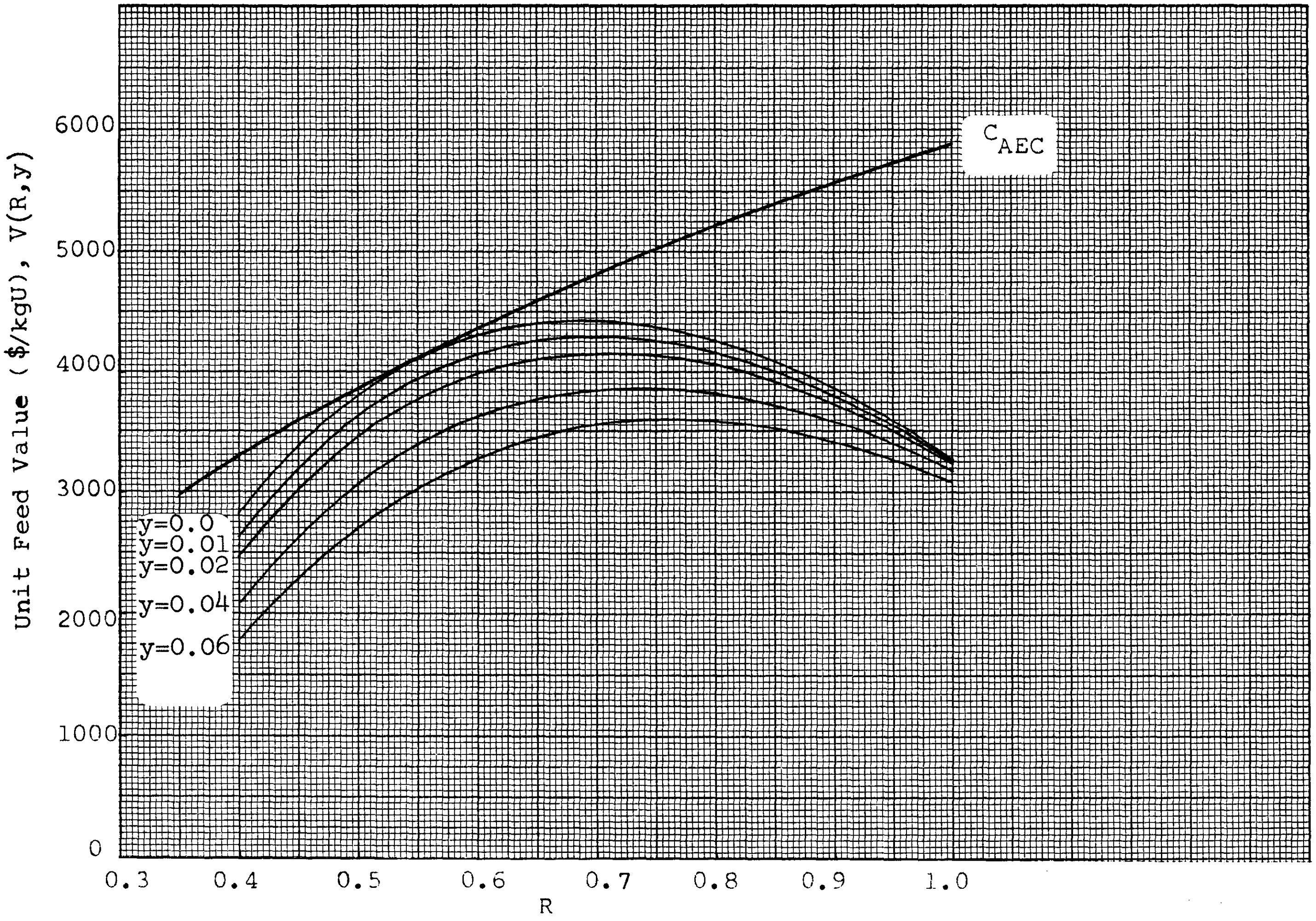


FIGURE VI.4 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$20/g, High Costs, L_F = 0.01

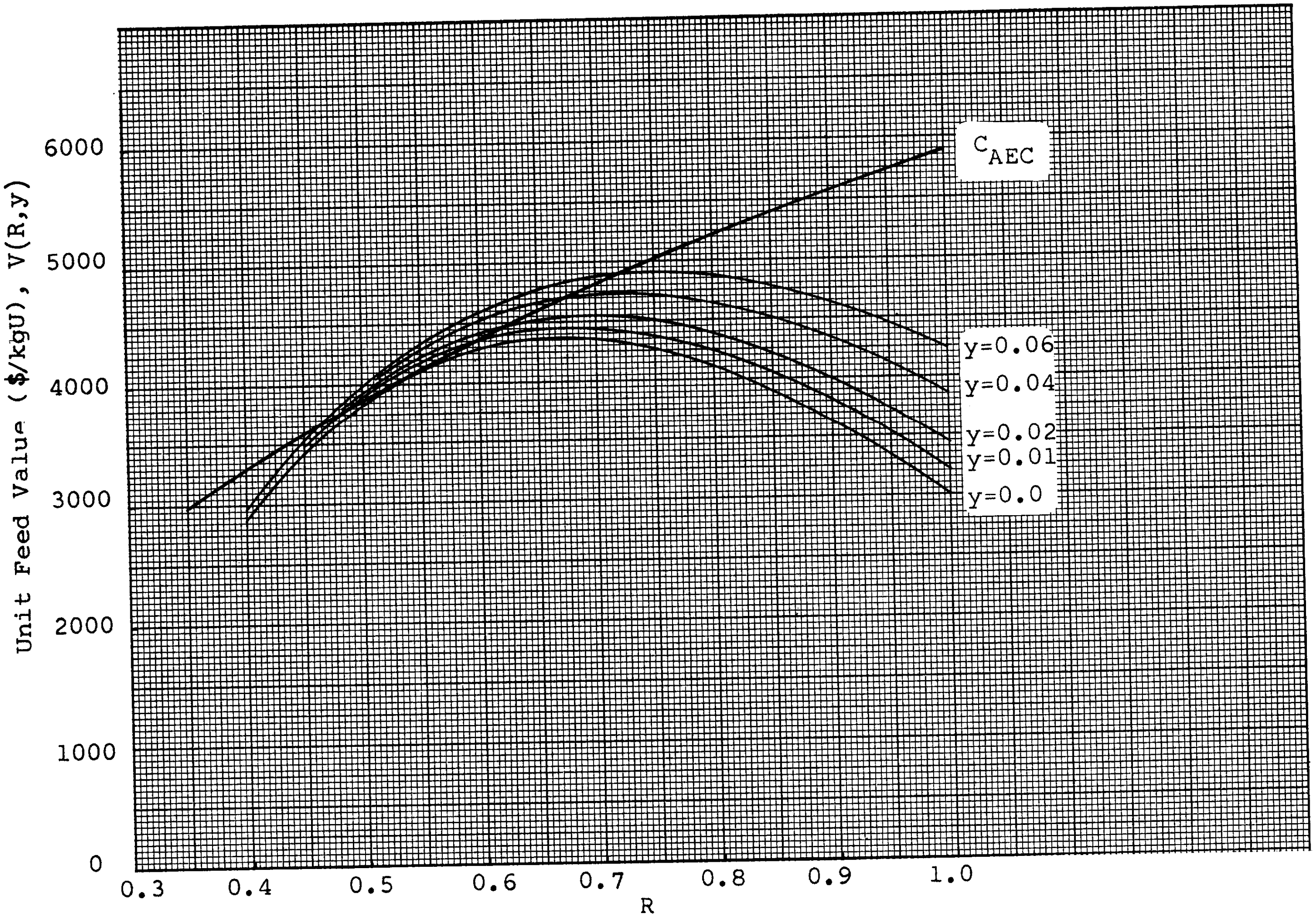


FIGURE VI.5 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$60/g, High Costs, L_F = 0.01

increasing C_N when R is greater than R* and increases when R is less than R*, for the same reasons which cause the reduction of R* as C_N increases. At C_N = \$20/g, the family of curves has become more closely spaced, and with an increase to \$60/g, the curves for non-zero U-236 content all lie above the y=0 line, indicating that the presence of U-236 increases the value of feed uranium for all y and R examined. At \$60/g, the feed value increases with increasing y over the range investigated. The sensitivity of feed value to Np price changes becomes greater as y increases because of the increasingly high Np-237 production rates shown in Figure IV.9.

At any (R,y) point, the feed value increases linearly with C_N.

Figure VI.6 shows results when the U_3O_8 price is set at \$6/lb and when C_N = \$0/g. The general appearance of this set of curves is the same as for the \$8/lb case, except for the general shift downward due to reduction of the AEC price scale and a slight shift to the right due to the increase in R*. Results for \$10/lb would also be similar to Figure VI.3 except for an upward shift caused by the higher prices on the AEC scale. Since the AEC price scale is not a linear function of U_3O_8 price, the value of feed with a given R and y varies non-linearly with $C_{U_3O_8}$.

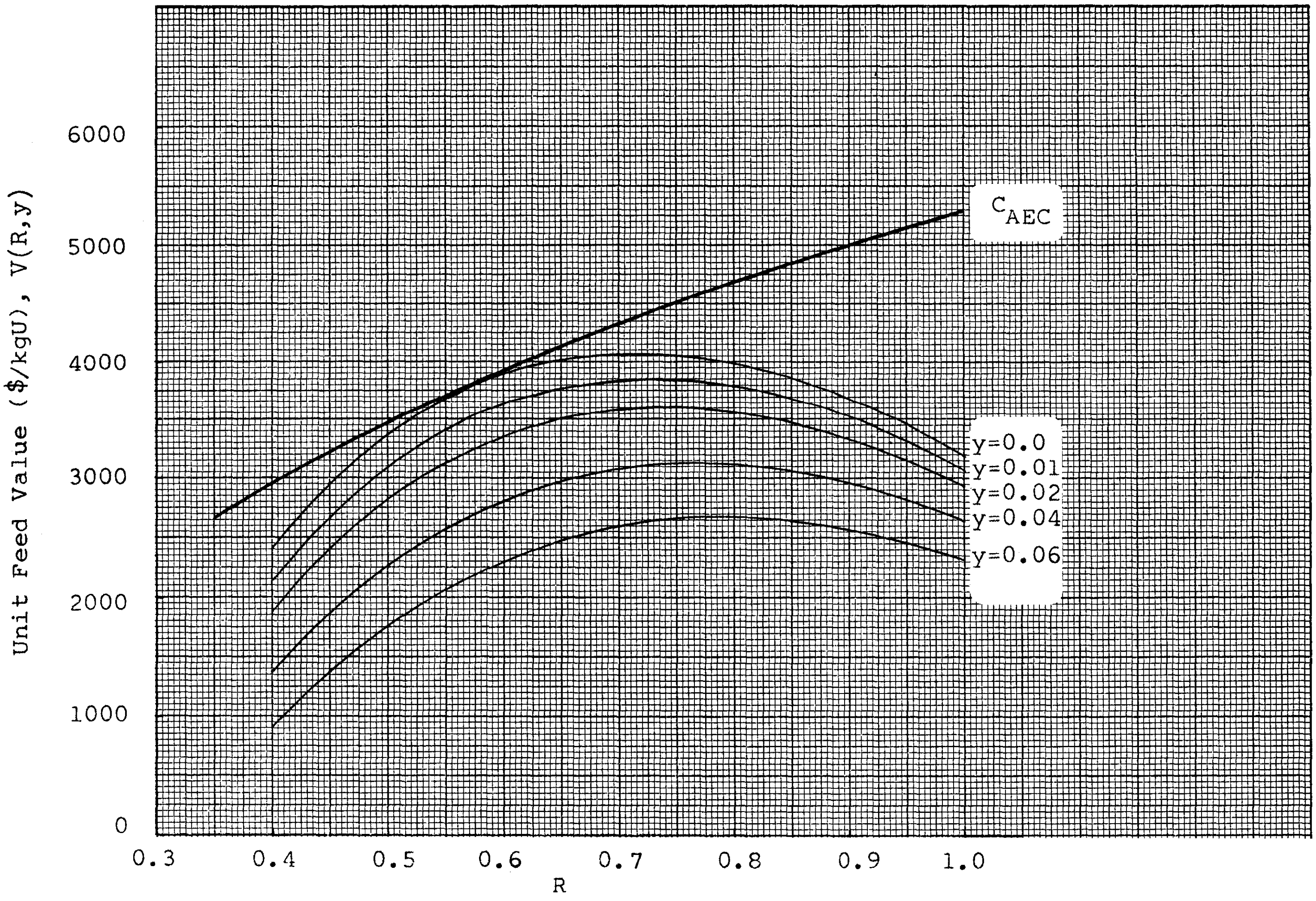


FIGURE VI.6 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = \$6/lb, C_N = \$0/g, High Costs, L_F = 0.01

When the low unit cost condition is assumed and when $C_N = \$0/g$, the family of curves is as shown in Figure VI.7. Comparison with Figure VI.3 indicates an increase of feed value for R less than R^* and a decrease of feed value for R greater than R^* , when unit costs are reduced. This reflects the smaller reduction of direct costs as burnup increases and the smaller economic penalty of low burnups, when unit costs are reduced.

When fabrication losses are reduced from 0.01 to 0.002, the feed value curves are shifted to higher R, as indicated by Figure VI.8. Otherwise, the general variation of feed value with R and y is similar to that for the $L_F = 0.01$ case. One minor difference is the greater decrease in feed value with increasing y in Figure VI.8.

2. Recycle to Diffusion Plant

The qualitative discussion following Equation VI.6 must be extended slightly to be applicable for this recycle scheme. From Equation V.5 we see that two new terms, $-b_6\Delta/F$ and $-b_7F_P/F$, must be included in the right side of Equation VI.6. In Table IV.2, an increase in y is seen to cause increases in F_R/F, N/F, Δ/F, and F_P/F and, in this case, a slight increase in K/F. For the plutonium prices being considered, this increase in K/F will be of slight consequence, and an increase of

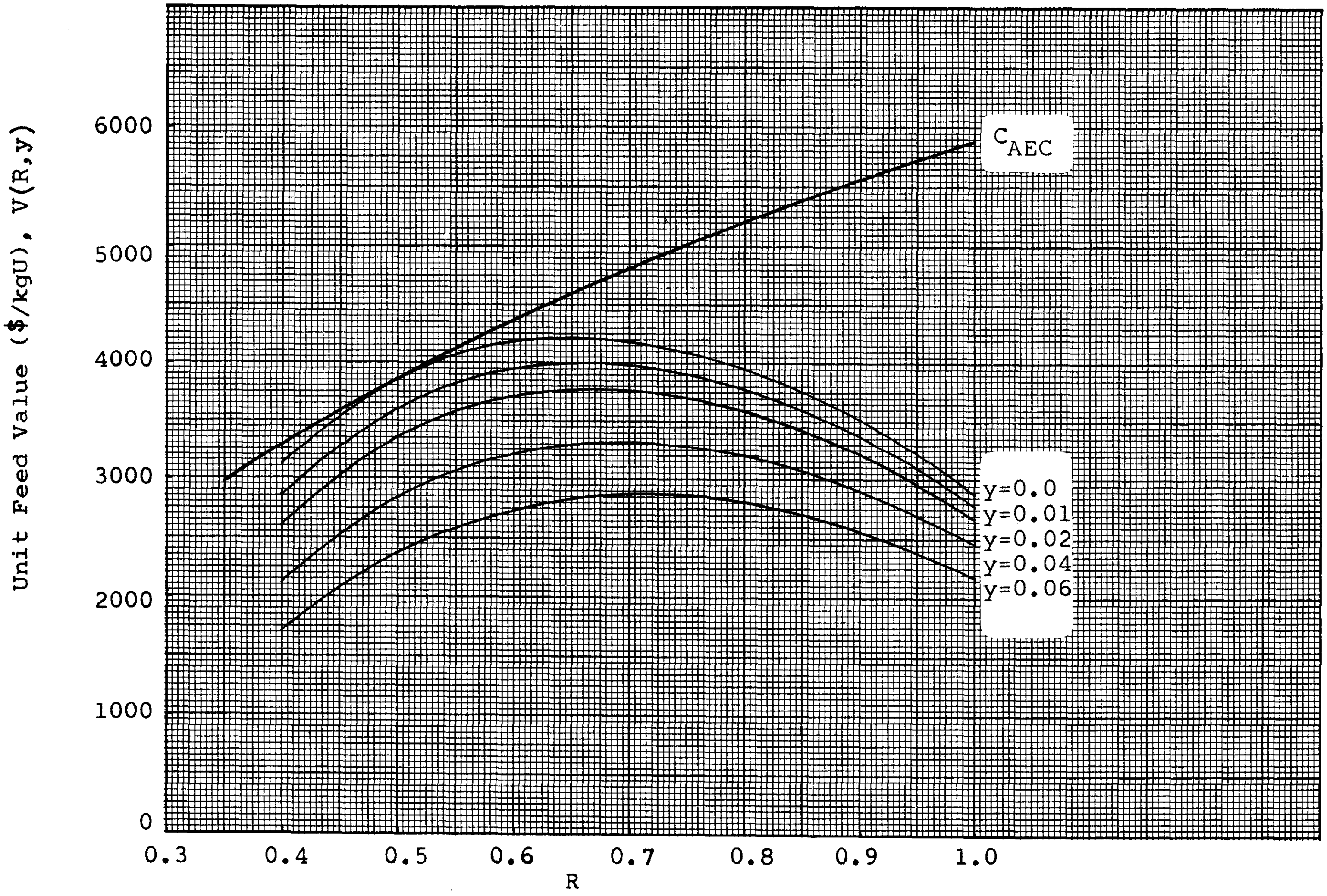


FIGURE VI.7 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, C_N = $0/g, Low Costs, L_F = 0.01

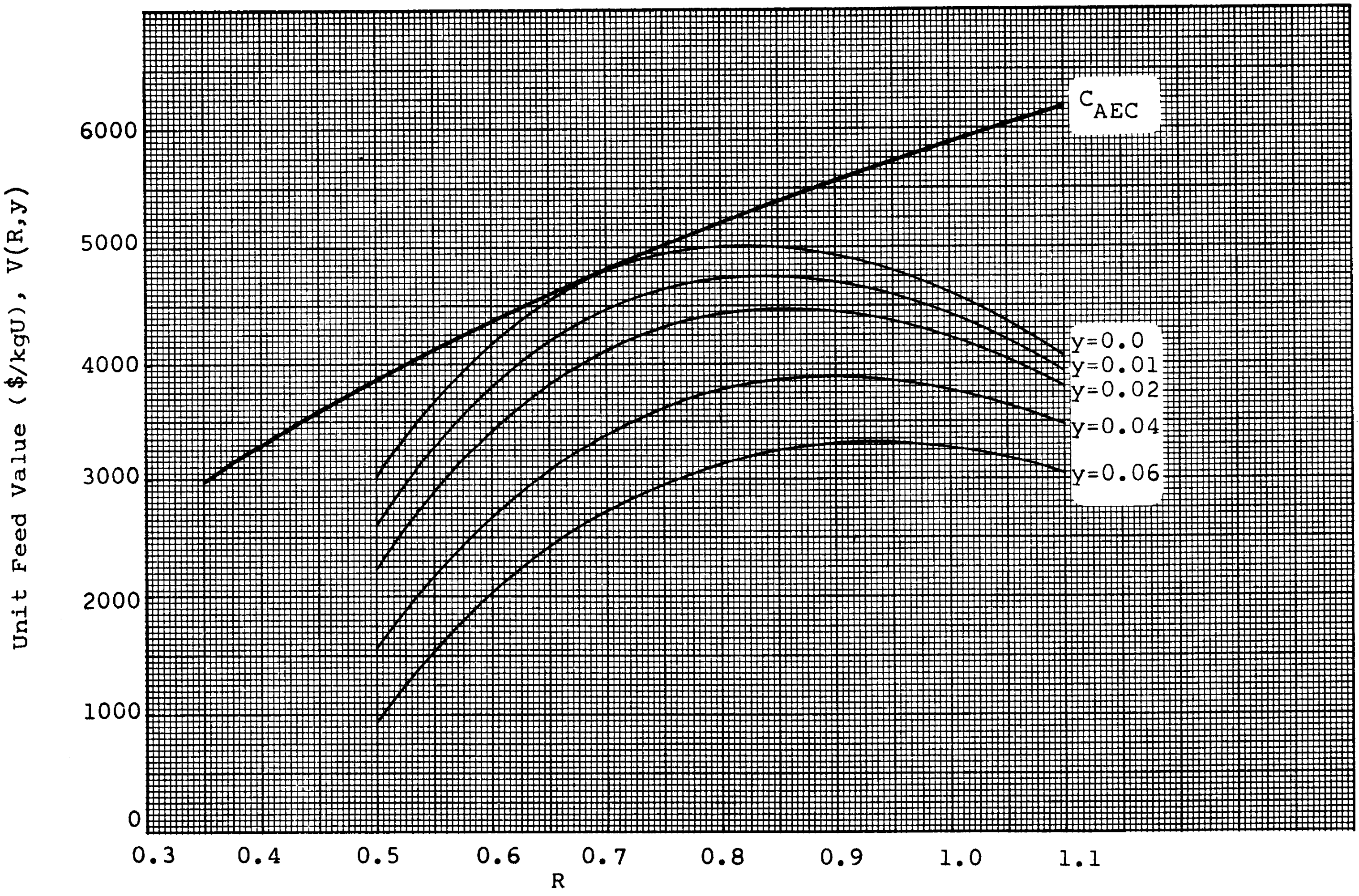


FIGURE VI.8 Unit Feed Value - Basic Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.002

U-236 content at fixed R will lead to a reduction in feed value unless the Np-237 price is sufficiently high for the increased Np-237 credit to override the effects of U-236 poisoning.

Figures VI.9, VI.10, and VI.11 show how feed value V(R,y) for recycle to a diffusion plant varies with R and y for C_N = \$0, \$20, and \$60/g, respectively, when high unit costs are assumed and when $L_F = 0.01$. The strong poisoning effect of U-236 at the lower end of the R-range is apparent in all three figures and forces the feed value to zero at values of R which increase with increasing U-236 content. As C_N increases, the increase in feed value becomes larger with increasing R, for constant y. Also, the increased Np-237 production rate which results from higher U-236 content causes the feed value for constant R to increase faster with increasing C_N as y becomes larger. These effects cause the overlapping of the lines at \$60/g. In Figure VI.11, an increase of U-236 content enhances the feed value for R greater than 0.035; however, for R less than 0.035 the y = 0.03 line lies below the y = 0 line, indicating that the poisoning effect overrides the additional Np credit when U-236 is present at this concentration. Lines for decreasing y remain above the y = 0 line over more of the R-range; however, for R less than 0.0275, the presence of U-236 at any level will reduce feed value when C_N is less than \$60/g.

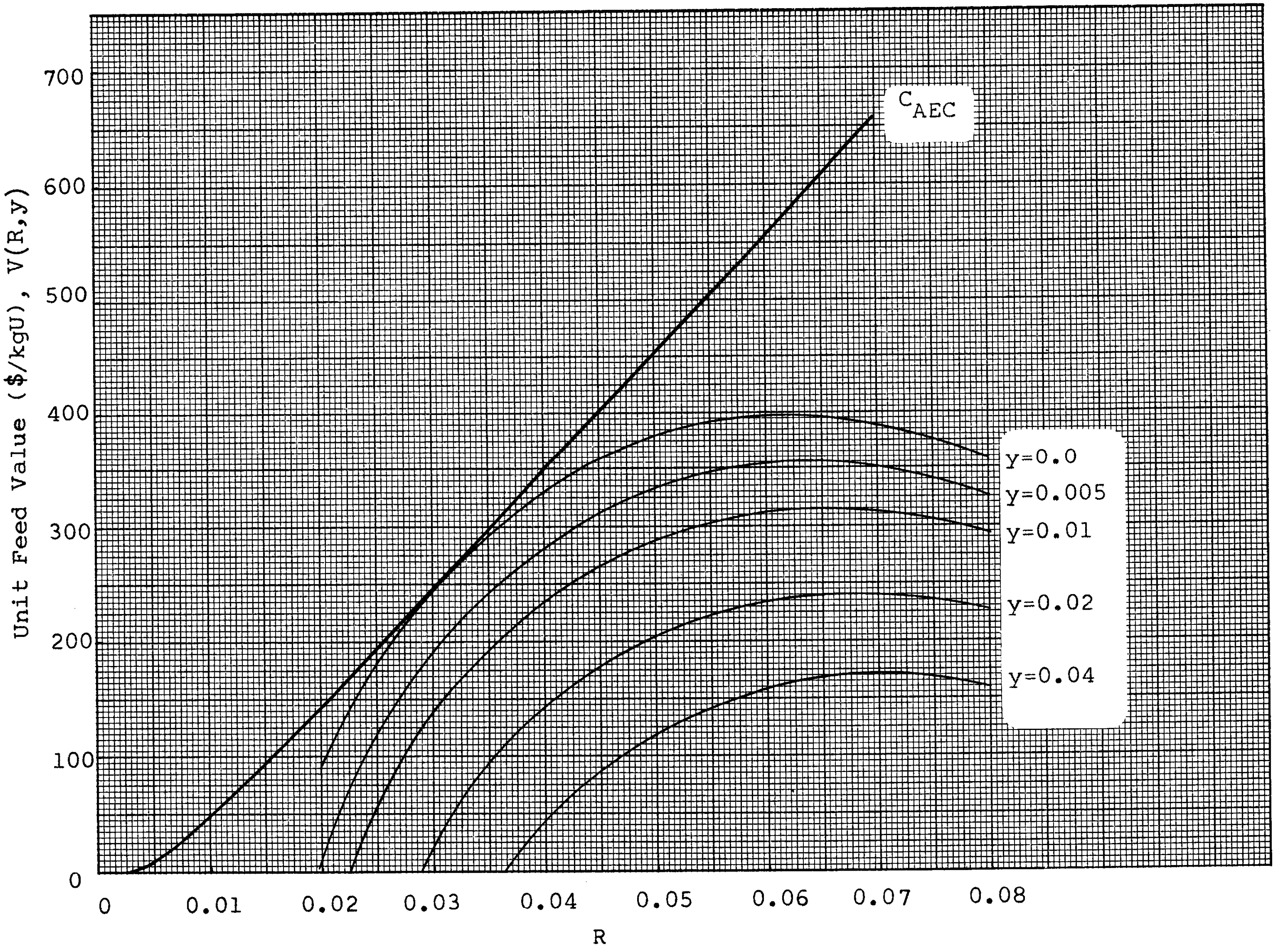


FIGURE VI.9 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, C_N = $0/g, High Costs, L_F = 0.01

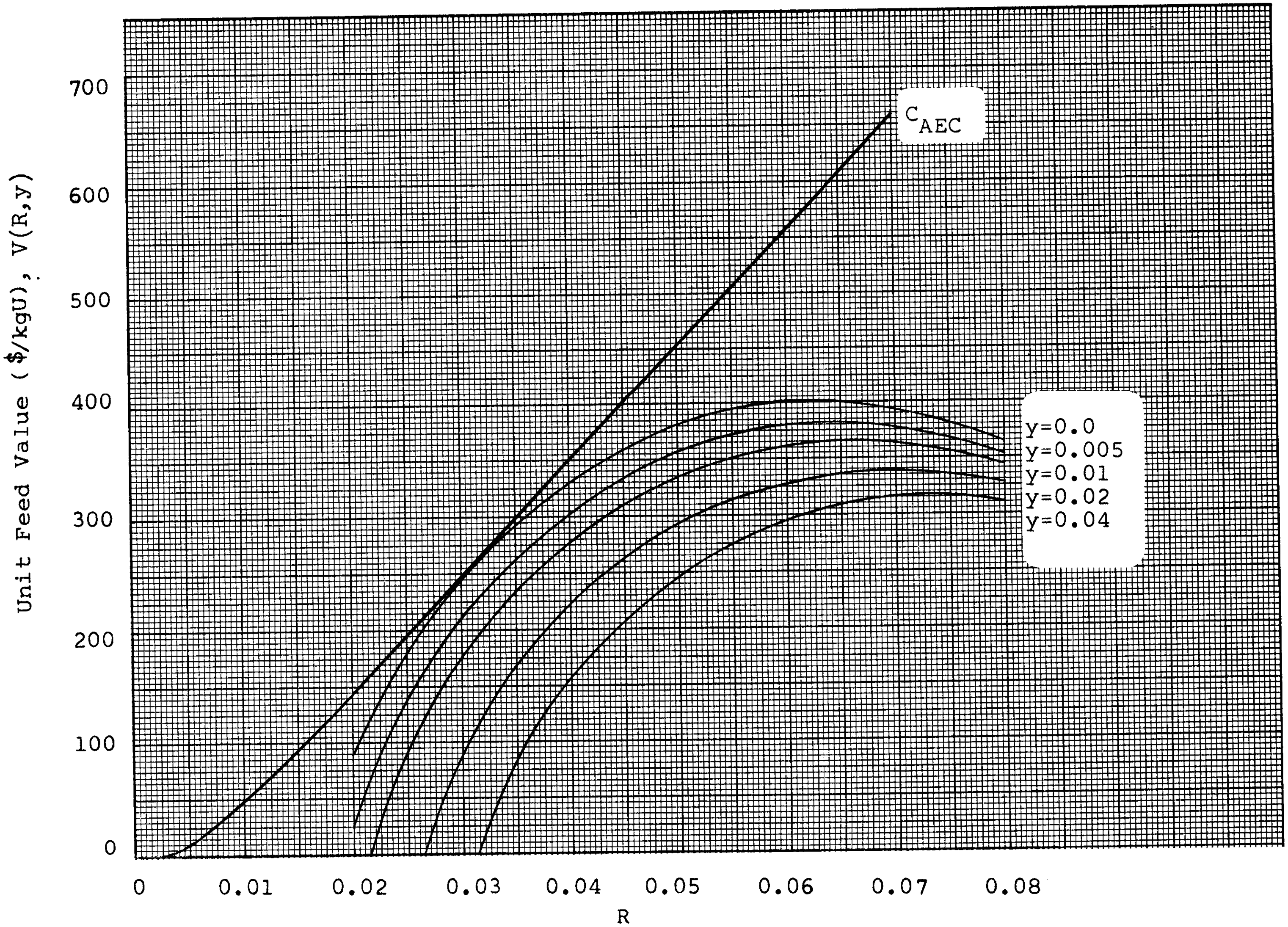


FIGURE VI.10 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$20/g, High Costs, L_F = 0.01

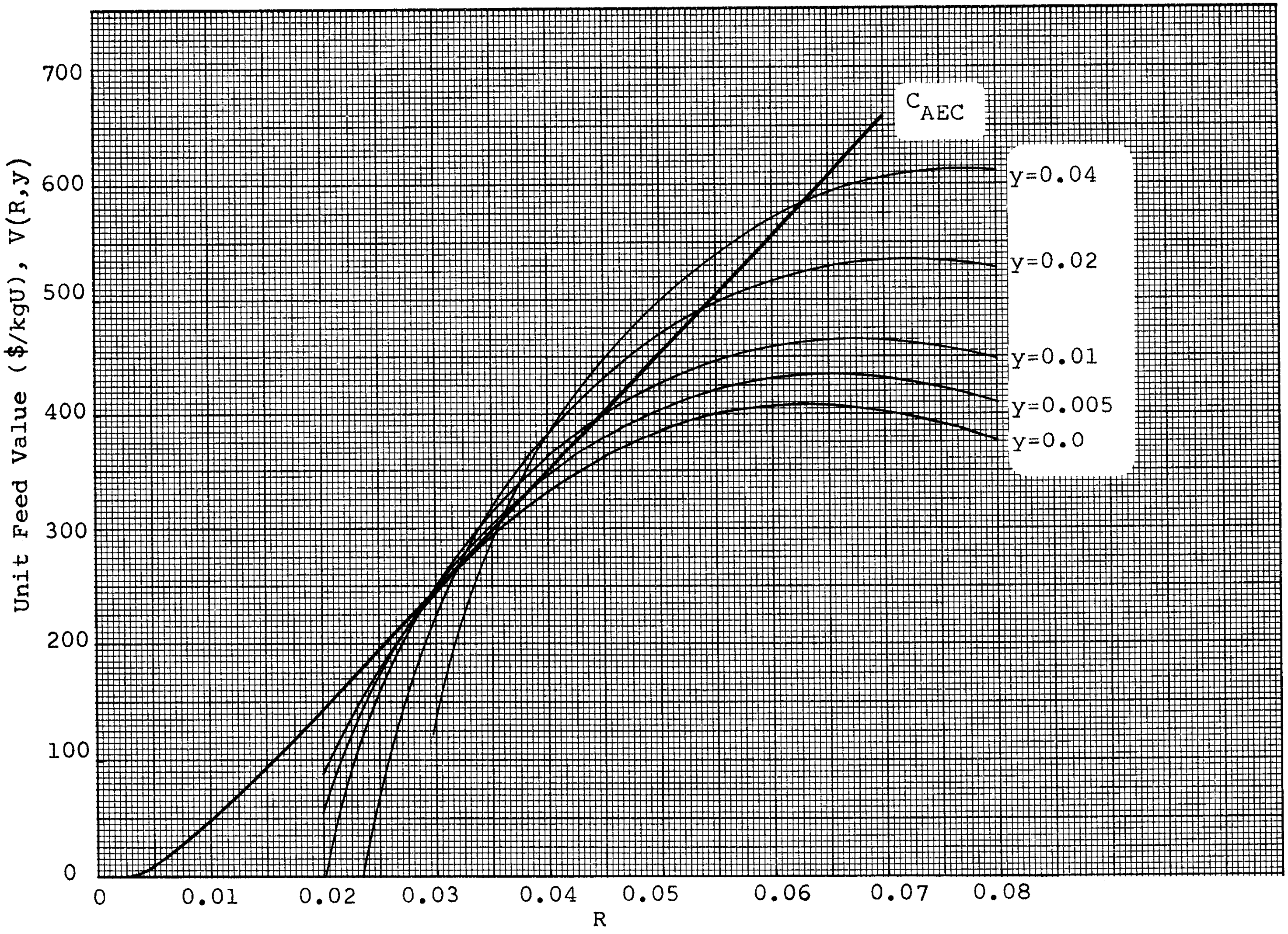


FIGURE VI.11 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, C_N = $60/g, High Costs, L_F = 0.01

Statements made for the recycle-to-fabrication case concerning the effects of a U_3O_8 price change and a unit cost reduction apply here as well. These results are shown for the present recycle scheme in Figures VI.12 and VI.13, respectively. The effect of reduced fabrication losses on feed value is insignificant here.

C. Uranium Values for Modified Modes of Operation

The fact that all the feed value curves for the basic recycle schemes demonstrate a dropoff toward zero value at both ends of the R-range indicates that modification of the feed composition prior to its use in the basic flowsheets could improve the unit value at many of the (R,y) points. This is particularly true for feed having so low an R that reactor operation cannot be sustained unless feed is first pre-enriched.

The maximum unit value of feed uranium has been calculated over the entire range of R[depleted (R = 0.005) to fully enriched (R = 15)] for various U-236 concentrations, for both basic recycle schemes, and for the following cases: all combinations of $C_{U_3O_8}$ = \$6, \$8, \$10/lb with C_N = \$0, \$60/g for L_F = 0.01 and high unit costs, as well as C_N = \$100/g for $C_{U_3O_8}$ = \$8/lb; $C_{U_3O_8}$ = \$8/lb and C_N = \$0, \$60/g for L_F = 0.01 and low unit costs; and, for the recycle-to-fabrication scheme only, $C_{U_3O_8}$ = \$8/lb and C_N = \$0/g for L_F = 0.002

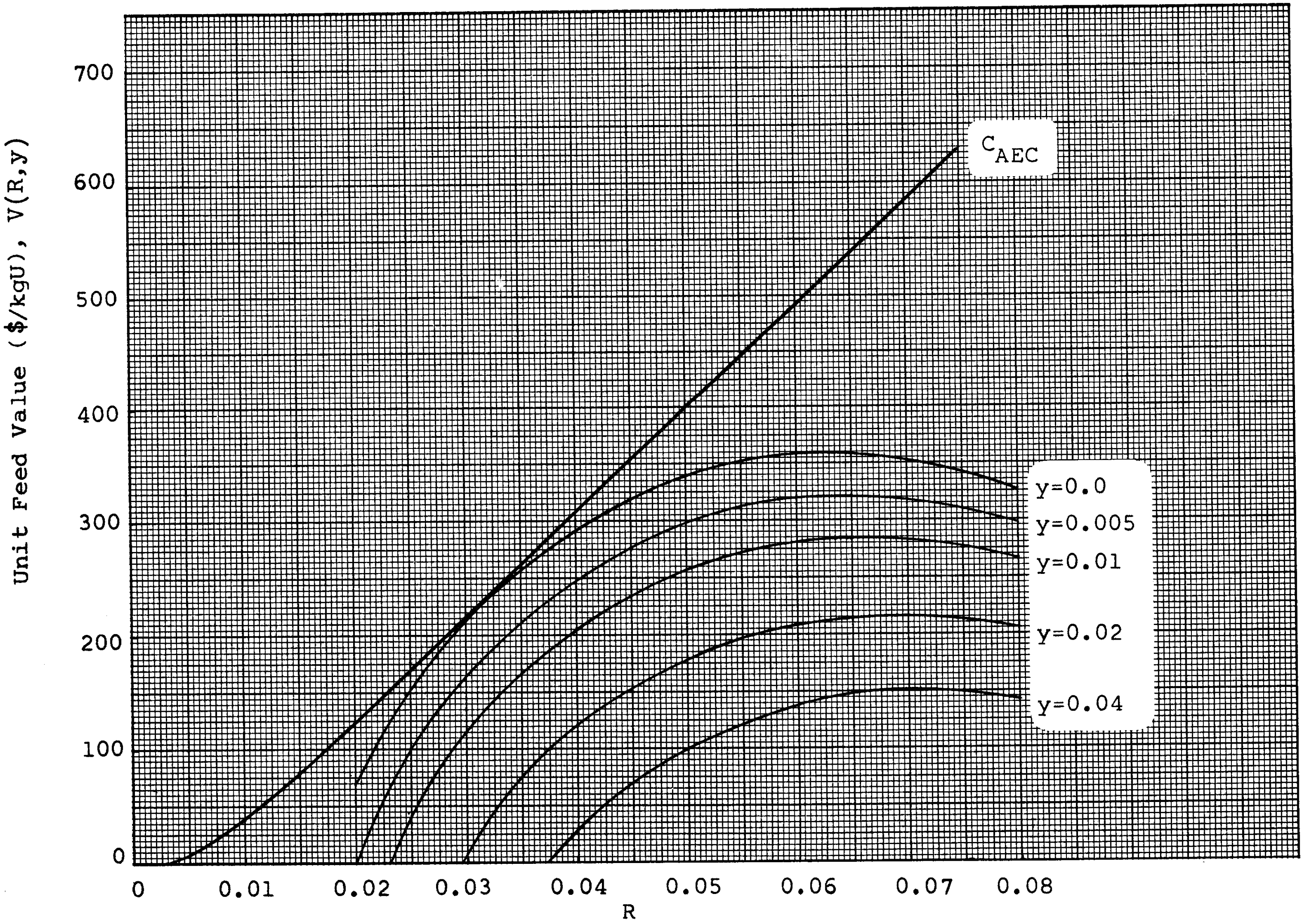


FIGURE VI.12 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = $6/lb, C_N = $0/g, High Costs, L_F = 0.01

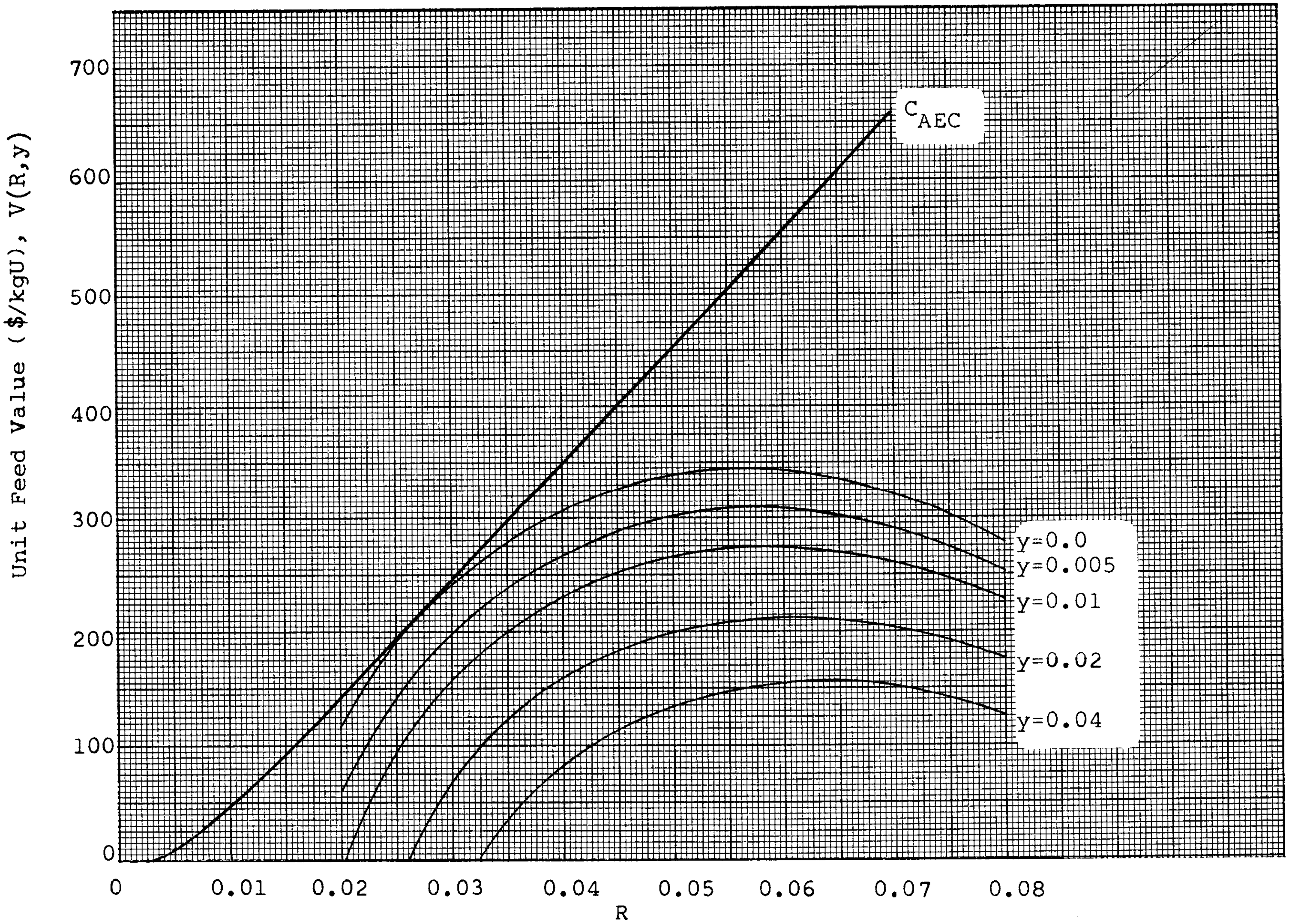


FIGURE VI.13 Unit Feed Value - Basic Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, Low Costs, L_F = 0.01

and high unit costs. In Appendix I, detailed unit value results are given and, at each (R,y) point, indication is made as to which mode of operation - pre-enrichment by gaseous diffusion, basic recycle scheme, or blending with natural uranium - yields the largest unit value. Optimized operating conditions are given when $V_B(R,y)$ and $V_D(R,y)$ are listed.

1. Maximization of Unit Value

a. Pre-Enrichment by Gaseous Diffusion

One important characteristic of the results for $V_D(R,y)$ is that the value of feed containing no U-236 is less than the corresponding price on the AEC scale for any R. This can be shown as follows. The general expression given by Equation V.8 for the value of the feed stream can be re-written with y, hence y_D as well, set to zero:

$$F_D V_D(R,0,R_D) = \frac{1}{1 + it_C}[(1-it_E)FV(R_D,0)-F_D C_{CT}-\Delta_D C_\Delta]. \tag{VI.7}$$

When $y = y_D = 0$, the separative work requirement is just the difference in the total value of the product and feed streams, based on the AEC price scale(12), or

$$\Delta_D C_\Delta = FC_{AEC}(R_D) - \frac{F_D}{1 + L_C}C_{AEC}(R). \tag{VI.8}$$

Inserting Equation VI.8 into Equation VI.7 and rearranging terms gives:

$$C_{AEC}(R) - V_D(R,0,R_D) = \frac{F}{F_D(1+it_C)}\left\{C_{AEC}(R_D)-V(R_D,0)[1-it_E]\right\}$$
$$+ \frac{C_{CT}}{1 + it_C} + C_{AEC}(R)[1 - \frac{1}{(1+it_C)(1+L_C)}] \qquad \text{(VI.9)}$$

Since $V(R_D,0)$ can never be greater than $C_{AEC}(R_D)$, the quantity in the curved braces of Equation VI.9 must be positive for any R_D; hence, for a specified R, $C_{AEC}(R)$ is greater than $V(R,0,R_D)$ for any value of R_D, including the optimum R_D. This leads to the inequality mentioned above,

$$V_D(R,0) < C_{AEC}(R), \text{ for all R.} \qquad \text{(VI.10)}$$

For $y = y_D = 0$ and for a specified R, Equation VI.9 indicates that $V_D(R,0,R_D)$ is maximized when R_D is such that the quantity

$$\frac{F}{F_D}\left\{C_{AEC}(R_D) - V(R_D,0)[1-it_E]\right\}$$

is a minimum. Since $(1-it_E)$ is about 0.975, the optimum R_D can be expected to be very close to R^*. Figure VI.14 shows the variation of $V_D(R,0,R_D)$ with R_D for $R = 0.01$ in the case of recycle to a diffusion plant. The optimum R_D is 0.0309, which is R^* for the case shown. Results for the same case but with $y = 0.005$ are also given in Figure VI.14. With the increase in y, the optimum R_D increases to about 0.0365 since the presence of U-236 in the diffusion plant product stream necessitates a higher R_D in order to assure a reasonably

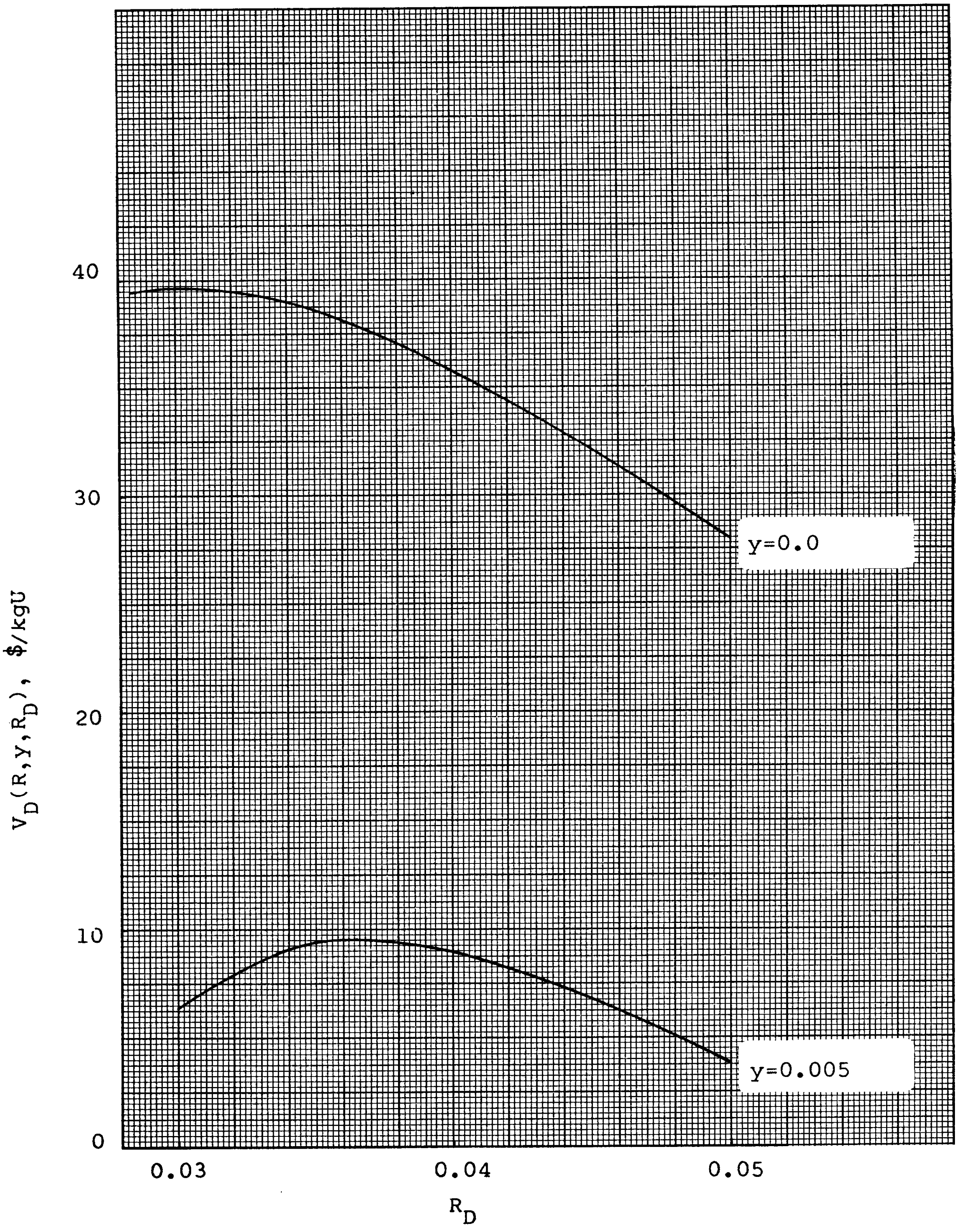


FIGURE VI.14 Variation of $V_D(R,y,R_D)$ with R_D and y for R=0.01 - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.01

high $V(R_D,y_D)$.

b. Blending with Natural Uranium

The location of the line for y=0 relative to the AEC price scale is one important characteristic of the $V_B(R,y)$ results. Some insight is provided by Figure VI.15, which shows the AEC scale for $C_{U_3O_8} = \$8/lb$ and the y=0 line for the basic recycle-to-diffusion-plant scheme, both plotted as functions of x, the weight fraction of U-235 in feed uranium. Note that x is used here rather than R since blending processes are more amenable to description in terms of x, since the "tie-line" representation of blending yields a straight line when weight fractions are used.

Since we seek the conditions which give the maximum unit value of feed having x greater than x*, where $x^* = \frac{R^*}{1 + R^*}$, the procedure is to anchor the lower end of the tie-line at C_{NAT}, i.e., at $C_{AEC}(x_{NAT})$, and to draw the straight line (the dashed line in the figure) having maximum slope which touches the basic feed value curve V(x,0) at some point. If the point of contact between tie-line and basic value curve occurs at x_o, then $V(x_o,0)$ is the unit value of product obtained by mixing natural uranium with uranium having $x > x_o$ and having a unit value given by the tie-line of greatest slope. It is apparent that the maximum attainable

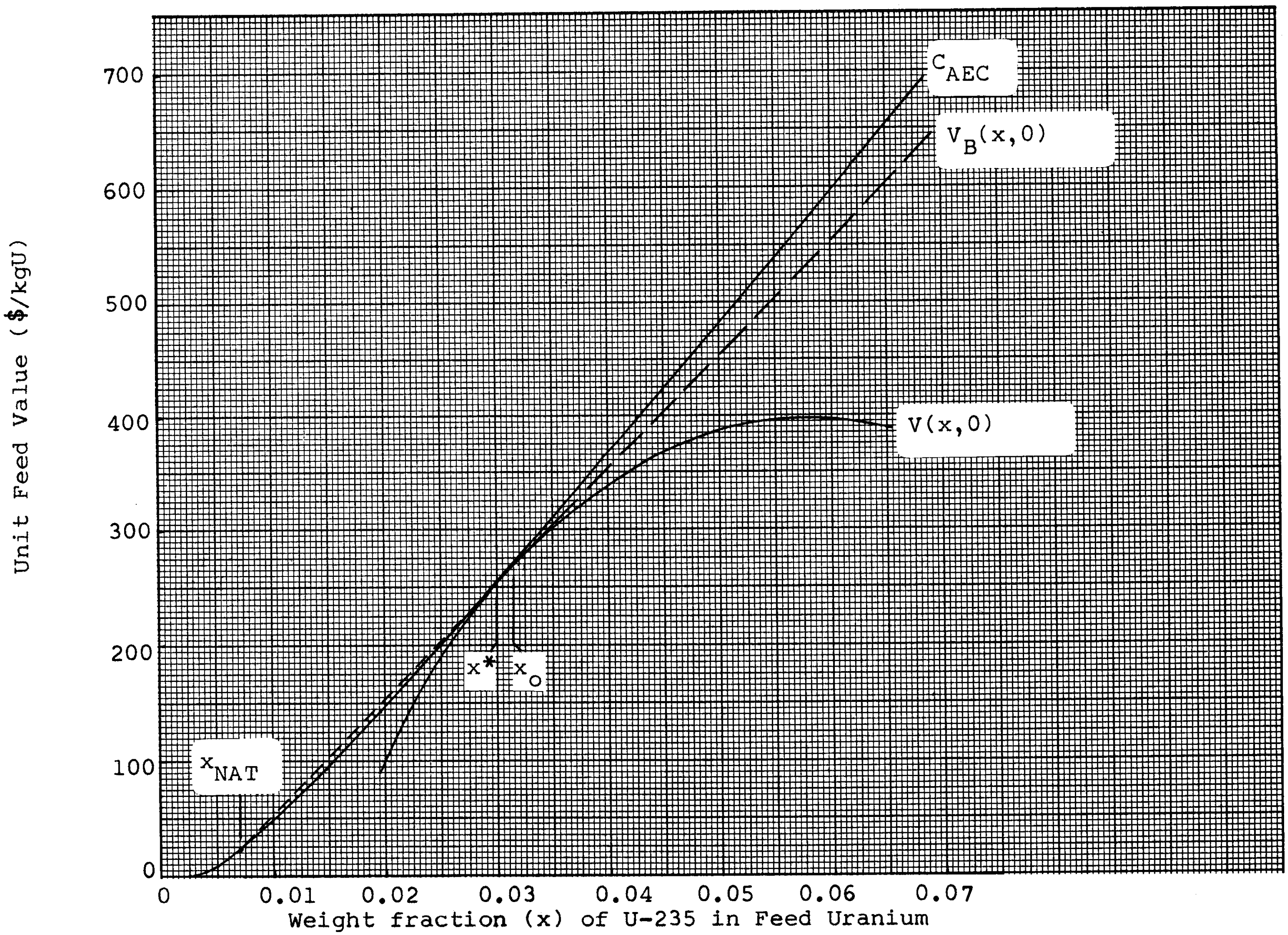


FIGURE VI.15 Tie-Line Representation of Blending with Natural Uranium-Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, C_N = $0/g, High Costs, L_F = 0.01

unit value for any x greater than x_o will lie along the line of maximum slope. Blending to a point other than x_o will lead to a lower unit feed value. For $x \leqslant x_o$, the maximum unit value is obtained by not blending at all, i.e., by keeping the upper end of the tie-line on the $V(x,0)$ curve, and then at low enough x, by using feed pre-enrichment. Thus, the portion of the tie-line for $x > x_o$ (long dashes) represents $V_B(x,0)$ while that for $x < x_o$ (short dashes) has no practical importance.

Due to the curvature of the AEC scale, particularly near x_{NAT}, x_o is somewhat greater than x^* ($x_o = 0.0315$ and $x^* = 0.0300$ for the case shown); however, when x^* is in the range obtained for recycle-to-fabrication (between 0.3 and 0.4), the curvature near x_{NAT} becomes less important and x_o effectively equals x^*.

The optimum fraction of natural uranium in the blended product can be written from the tie-line as

$$\epsilon = \frac{x - x_o}{x - x_{NAT}}, \text{ for } x \geqslant x_o .$$

Thus, as x increases, ϵ also increases and more natural uranium is required for blending; as a result, the loss in value due to mixing streams of different U-235 content becomes greater with increasing x and the $V_B(x,0)$ line diverges from the AEC scale. The corresponding $V_B(R,0)$ line behaves the same way, of course.

Close agreement was obtained between $V_B(x,0)$, ϵ, and x_o values obtained graphically and those obtained from the analytical procedure wherein ϵ is varied to obtain optimum conditions. This agreement insures the applicability of the general procedure to cases where $y > 0$, which are not amenable to simple geometrical investigation. When $y > 0$, the optimum composition of the blended product is still that which maximizes the tie-line slope, but the added complication is that each (R,y) point must be analyzed separately since the blending operation now affects y_B as well as R_B.

It is interesting to note that, if the uranium used in blending could have any U-235 content x_M in place of x_{NAT}, the maximum tie-line slope would occur as x_M approaches x^* and would be simply the slope of the $C_{AEC}(x)$ line at x^*. Although the absolute maximum unit value of feed uranium would be obtained, the amount of feed uranium used in blending would approach zero!

c. Effect of Operating Mode on Maximum Unit Value

It has already been indicated that no single mode of operation will result in the most economically advantageous fuel cycle operation over the entire feed composition range, i.e., the mode of operation which gives the highest possible unit feed value will change as R increases from the depleted to fully-enriched condition. It will be seen that the most economically advantageous mode of operation may also change at a given R as y increases.

Figure VI.16 shows a superposition of the lines for $V_D(R,y)$, $V(R,y)$, and $V_B(R,y)$ overranges of R and y for recycle to a diffusion plant when $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, $L_F = 0.01$, and for high unit costs. At any (R,y) point, the largest of $V_D(R,y)$, $V(R,y)$ and $V_B(R,y)$ is defined as $V_m(R,y)$ and represents the maximum unit price which could be paid for this feed without incurring a fuel cycle cost greater than C_E^* when uranium is recycled according to the scheme being considered. In comparing Figure VI.16 with the basic value curves of Figure VI.9, the most striking difference is that lines representing $V_m(R,y)$ increase monotonically with R for each y-value and lie much closer to the AEC scale when R is far from R*. As R increases from the low to high ends of the range, at constant y, the operating modes which yield $V_m(R,y)$ change. For low R values, it is advantageous to pre-enrich feed in a diffusion plant, but as R increases it becomes economically advantageous to operate according to the basic recycle flowsheet. As y increases, the intersection between $V_D(R,y)$ and $V(R,y)$ occurs at higher R, reflecting the increased poisoning due to U-236 and the resulting need to increase the U-235 content of uranium fed to fabrication in order to maintain reasonable burnup. Finally, after a rather narrow range in R over which basic recycle operation gives $V_m(R,y)$, it becomes

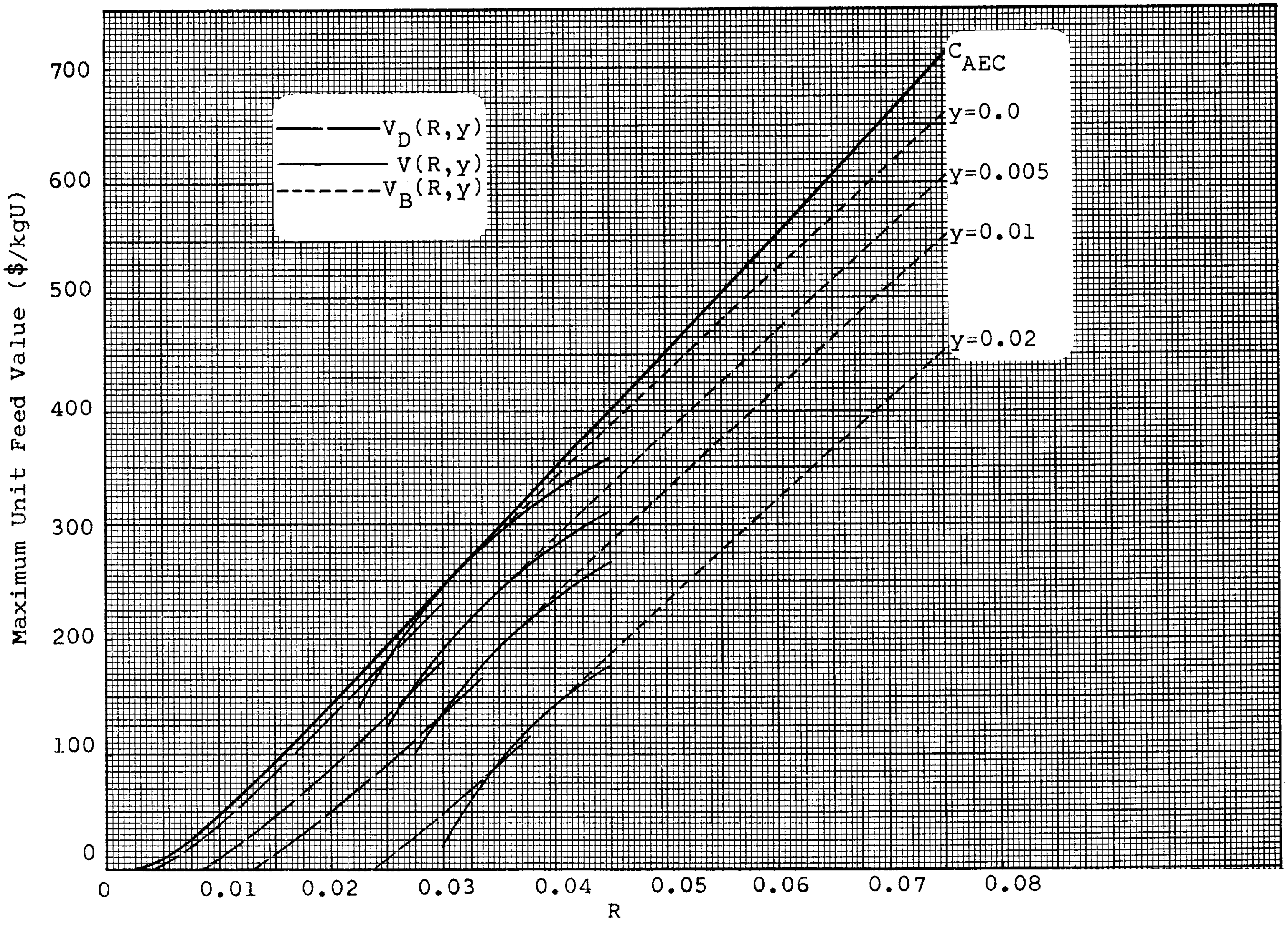


FIGURE VI.16 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8} = \$8/\text{lb}$, $C_N = \$0/\text{g}$, High Costs, $L_F = 0.01$

advantageous to blend feed with natural uranium for the remainder of the R range, although for points immediate to the intersection of V(R,y) and $V_B(R,y)$ the amount of natural uranium required for blending is so small that blending might not actually be practical. Results for $V_B(R,y)$ are given in Appendix I for R up to 15, but the graph was terminated at R = 0.08 for convenience.

Figure VI.17 shows how an increase from C_N = \$0/g to C_N = \$60/g affects the results of Figure VI.16. Only the lines for y=0 and y=0.02 are shown in Figure VI.17 since all lines are so closely spaced, but it is apparent that for C_N = \$60/g the presence of U-236 increases maximum feed value over the entire range of R. This might be questioned since the y = 0.02 line for $V_D(R,y)$ is terminated at R = 0.02 but the enlarged view of the low-R range shown in Figure VI.18 shows that the y = 0.005 line lies above the y=0 line everywhere and the same can be expected for y = 0.01 and y = 0.02. At the tails abundance ratio of R = R_W = 0.0025372, the unit feed value must be negative for all y. The lines for y = 0.01 and y = 0.02 were terminated because extension to lower R would have led to y_D being greater than 0.04 and would have required extrapolation of the basic value results, V(R,y), which extend only up to y = 0.04.

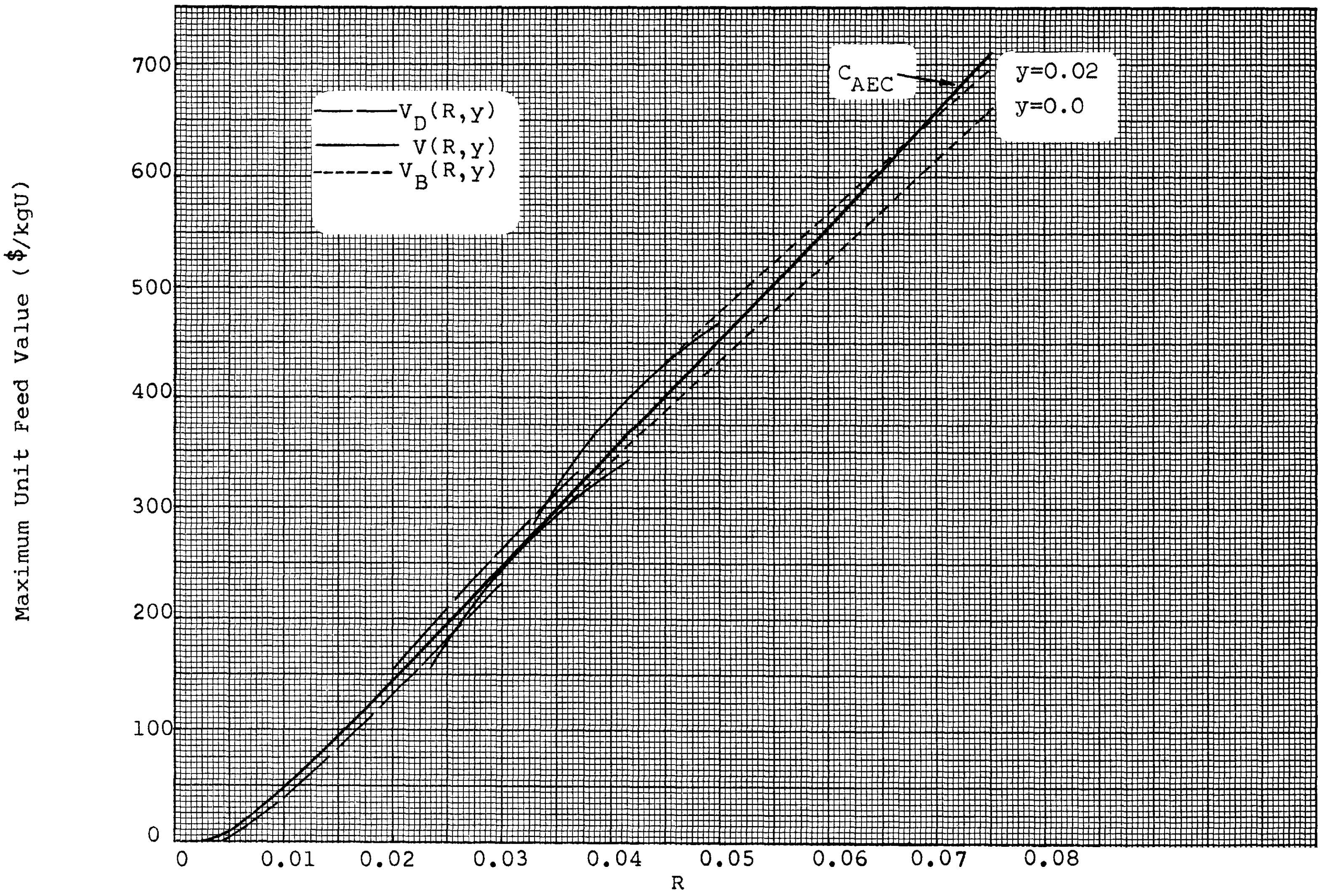


FIGURE VI.17 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$60/g, High Costs, L_F = 0.01

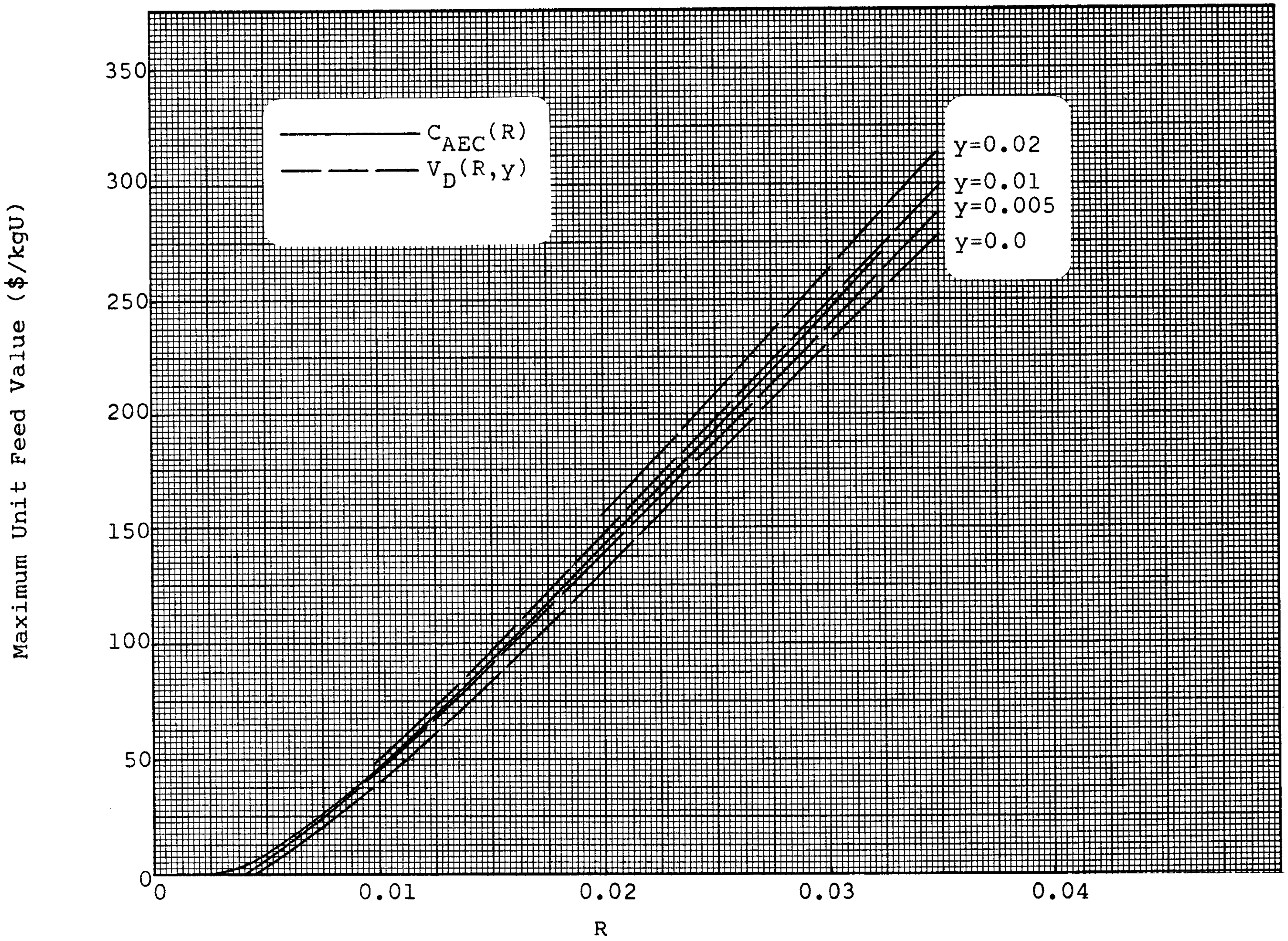


FIGURE VI.18 Maximum Unit Feed Value at Low R - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$60/g, High Costs, L_F = 0.01

The fact that the $V_m(R,y)$ lines for $y > 0$ now lie above the y=0 line represents a drastic change from the intersecting basic value lines of Figure VI.11. The sharp dropoff of the feed value lines for $y > 0$ at low R, caused by excessive U-236 poisoning and resulting low burnups, is averted by pre-enriching the feed to a level suitable for maintaining high burnup.

Intersection of $V(R,y)$ with $V_B(R,y)$ occurs at higher R for C_N = \$60/g than for \$0/g, since $V(R,y)$ has been shown to increase with C_N more rapidly as R increases, thus making it economically advantageous to operate according to the basic recycle scheme over a wider range of R at C_N = \$60/g.

An important observation is that the change in $V_m(R,0)$ when C_N increases from \$0/g to \$60/g is less than 0.5% over the entire R range - from 0.005 to 15 - as can be seen from the tabulated results in Appendix I.

Although we have illustrated the effect of operating mode on unit feed value by using recycle-to-diffusion-plant results, the trends indicated are similar for recycle to fabrication with minor differences which will be pointed out in the next section.

2. Recycle to Fabrication

In Figures VI.19, VI.20, and VI.21, results corresponding to C_N = \$0, \$60, and \$100/g are given for

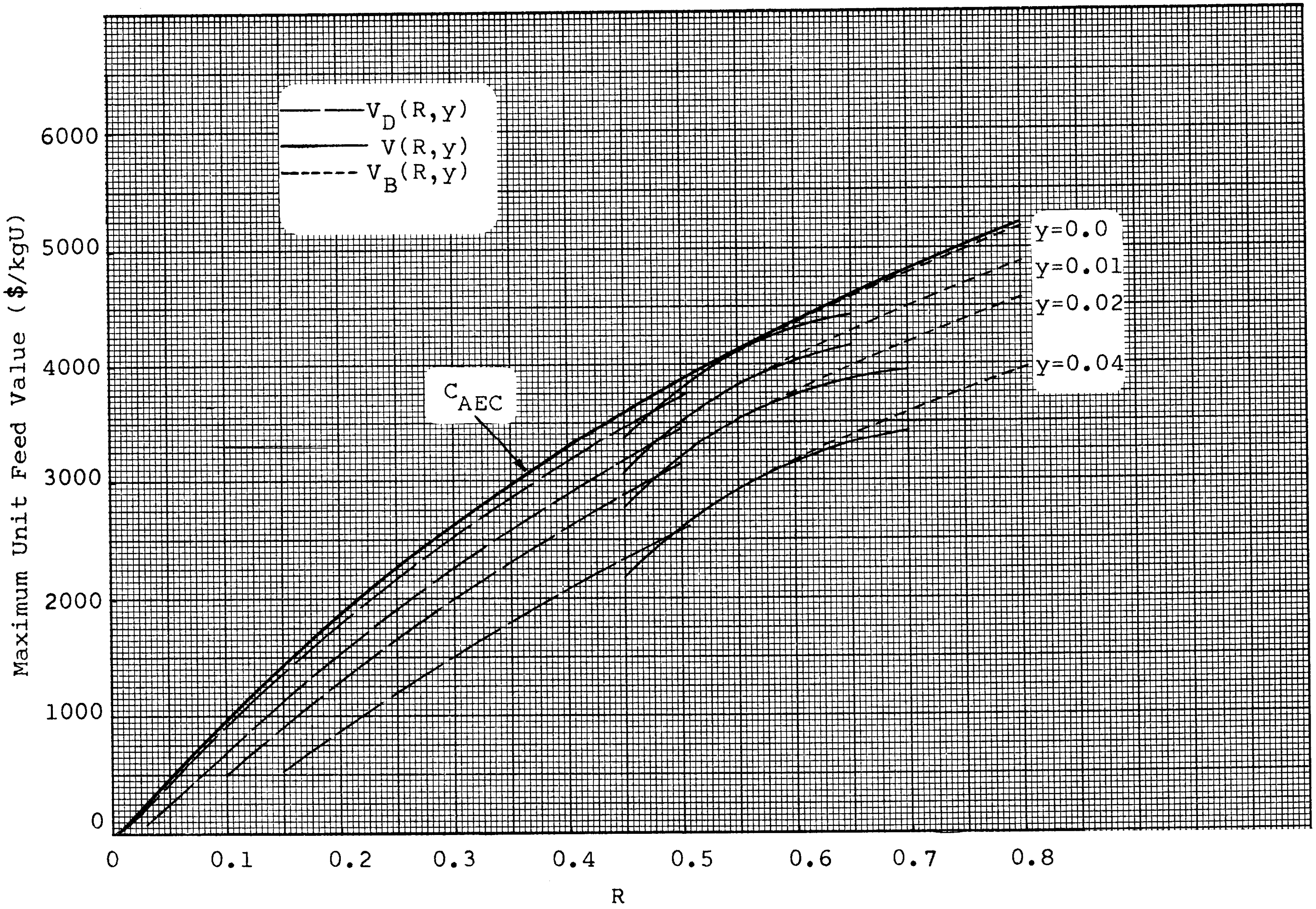


FIGURE VI.19 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, C_N = $0/g, High Costs, L_F = 0.01

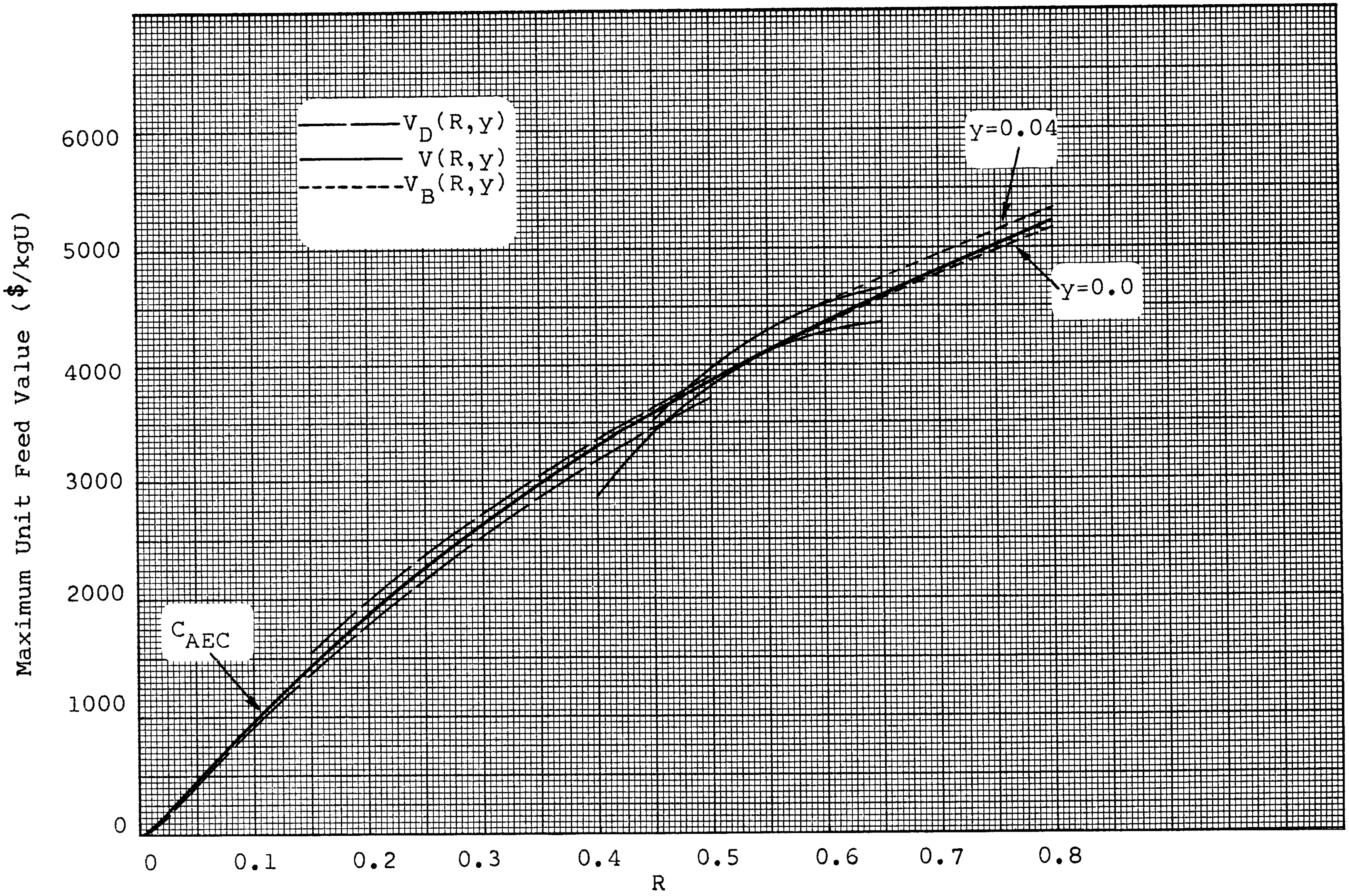


FIGURE VI.20 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, C_N = $60/g, High Costs, L_F = 0.01

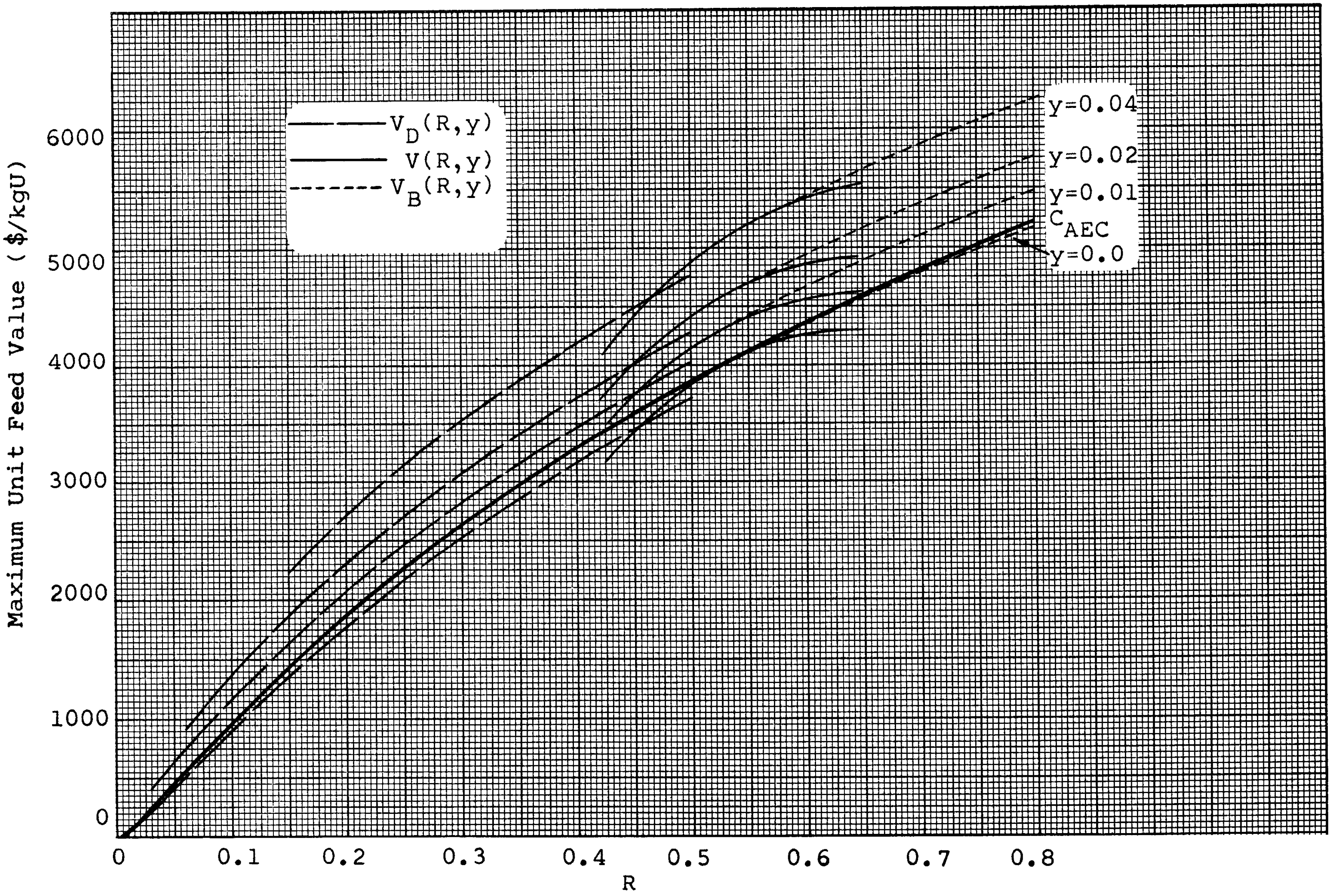


FIGURE VI.21 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$100/g, High Costs, L_F = 0.01

the three modes of operation when $C_{U_3O_8}$ = \$8/lb, L_F = 0.01, and for high unit costs. The shift of R* to much higher values than for the recycle-to-diffusion-plant case makes it economically advantageous to utilize the pre-enrichment mode over a much wider range of R when using this recycle scheme; however, the position of the basic value curves at such high R-values reduces the range over which $V_m(R,y)$ is obtained by blending with natural uranium.

As before, the lines for $y > 0$ were terminated at the low-R end in order to avoid extrapolation of the basic value tables, which in this case extended up to $y = 0.10$. However, at C_N = \$60/g, it is apparent from Figure VI.20 and from the enlarged view of the low-R range shown in Figure VI.22 that the presence of U-236 increases the maximum attainable feed value over the entire range of R for the values of y considered. Figure VI.21 shows how an increase of C_N to \$100/g leads to even greater enhancement of feed value when U-236 is present in increasingly high concentrations.

The shifts in the intersection points between $V(R,y)$ and $V_B(R,y)$ as C_N increases are not so apparent for this recycle scheme, since R* becomes smaller with increasing C_N and since $V(R,y)$ does not show strong preferential increase with increasing R.

As in the recycle-to-diffusion-plant case, the change in $V_m(R,0)$ when C_N changes from \$0/g to \$100/g

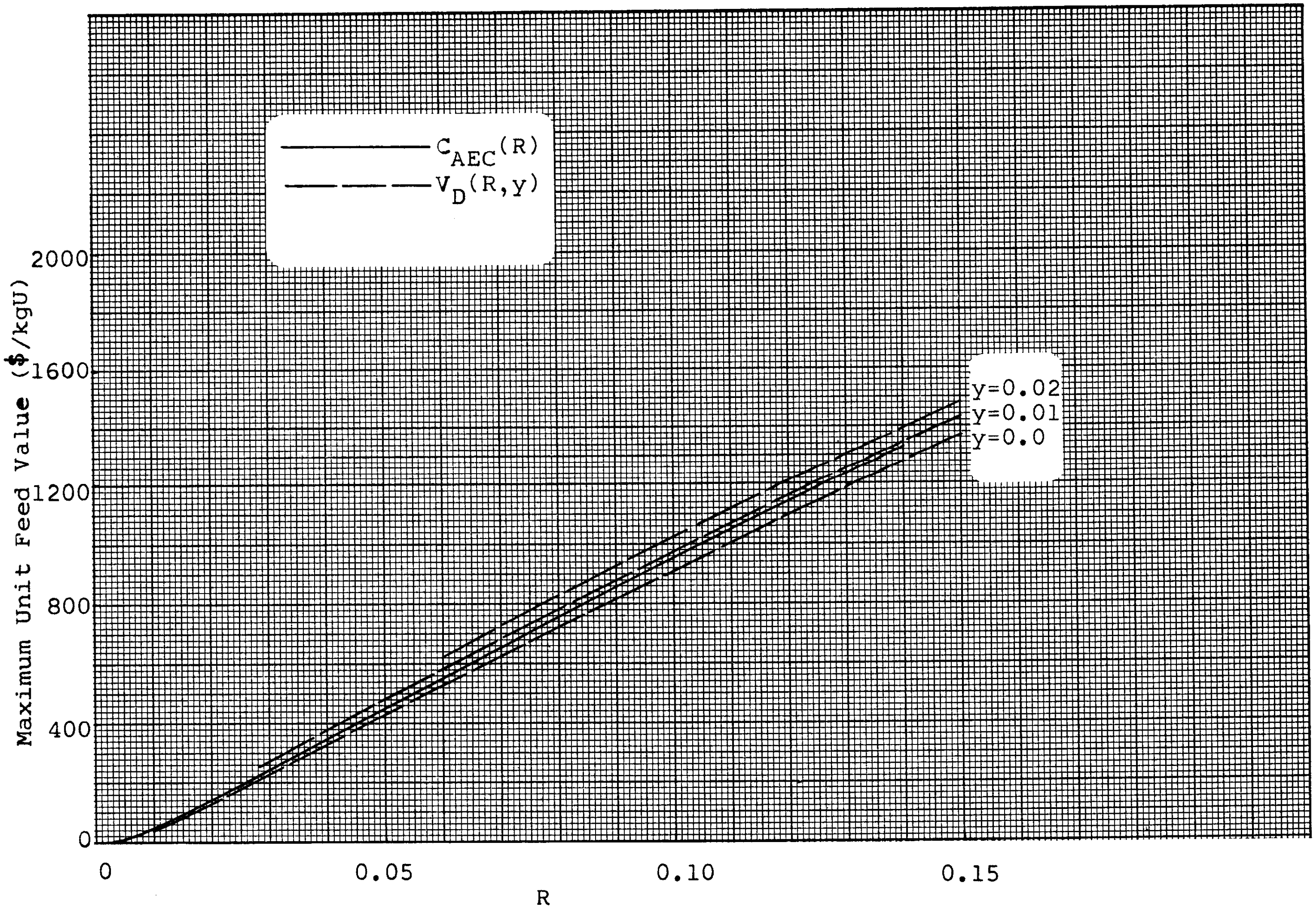


FIGURE VI.22 Maximum Unit Feed Value at Low R-Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, C_N = $60/g, High Costs, L_F = 0.01

at constant R is very small - less than 1.0% near R* and less than 0.2% for all other R.

When $C_{U_3O_8}$ is changed from \$8/lb to \$6/lb and to \$10/lb, with C_N = \$0/g, the results are shown in Figures VI.23 and VI.24, respectively. Figure VI.25 shows results for the low unit cost condition, again at C_N = \$0/g. These results exhibit the same trends and have differences caused only by changes in R* and by general upward or downward shifts caused by the effect of $C_{U_3O_8}$ on the AEC price scale. When fabrication losses are 0.002 instead of 0.01, the increase of R* leads to a shift of the V(R,y) curves to higher R and the desirability of pre-enriching feed over a wider range of R. This is indicated in Figure VI.26, for the high unit cost condition, $C_{U_3O_8}$ = \$8/lb, and C_N = \$0/g.

3. Recycle to Diffusion Plant

Figures VI.16 and VI.17 showed results for $V_D(R,y)$, V(R,y), and $V_B(R,y)$ for C_N = \$0/g and \$60/g when $C_{U_3O_8}$ = \$8/lb, L_F = 0.01, and for high unit costs. The corresponding results for C_N = \$100/g are shown in Figure VI.27, which indicates the significant increase in the feed value at all R as the U-236 content becomes greater. The range of R over which it is economically advantageous to operate according to the basic recycle flowsheet is wider at C_N = \$100/g than for either C_N = \$0/g or C_N = \$60/g and becomes wider

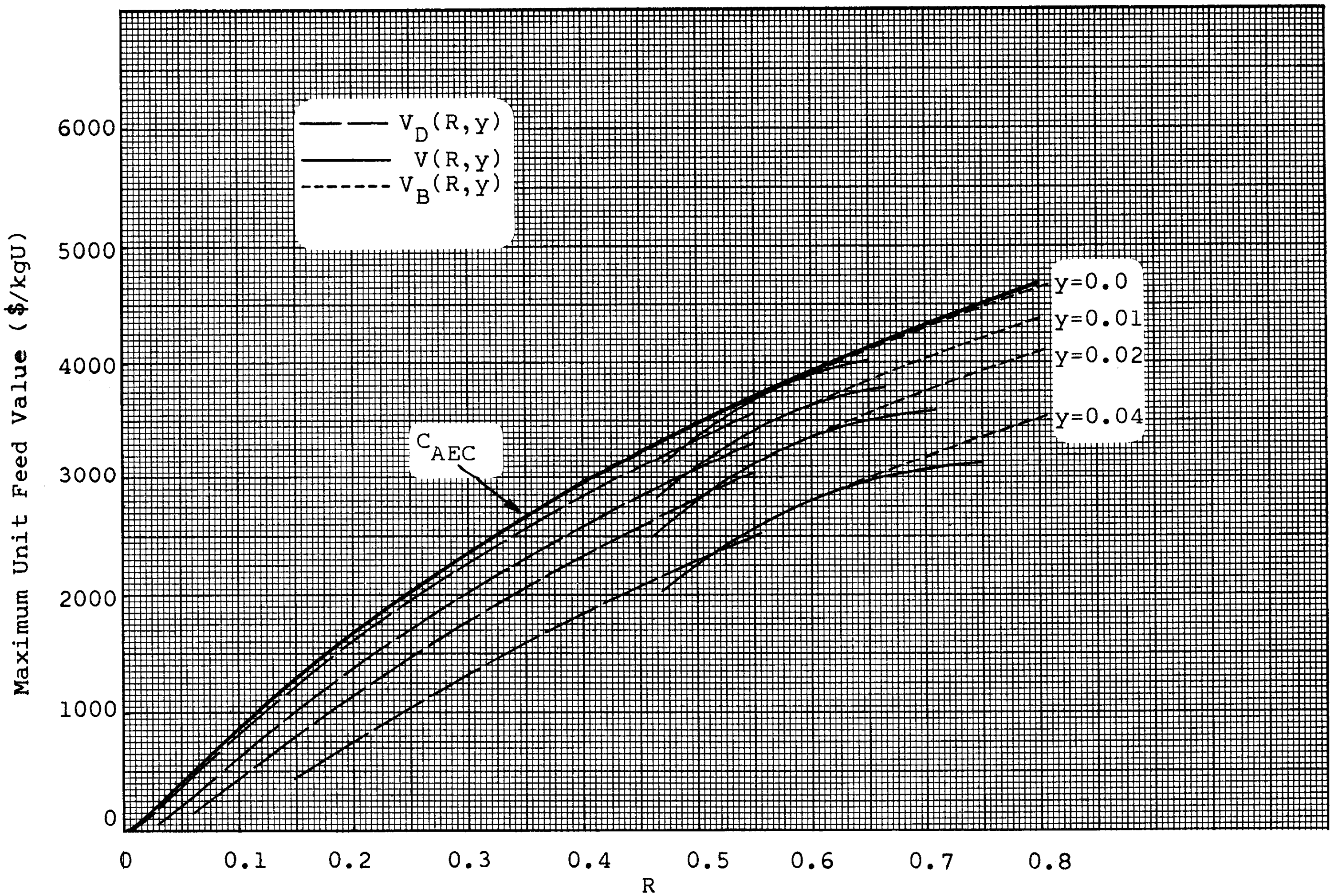


FIGURE VI.23 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$6/lb, C_N = \$0/g, High Costs, L_F = 0.01

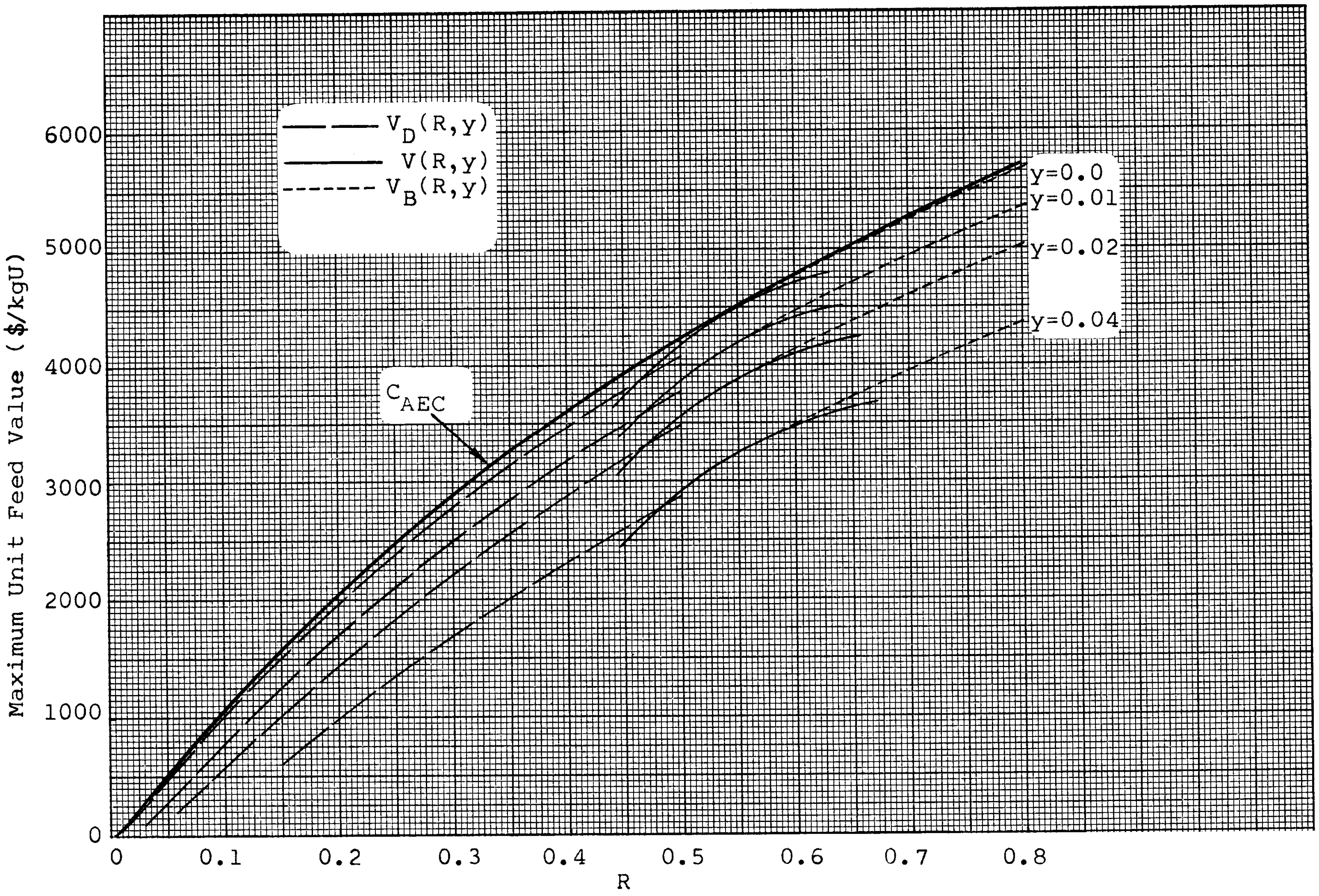


FIGURE VI.24 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$10/lb, C_N = \$0/g, High Costs, L_F = 0.01

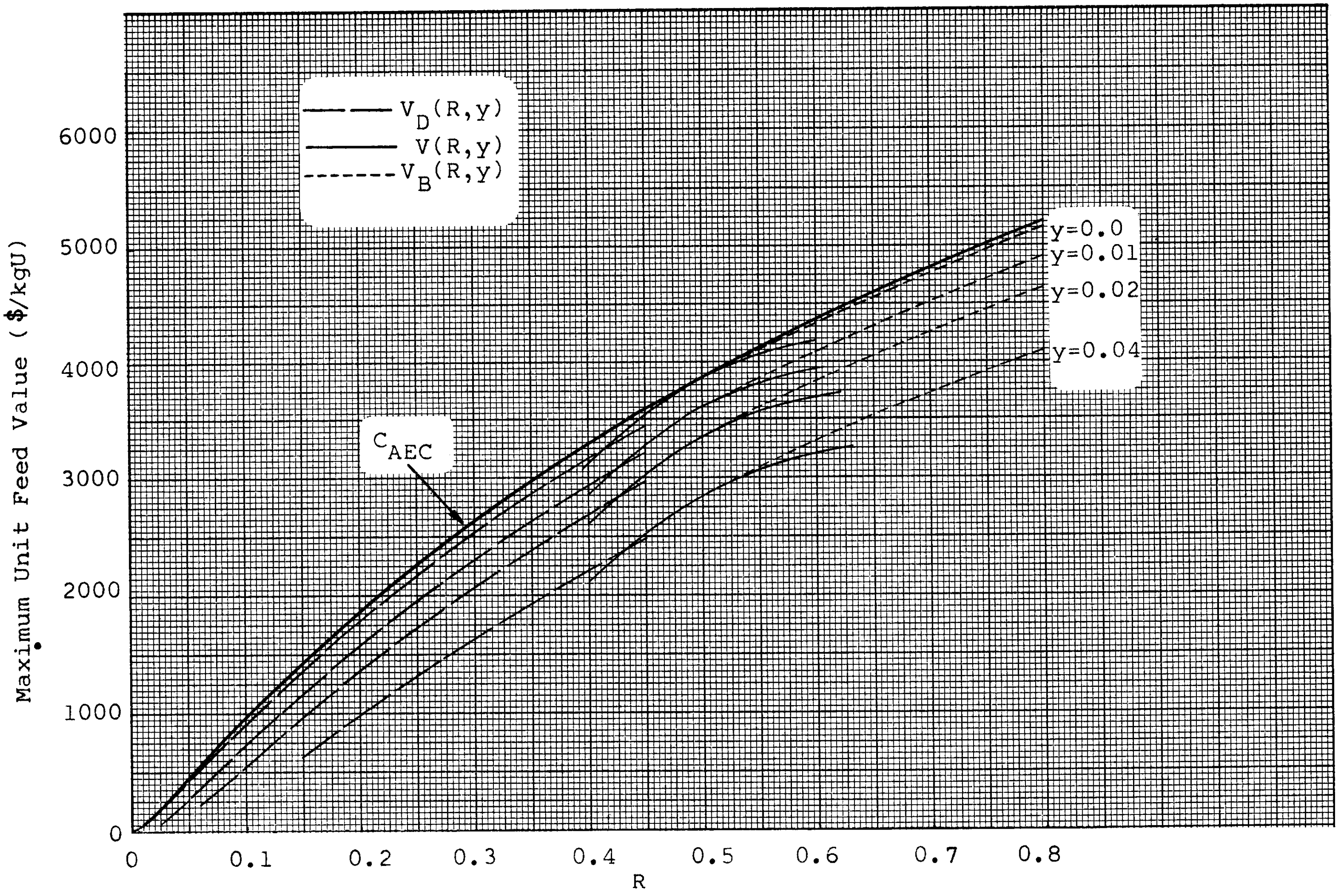


FIGURE VI.25 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, Low Costs, L_F = 0.01

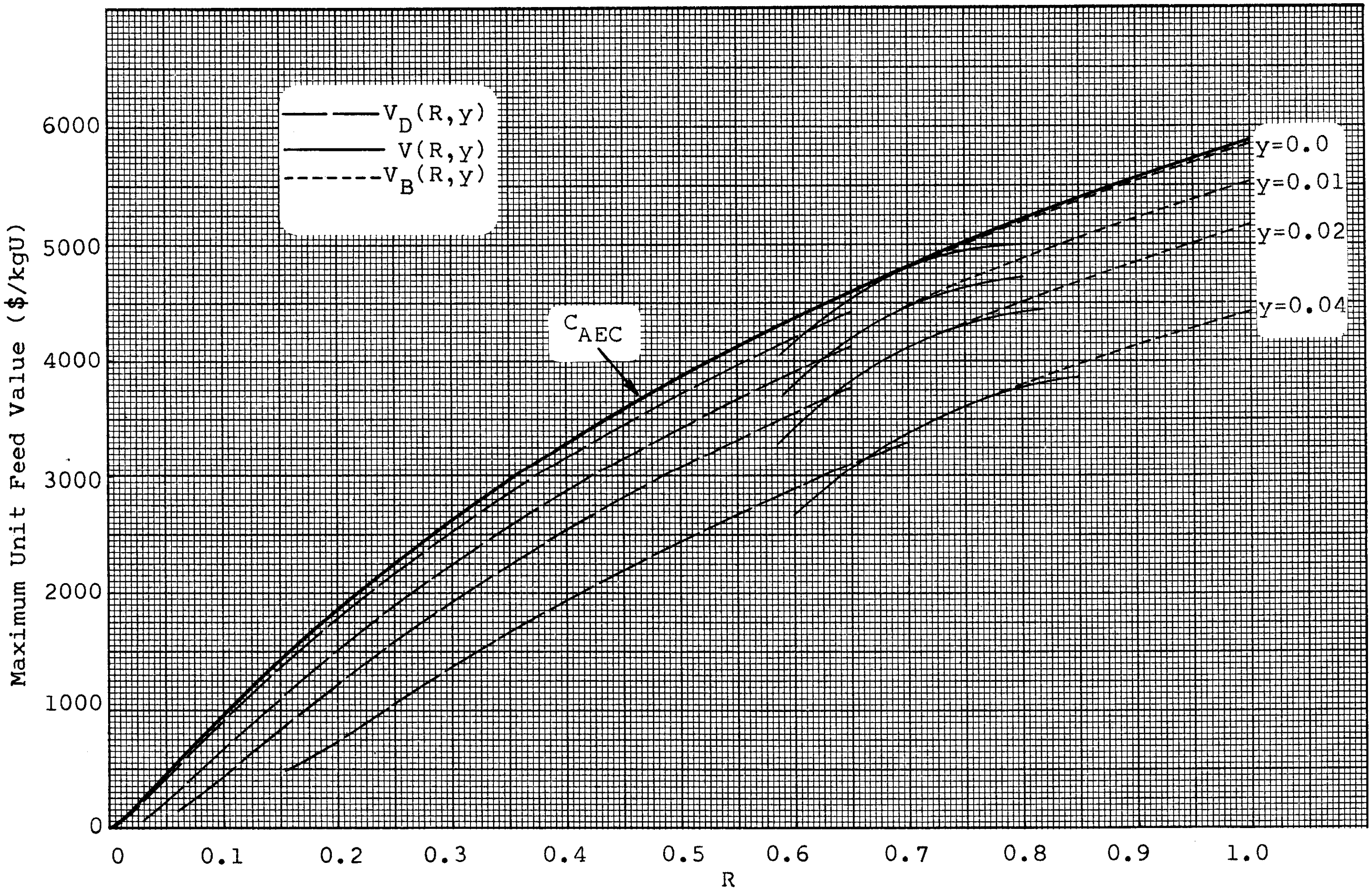


FIGURE VI.26 Maximum Unit Feed Value - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.002

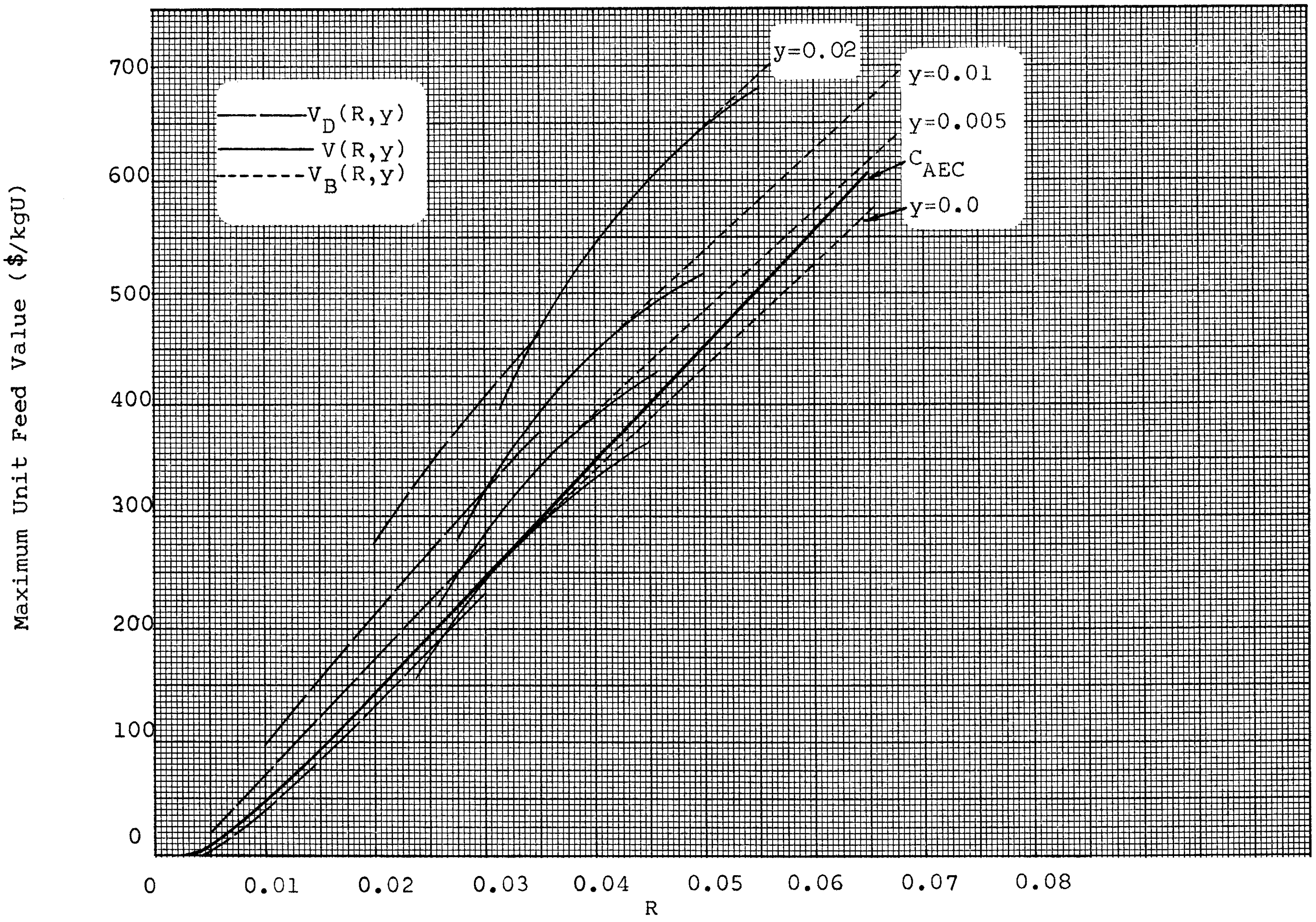


FIGURE VI.27 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$100/g, High Costs, L_F = 0.01

as y increases at C_N = \$100/g.

Changes in the price of U_3O_8 and the unit cost condition shift R* and the general position of the V(R,y) results, but do not affect the general trends described previously. Results for $C_{U_3O_8}$ = \$6/lb and \$10/lb, with C_N = \$0/g and high unit costs, are shown in Figures VI.28 and VI.29, respectively, while Figure VI.30 shows results for the low unit cost condition when $C_{U_3O_8}$ = \$8/lb and C_N = \$0/g.

4. Effect of Recycle Scheme on Unit Value

The maximum value of uranium of a given isotopic composition depends strongly on the recycle scheme selected by the PWR operator. In Table VI.2 the maximum unit values of some typical feed materials when used in connection with the two recycle schemes are compared for $C_{U_3O_8}$ = \$8/lb, L_F = 0.01, high unit costs, and for both C_N = \$0/g and C_N = \$60/g. It is important to remember that R* is near 0.03 and 0.55, respectively, for recycle to a diffusion plant and to fabrication.

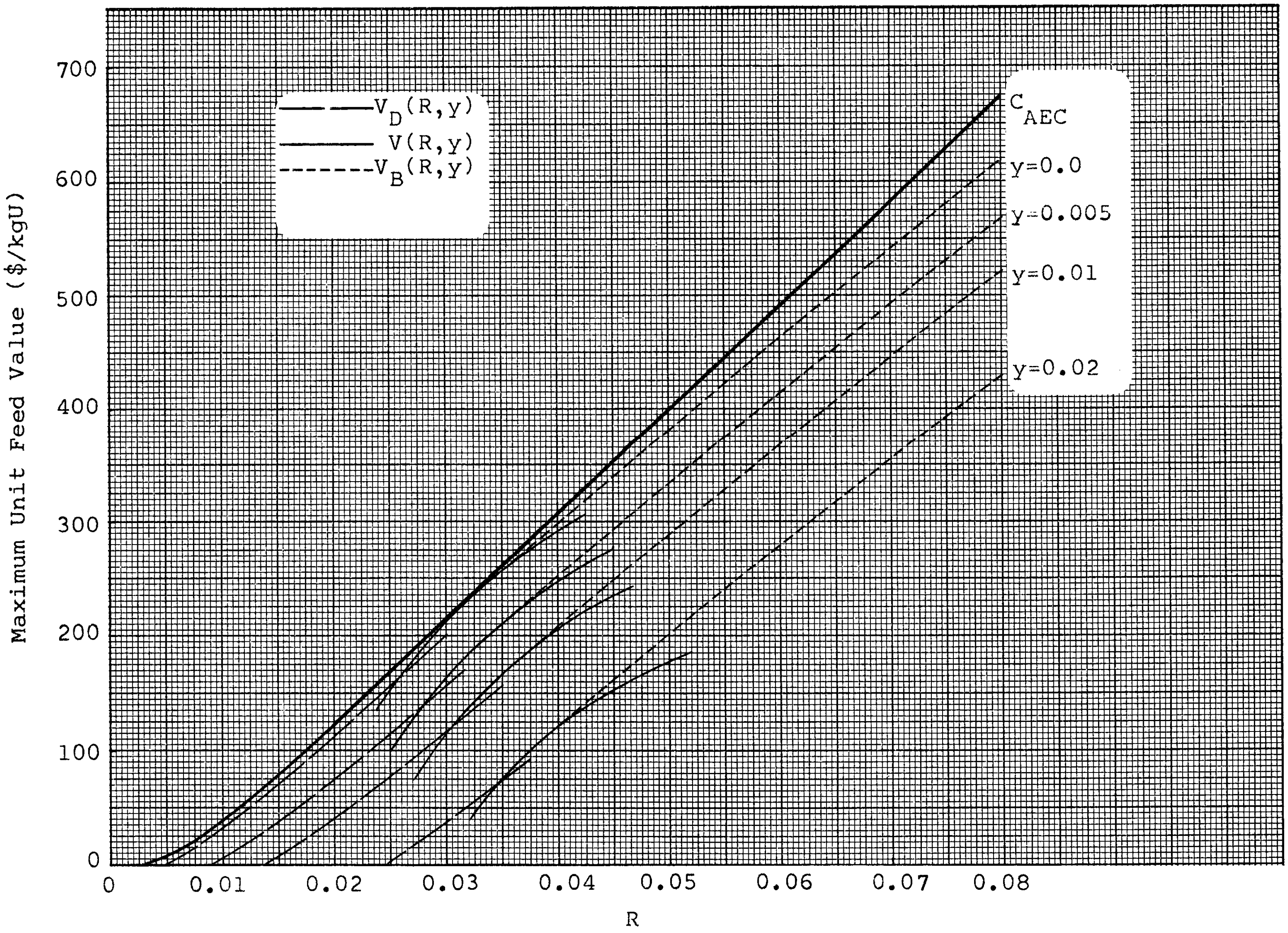


FIGURE VI.28 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$6/lb, C_N = \$0/g, High Costs, L_F=0.01

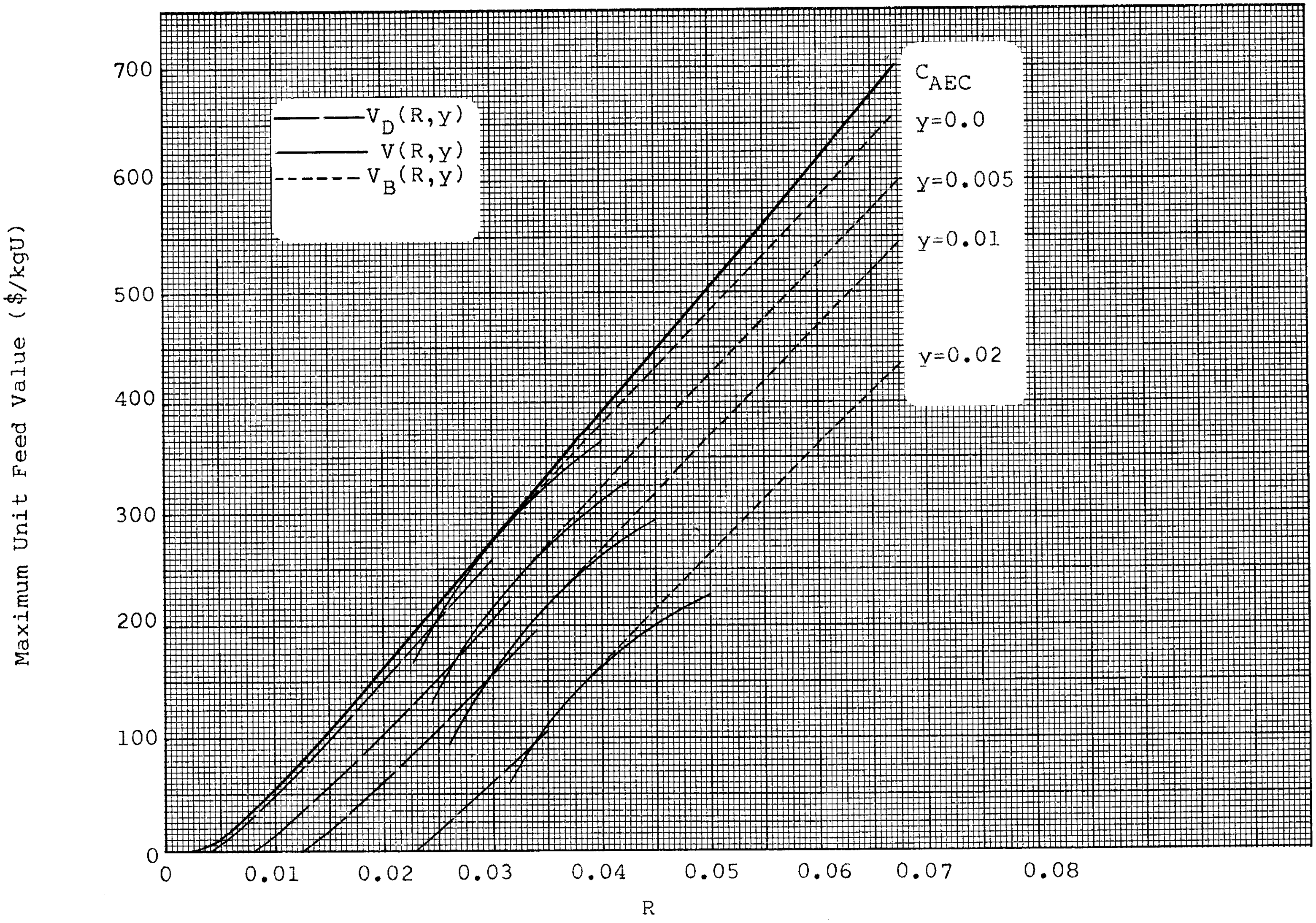


FIGURE VI.29 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$10/lb, C_N = \$0/g, High Costs, L_F = 0.01

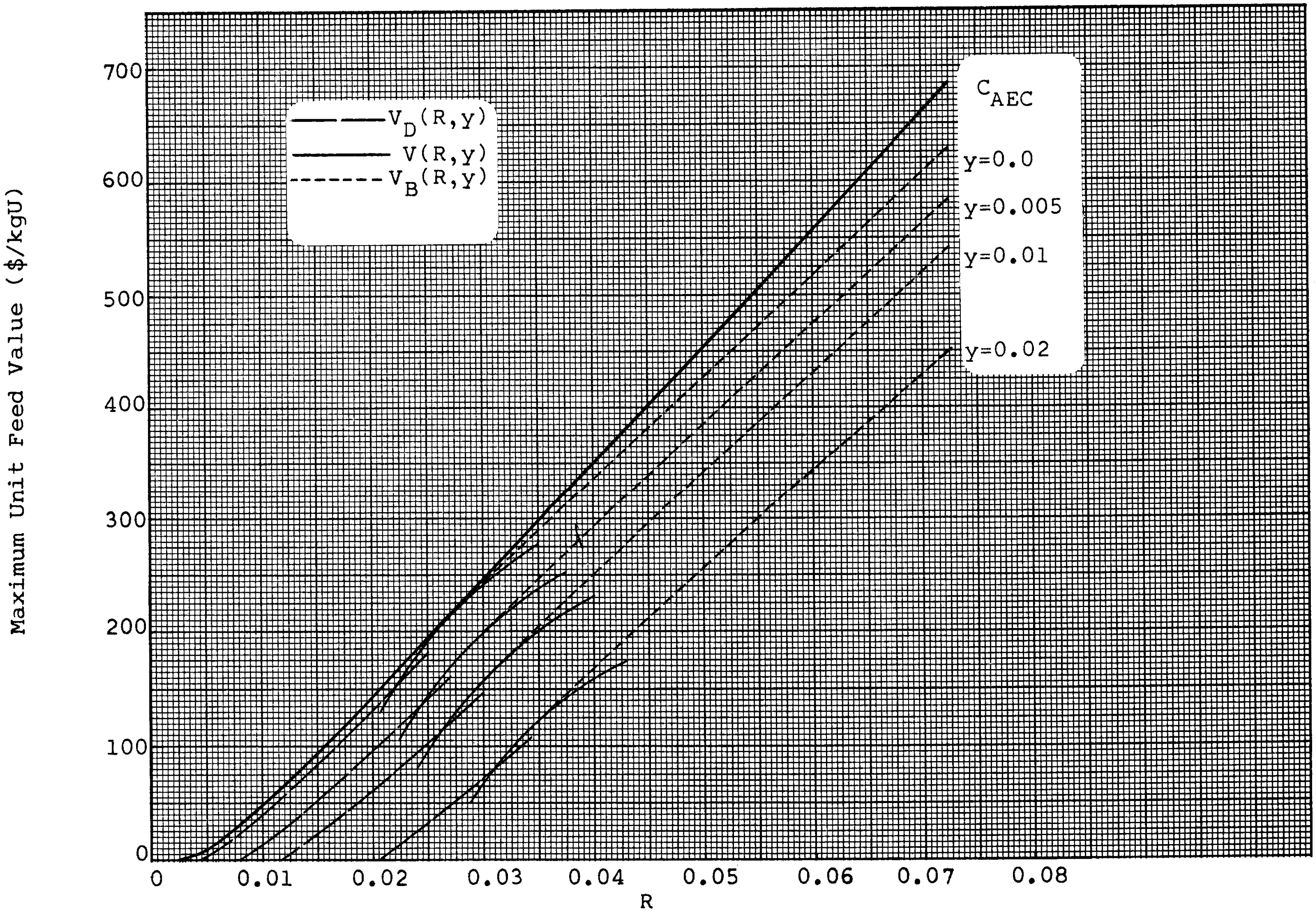


FIGURE VI.30 Maximum Unit Feed Value - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, Low Costs, L_F = 0.01

TABLE VI.2 Effect of Recycle Scheme on Maximum Unit Feed Value

$C_{U_3O_8} = \$8/\text{lb}, L_F = 0.01$, high unit costs

R	y	C_N	Recycle to Fabrication $V_m(R,y)$	Recycle to Fabrication Mode	Recycle to Diffusion Plant $V_m(R,y)$	Recycle to Diffusion Plant Mode
0.01	0	$0/g	$39.22/kgU	pre-enr.	$39.66/kgU	pre-enr.
0.03	0	0	229.37	pre-enr.	244.45	basic
	0.01	0	75.26	pre-enr.	137.96	basic
		60	274.95	pre-enr.	249.63	basic
0.10	0	0	913.87	pre-enr.	870.63	blend
	0.01	0	694.31	pre-enr.	760.05	blend
		60	976.08	pre-enr.	882.41	blend
0.50	0	0	3795.42	basic	3321.41	blend
	0.01	0	3503.72	basic	3184.80	blend
		60	3895.40	basic	3310.27	blend
6	0	0	10036.45	blend	8616.77	blend
	0.15	0	4902.52	blend	5821.98	blend
		60	9740.45	blend	7676.02	blend

VII. PENALTIES AND BENEFITS FROM U-236 AND Np-237

A. Definition of U-236 Penalty

The concept of a U-236 penalty was developed to provide a convenient way of expressing the effect of U-236 on feed value which would be less dependent upon R and y than are the unit values themselves. The U-236 penalty $\delta(R,y)$ is defined as the reduction in total value per gram of U-236 when y kg of U-236 are added to (1-y) kg of U-235 plus U-238 having U-235 to U-238 weight ratio R. This definition can be written in symbolic form as:

$$\delta(R,y) = \frac{(1-y)V_m(R,0) - V_m(R,y)}{1000y}, \ \$/\text{g U-236}. \tag{VII.1}$$

Note that maximum unit feed values, regardless of the operating mode required to obtain them, are used at points (R,0) and (R,y) in obtaining $\delta(R,y)$. A negative penalty indicates that the presence of U-236 causes a mixture of (1-y) units of U-235 plus U-238 with y units of U-236 to have a higher total value than the (1-y) units of U-235 plus U-238 alone.

Other definitions are possible for the U-236 penalty, but the one given above has proven to be more convenient and less arbitrary than others considered. One alternative definition of some interest is discussed at the end of Section VII.

B. U-236 Penalty Results

Results for $\delta(R,y)$ have been obtained for all points having $y > 0$ which were considered in the feed value maximization portion of the study and are listed in the tables of Appendix I.

1. Components of Overall Penalty Curves

The use of V_m in the penalty definition, Equation VII.1, permits the situation wherein $V_m(R,0)$ and $V_m(R,y)$ could correspond to operation according to two different modes. It has been shown in Section VI, Part C, that the R-value at which $V_D(R,y)$ and $V(R,y)$ intersect will generally be different for each value of y considered. The same is true of the intersection between $V(R,y)$ and $V_B(R,y)$. As a result, $\delta(R,y)$ could be based on $V(R,0)$ and $V_D(R,y)$ over a limited range of R, at constant y, while other combinations such as $V_B(R,0)$ and $V(R,y)$ can arise in the penalty calculations, as is obvious from examining the curves of $V_m(R,y)$ shown earlier.

It is instructive to examine penalty results based on the following modified definitions:

$$\delta_1(R,y) = \frac{(1-y)V_D(R,0) - V_D(R,y)}{1000y}, \qquad \text{(VII.2)}$$

$$\delta_2(R,y) = \frac{(1-y)V(R,0) - V_D(R,y)}{1000y}, \qquad \text{(VII.3)}$$

$$\delta_3(R,y) = \frac{(1-y)V(R,0) - V(R,y)}{1000y}, \qquad \text{(VII.4)}$$

$$\delta_4(R,y) = \frac{(1-y)V_B(R,0) - V(R,y)}{1000y} , \qquad \text{(VII.5)}$$

and $$\delta_5(R,y) = \frac{(1-y)V_B(R,0) - V_B(R,y)}{1000y} . \qquad \text{(VII.6)}$$

These modified penalties are plotted in Figure VII.1 for the recycle-to-diffusion-plant case for y = 0.005, $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, and high unit costs. The entire range of R is shown, from low- to fully-enriched (R=15) uranium. By comparing the lines for y=0 and y = 0.005 in Figure VI.16, we can see how the overall line for $\delta(R,0.005)$, as defined by Equation VII.1, is composed of segments of the individual δ_i lines plotted in Figure VII.1. The use of $V_m(R,0)$ and $V_m(R,0.005)$ in the definition of $\delta(R,y)$ causes the overall $\delta(R,0.005)$ line to follow δ_1 until δ_1 intersects δ_2, after which δ follows δ_2 until δ_2 intersects δ_3, and so on.

The construction of the penalty curves presented later in this section was not carried out by separate calculation of all the component δ_i lines, but instead is accomplished by determining $\delta(R,y)$ from $V_m(R,y)$ results at discrete (R,y) points. As a result, the irregularities which are unavoidably present in all penalty curves will not be presented quite as accurately as above, since the discrete (R,y) points chosen do not necessarily correspond to intersection points between $V_D(R,y)$, $V(R,y)$, and $V_B(R,y)$. For example, the very small segment where $\delta = \delta_4$ would not be seen in a normal penalty curve, while the $\delta = \delta_2$ segment and the

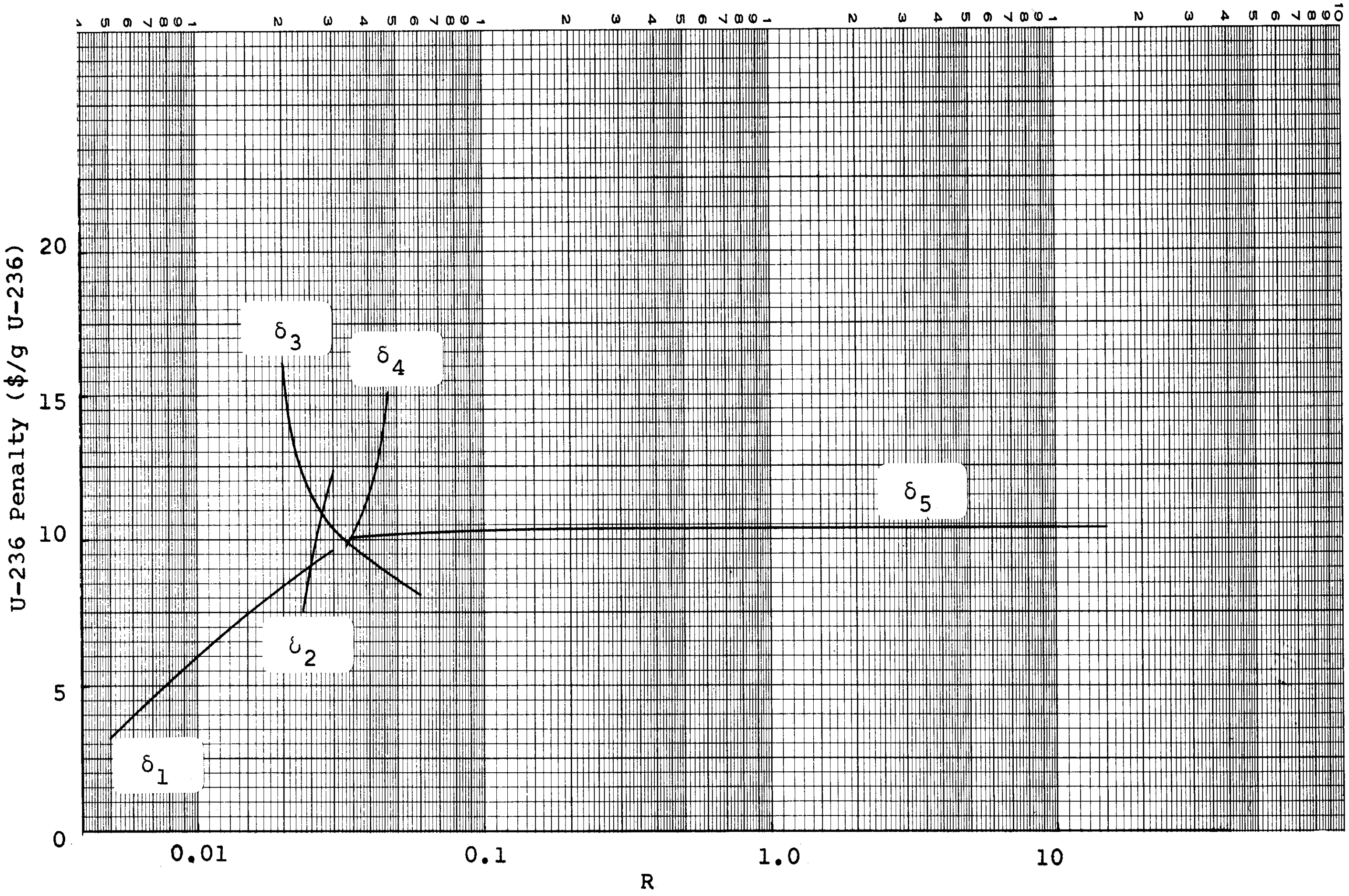


FIGURE VII.1 Components of U-236 Penalty Curve for y=0.005 - Recycle to Diffusion Plant: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs, L_F = 0.01

details near the intersection of δ_2 and δ_3 are not always exact. The detailed irregularities in the penalty curves are not of great practical importance, however.

Except for the $\delta = \delta_1$ segment, the penalties for all R fall within a narrow band centered at about \$10/g. The nature of the $\delta = \delta_1$ segment can be examined in the following way. Using Equation V.8, expressions for $V_D(R,0)$ and $V_D(R,y)$ can be obtained and are inserted into Equation VII.2 to give an expression for $\delta_1(R,y)$. If $(1-it_E)$ and $(1+it_C)$ are both approximated by unity and if the difference between Δ_D/F_D for $y=0$ and for $y > 0$ is neglected, then $\delta_1(R,y)$ can be written as

$$\delta_1(R,y) \cong \frac{(1-y)\left[\frac{F}{F_D}V(R_D,0)\right]_{y=0} - \left[\frac{F}{F_D}V(R_D,y_D)\right]_{y>0}}{1000y} \; . \tag{VII.7}$$

Another reasonable assumption is that F/F_D is only slightly different for $y=0$ and $y > 0$. A much cruder approximation is that the optimum value of R_D is the same for $y=0$ and $y > 0$; furthermore, this optimum R_D is taken as R^*, since it was shown in Section VI, Part C1, that R^* is very close to the optimum R_D when $y=0$. This last approximation is reasonable for low y, but becomes cruder as y increases. By utilizing these assumptions, Equation VII.7 can be rewritten as

$$\delta_1(R,y) \cong \frac{F}{F_D}\left[\frac{(1-y)V(R^*,0) - V(R^*,y_D)}{1000y}\right] . \quad \text{(VII.8)}$$

The bracketed quantity in Equation VII.8 can be approximated by $\delta_3(R^*,y_D)\ y_D/y$ when the difference between $(1-y)$ and $(1-y_D)$ is neglected. Equation VII.8 then becomes

$$\delta_1(R,y) \cong \frac{Fy_D}{F_D y}\delta_3(R^*,y_D) = \alpha\delta_3(R^*,y_D), \quad \text{(VII.9)}$$

where α is the fraction of the total U-236 contained in the feed uranium which remains in the upgraded feed stream leaving the diffusion plant. The remainder of the U-236 is either discharged in the tails stream or is lost during conversion of UO_3 to UF_6.

When $\delta_3(R^*,y_D)$ varies sufficiently slowly with y_D, then, within the limitations of the various approximations made in reaching Equation VII.9, $\delta_1(R,y)$ will vary almost directly with α. Therefore, the decrease in δ_1 with decreasing R which is obvious in Figure VII.1 is due in large part to the fact that α decreases with decreasing R, i.e., the fractional loss of U-236 in the tails stream increases when feed is introduced to the diffusion plant at a point nearer to the tails end.

Another feature of Figure VII.1 is that δ_5 becomes effectively constant as R increases. Furthermore, under certain conditions δ_5 will tend to approach the same constant value regardless of the value of y being examined. This can be shown by first inserting expressions for $V_B(R,0)$ and $V_B(R,y)$, obtained from Equation V.9, into Equation VII.6 to give the following general equation for $\delta_5(R,y)$:

$$\delta_5(R,y) = \frac{(1-y)\left[\frac{V(R_B,0)\ -\epsilon C_{NAT}}{1\ -\ \epsilon}\right]_{y=0} - \left[\frac{V(R_B,y_B)\ -\epsilon C_{NAT}}{1\ -\ \epsilon}\right]_{y>0}}{1000y}$$

(VII.10)

Next, it is assumed that for high R the maximum unit values for y=0 and y > 0 are achieved by blending to the same R_B; in addition, R_B is taken as R^* since it was shown in Section VI, Part C1, that optimum blending for y=0 occurs when R_B is only slightly greater than R^*. With this assumption, it is reasonable to take the optimum values of ϵ as the same for both y=0 and y > 0, so that Equation VII.10 can be approximated at high R by

$$\delta_5(R,y) \cong \frac{1}{1-\epsilon}\left[\frac{(1-y)V(R^*,0)\ -\ V(R^*,y_B)}{1000y}\right]. \qquad \text{(VII.11)}$$

From Equation IV.24, $(1-\epsilon)$ can be replaced by y_B/y; also, the bracketed quantity in Equation VII.11 can be approximated by $\delta_3(R^*,y_B)\ y_B/y$ when the difference between (1-y) and $(1-y_B)$ is neglected. The approximation for $\delta_5(R,y)$ at high R then becomes

$$\delta_5(R,y) \cong \delta_3(R^*,y_B)\ . \qquad \text{(VII.12)}$$

Since y_B becomes nearer to zero as R increases, and if $\delta_3(R^*,y_B)$ is affected only slightly by small y_B variations, $\delta_5(R,y)$ will approach constancy at sufficiently high R, independent of y, provided the approximations which lead to Equation VII.12 are valid.

2. Recycle to Fabrication

In examining the penalty curves shown in this section and the following section, the reader is cautioned against attaching importance to all detailed variations. All $V_m(R,y)$ data result from one or more interpolation procedures and, when modified operating modes are involved, non-zero convergence criteria are applied during the feed value maximization processes. Inaccuracies which can result when taking differences between $V_m(R,y)$ data could possibly alter real (but unimportant) trends in the penalties shown; thus, the penalty curves should be used only to indicate broad trends and the general level of the U-236 penalty for various economic conditions.

In Figure VII.2, penalty results are shown for the $C_{U_3O_8}$ = \$8/lb, L_F = 0.01, high unit cost case, for three Np-237 prices - \$0, \$60, and \$100/g. The negative penalties for C_N = \$60/g and C_N = \$100/g indicate that the presence of U-236 in feed enhances the value of U-235 plus U-238. The difficulty of assigning a single meaningful penalty at each C_N is obvious, but it is convenient to arbitrarily define a "penalty level", $\bar{\delta}$, as the approximate penalty at R*. For recycle to a diffusion plant, $\delta(R^*,y)$ does not show a strong variation with y and a representative $\bar{\delta}$ can be selected with little difficulty. For recycle to fabrication, however, the

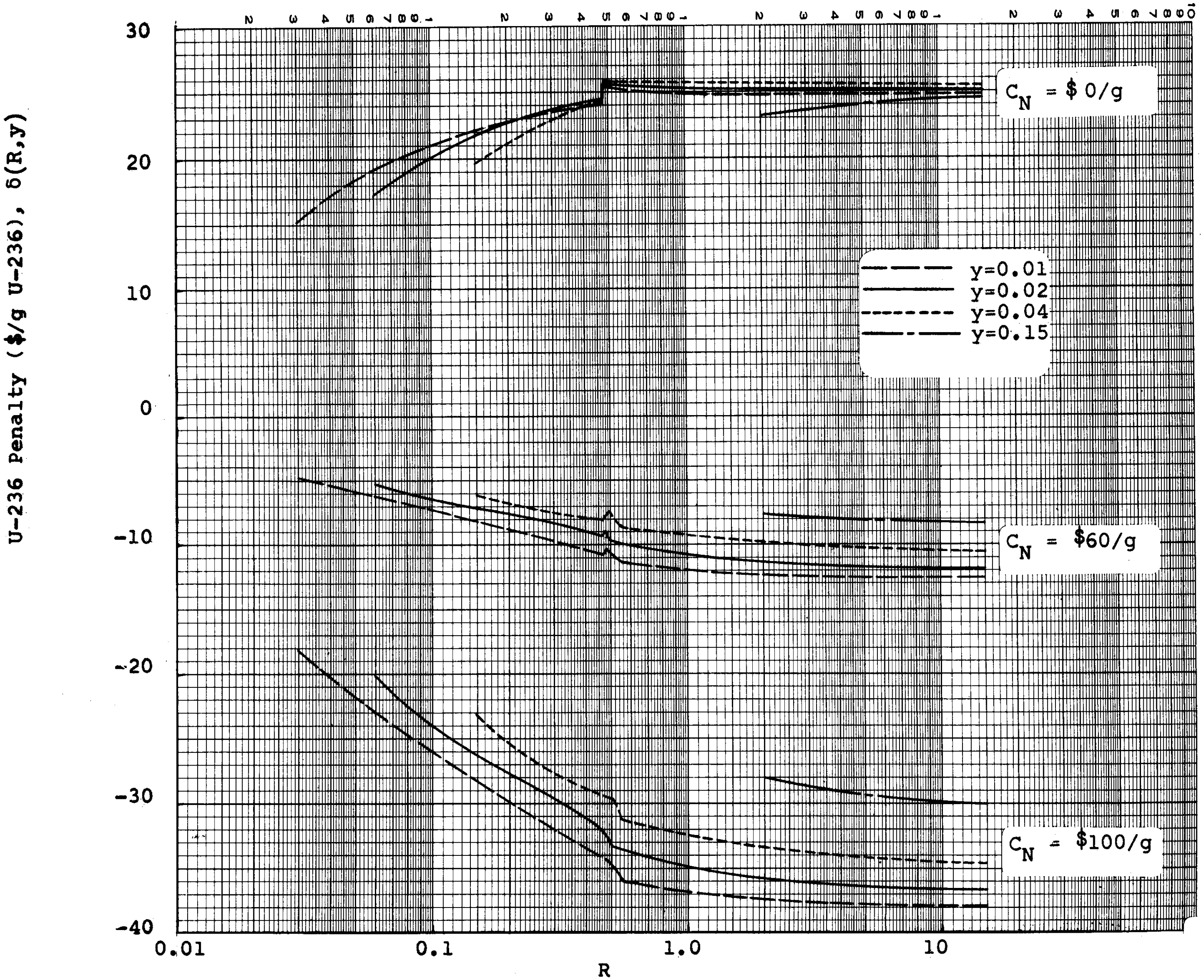


FIGURE VII.2 U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

effect of y on $\delta(R^*,y)$ is strong enough to necessitate the choice of a single y value as a basis for selecting $\bar{\delta}$. The choice of $y = 0.02$ appeared to give the most representative values of $\bar{\delta}$ for this recycle scheme.

The strong effect of increasing C_N is indicated by a reduction of $\bar{\delta}$ from \$25.5/g to -\$10/g to -\$33.5/g as C_N increases from \$0/g to \$60/g to \$100/g. The dependence of $\delta(R,y)$ on C_N is investigated in more detail in Part C of this section. The dependence on y becomes more pronounced as C_N increases, which indicates that Np-237 production increases at a less-than-linear rate with increasing y. For $R < 0.5$, the loss of U-236 in the diffusion plant tails stream tends to reduce the penalty below the "penalty level" for C_N = \$0/g; however, for C_N = \$60/g and C_N = \$100/g, this loss of U-236 serves to increase the penalty as R decreases below 0.5, since the presence of U-236 in the upgraded feed stream is now economically beneficial. All lines approach constant penalties as R becomes large, but the assumptions which lead to Equation VII.12 are apparently not strictly valid for this recycle scheme, particularly at C_N = \$60/g and C_N = \$100/g.

Figures VII.3 and VII.4 give results for $C_{U_3O_8}$ = \$6/lb and \$10/lb, respectively, at both C_N = \$0/g and \$60/g. The penalty curves retain the same general appearance as for the \$8/lb case, but $\bar{\delta}$ decreases as

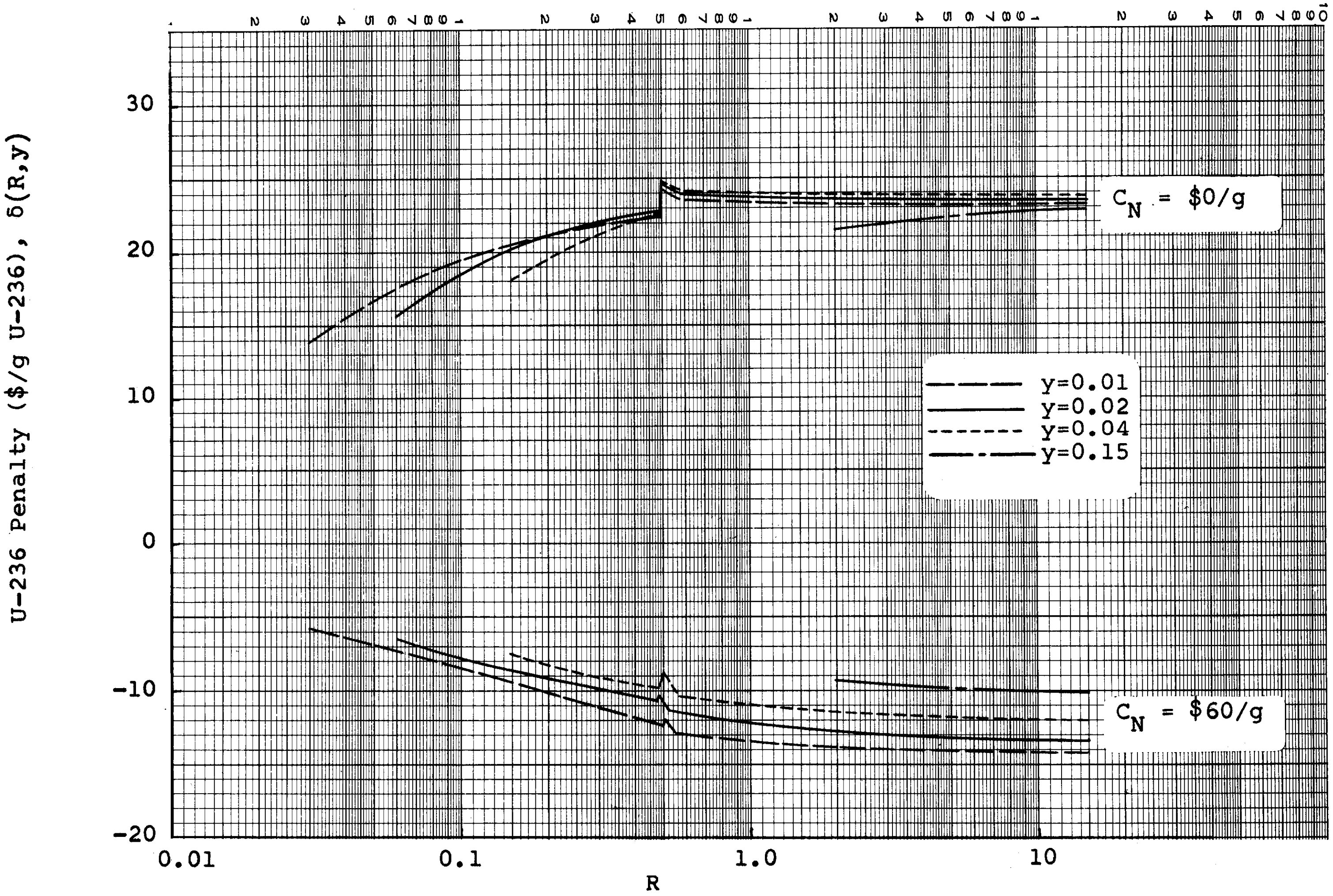


FIGURE VII.3 U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = $6/lb, High Costs, L_F = 0.01

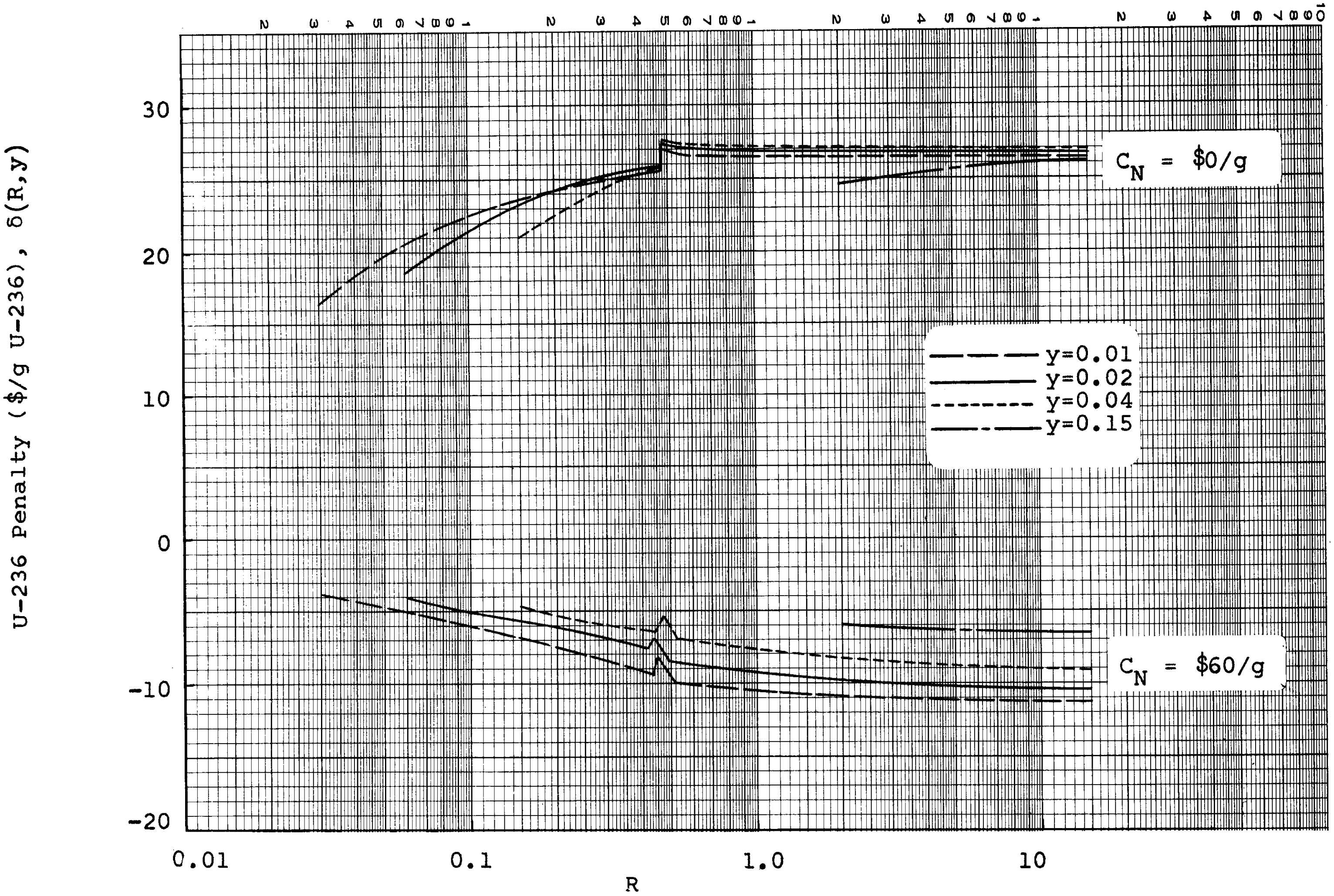


FIGURE VII.4 U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = $10/g, High Costs, L_F = 0.01

$C_{U_3O_8}$ decreases. For C_N = \$0/g and \$60/g, respectively, $\bar{\delta}$ results for $C_{U_3O_8}$ = \$6/lb are about \$24/g and -\$11.5/g while for $C_{U_3O_8}$ = \$10/lb these become \$27/g and -\$8.5/g. The variation of δ(R,y) with $C_{U_3O_8}$ is considered in more detail in Part C of this section.

Penalties for the low unit cost case, at $C_{U_3O_8}$ = \$8/lb, are shown in Figure VII.5. The penalty levels of \$21.5/g and -\$13.5/g, at C_N = \$0/g and \$60/g, respectively, are about \$4/g lower than for the corresponding high unit cost cases.

In Figure VII.6, it is shown that a decrease of L_F from 0.01 to 0.002 effects an increase in $\bar{\delta}$ from \$25.5/g to \$30/g.

3. Recycle to Diffusion Plant

Figure VII.7 shows δ(R,y) results for C_N = \$0, \$60, and \$100/g for the $C_{U_3O_8}$ = \$8/lb, L_F = 0.01, high unit cost case. For the three C_N values, $\bar{\delta}$ now decreases from \$10/g to -\$1.5/g to -\$9/g, levels which are significantly smaller in magnitude than for recycle to fabrication, for reasons discussed in the next part of this section. For each C_N value, δ(R,y) tends to lose both its R and y dependence as R becomes very large, which indicates that the assumptions inherent in Equation VII.12 are more generally valid for this recycle scheme.

Results for $C_{U_3O_8}$ = \$6/lb and \$10/lb are shown in Figures VII.8 and VII.9, respectively. For $C_{U_3O_8}$ = \$6/lb, $\bar{\delta}$ decreases to \$9/g and -\$2.5/g at C_N = \$0/g and

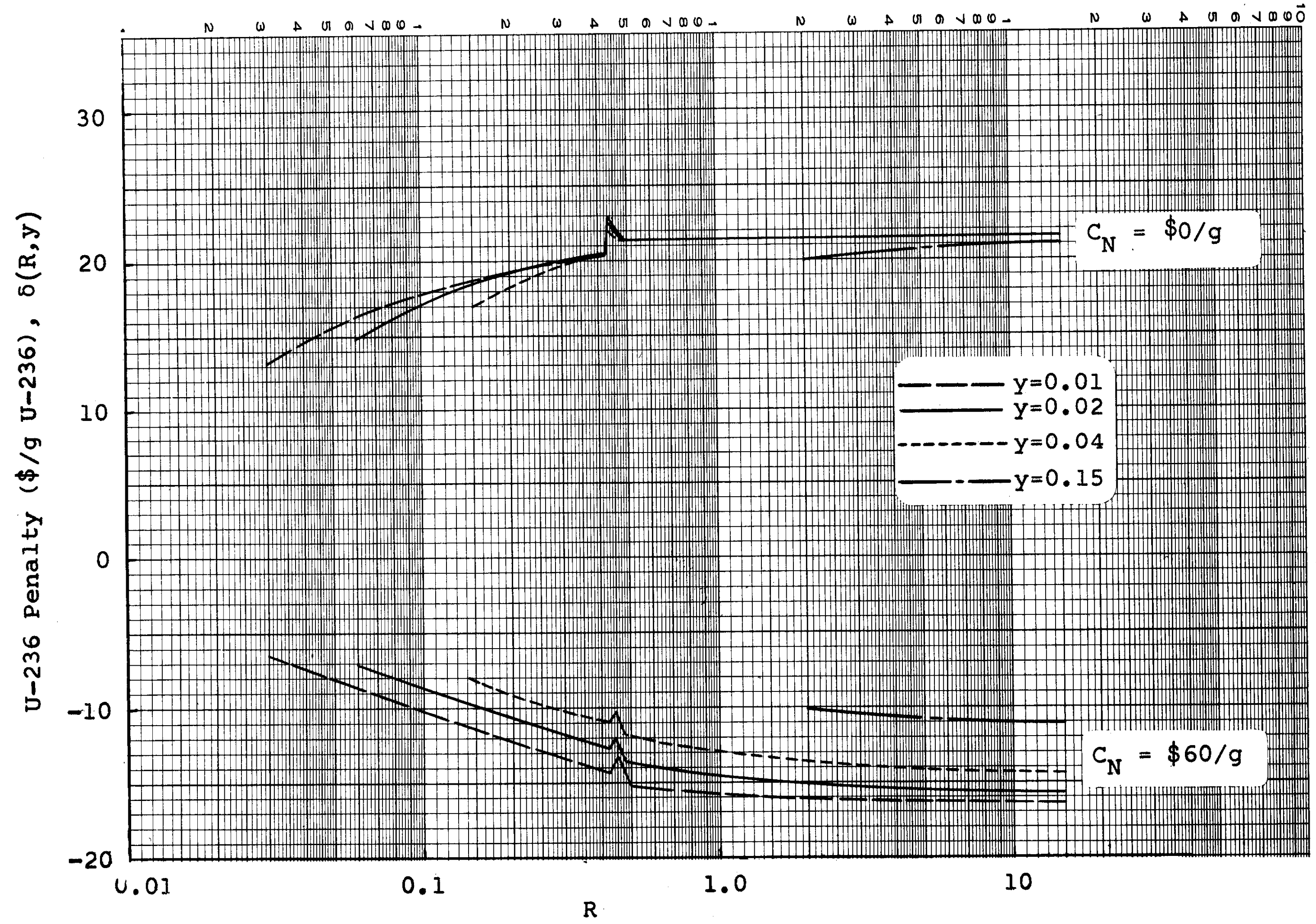


FIGURE VII.5 U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, Low Costs, L_F = 0.01

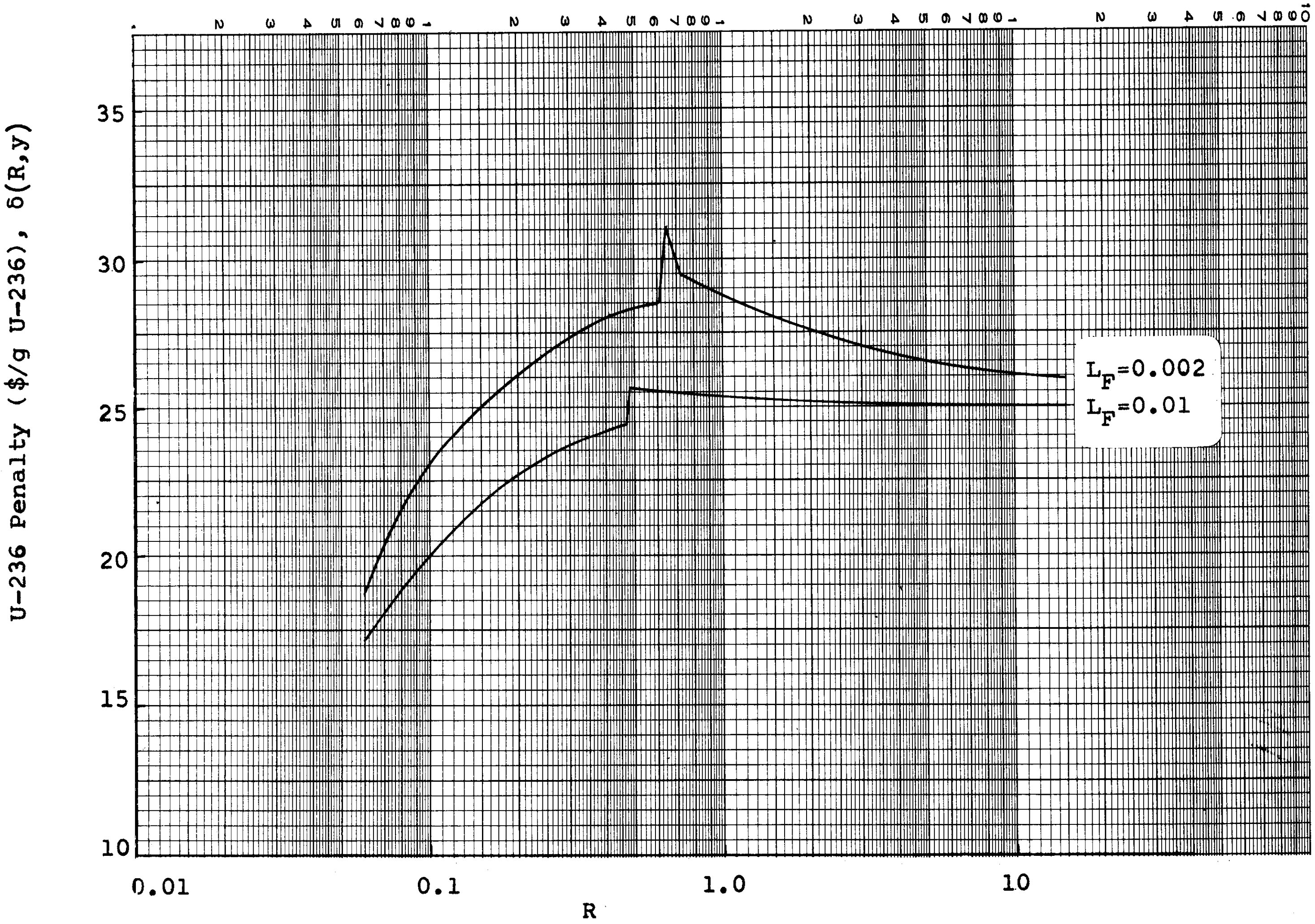


FIGURE VII.6 U-236 Penalty for y=0.02 - Recycle to Fabrication: $C_{U_3O_8}$ = \$8/lb, C_N = \$0/g, High Costs

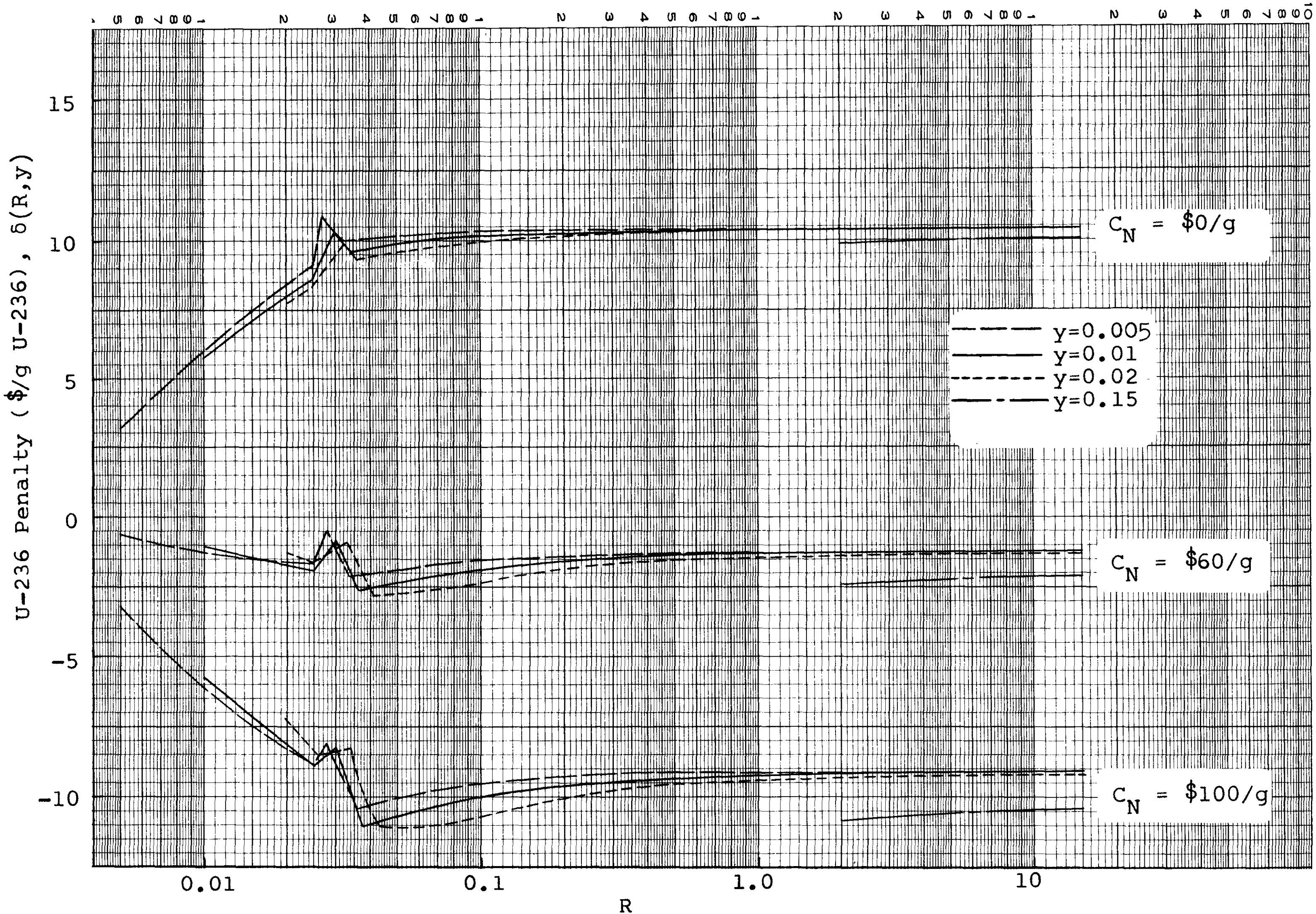


FIGURE VII.7 U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

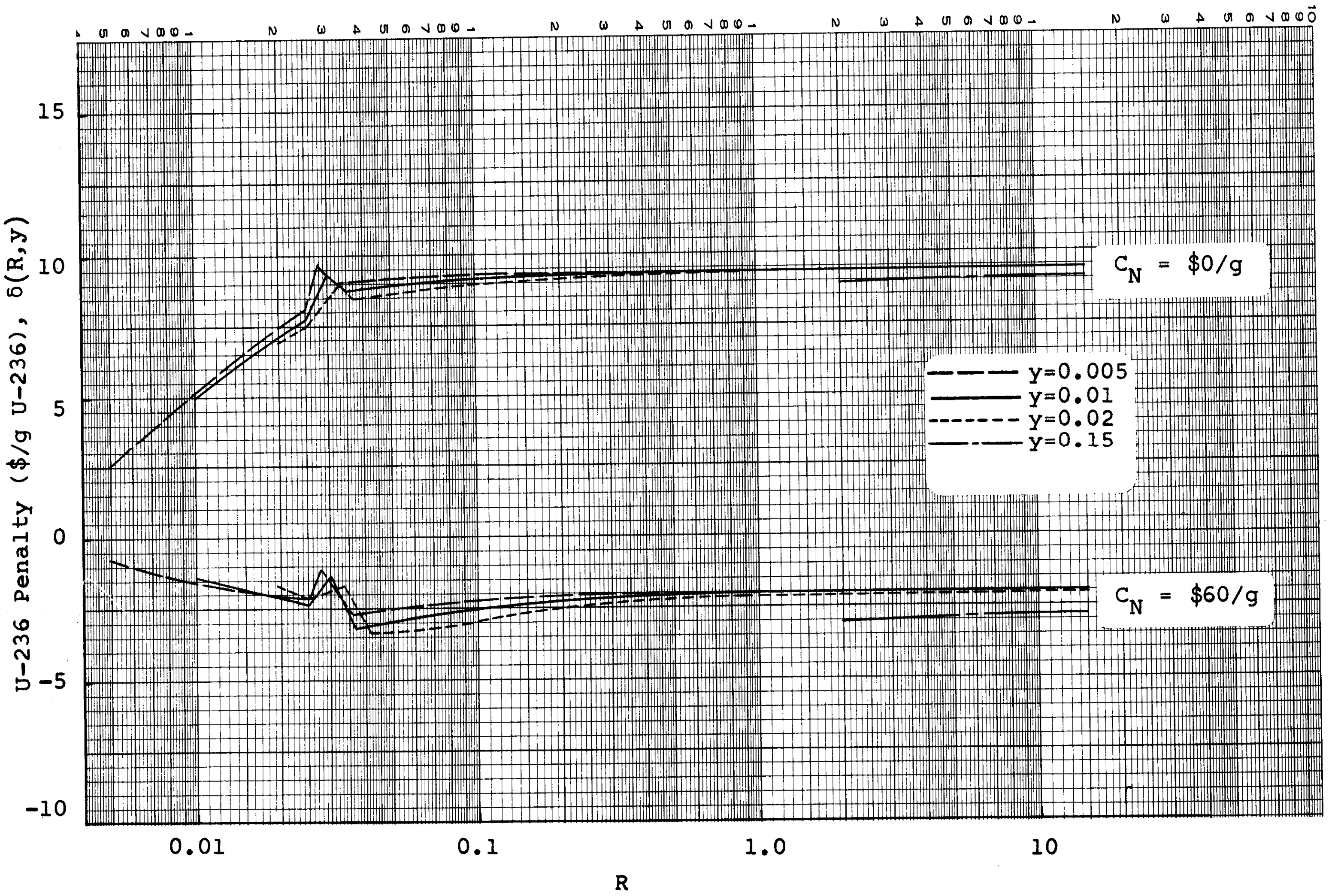


FIGURE VII.8 U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $6/lb, High Costs, L_F = 0.01

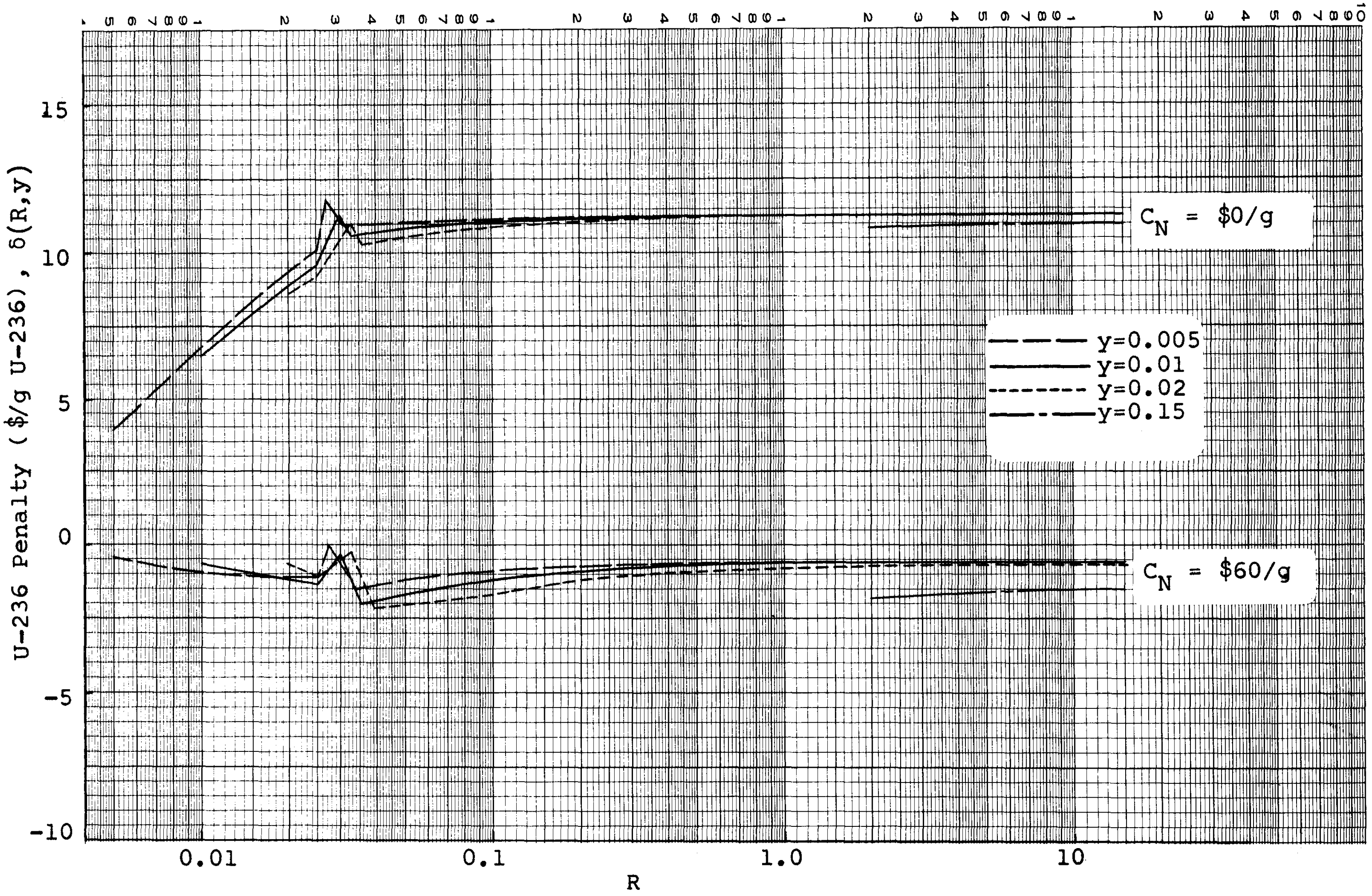


FIGURE VII.9 U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $10/lb, High Costs, L_F = 0.01

\$60/g, while the corresponding penalty levels for $C_{U_3O_8}$ = \$10/lb are \$11/g and -\$0.5/g.

When the low unit cost condition is employed, with $C_{U_3O_8}$ = \$8/lb, $\bar{\delta}$ decreases by about \$1.5/g to \$8.5/g and -\$2.5/g for C_N = \$0/g and \$60/g, respectively. Results for this case are shown in Figure VII.10.

It is interesting to note that, in general, for this recycle scheme the presence of U-236 in increasing concentration tends to decrease $\delta(R,y)$ slightly in the region where the blending-with-natural-uranium mode is utilized, whereas $\delta(R,y)$ increases with increasing y for recycle to fabrication. The reason for this is extremely complex but is due in part to the fact that, when recycling to a diffusion plant, as y increases the tendency to blend to increasingly high R_B is stronger than for recycle to fabrication. Reference to Figures VI.3 and VI.9 indicates that this tends to reduce the difference between $V(R_B,0)$ for y=0 and $V(R_B,y_B)$ for $y > 0$ as compared with the situation wherein R_B changes slightly or not at all as y increases.

C. U-236 Penalty Variations

The major effects which influence the variation of $\bar{\delta}$ can be determined by a detailed analysis of the penalties near R* for representative cases. From Equation VI.1, an expression for V(R,y) can be written as

$$V(R,y) = \frac{24LPC_E^* - M(R,y)}{F(R,y)}, \qquad \text{(VII.13)}$$

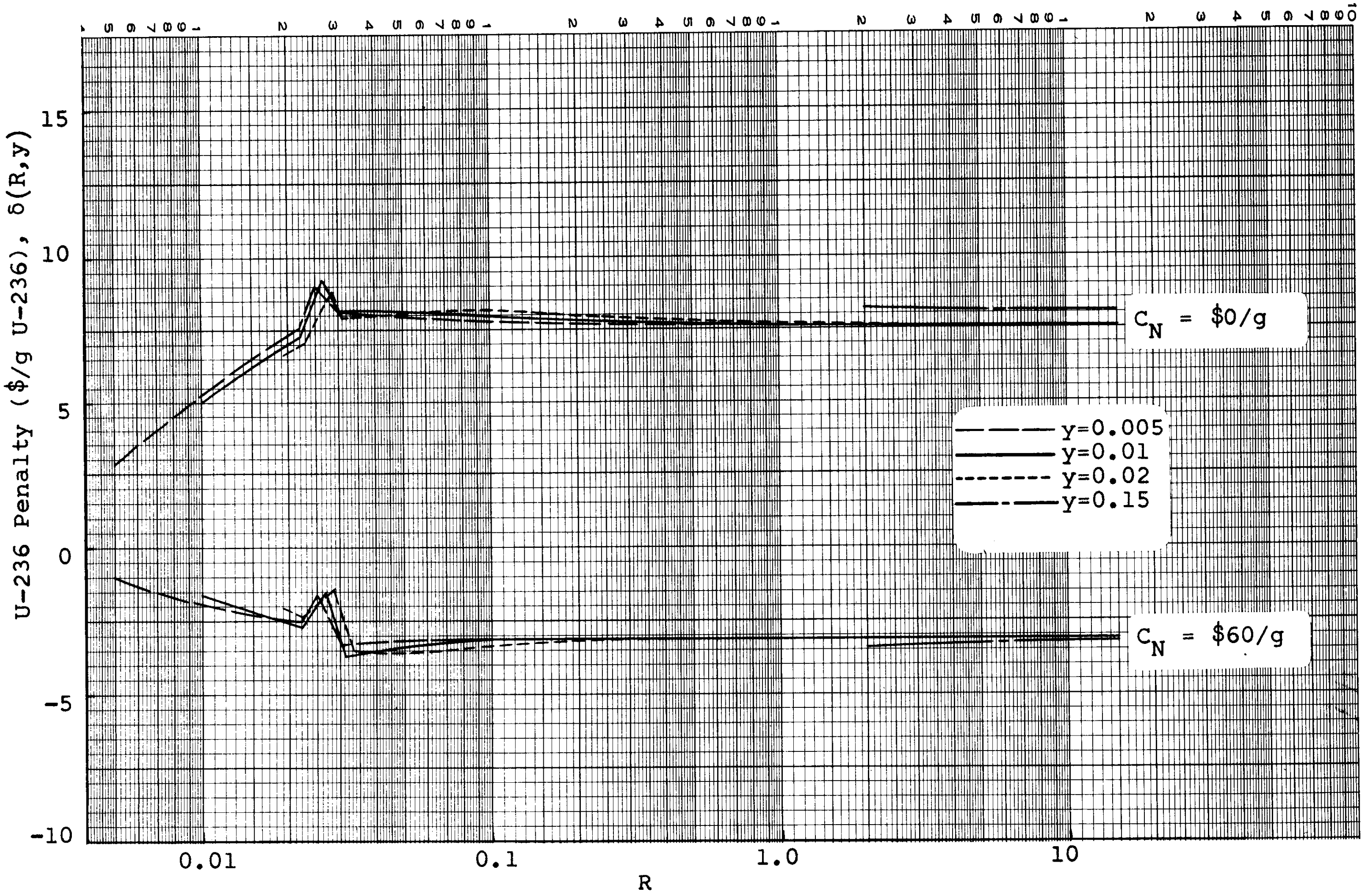


FIGURE VII.10 U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, Low Costs, L_F = 0.01

where F has been written to show dependence on R and y. Using Equations VII.4 and VII.13, the following relation can be formed:

$$1000y\delta_3(R,y) = (1-y)\left[\frac{24LPC_E^*}{F(R,0)} - \frac{M(R,0)}{F(R,0)}\right] - \frac{24LPC_E^*}{F(R,y)} + \frac{M(R,y)}{F(R,y)} \ . \qquad \text{(VII.14)}$$

Equation VII.14 can be written in condensed form as

$$1000y\delta_3(R,y) = 24LPC_E^*\beta + \eta \ , \qquad \text{(VII.15)}$$

where

$$\beta = \frac{1-y}{F(R,0)} - \frac{1}{F(R,y)} \ , \qquad \text{(VII.16)}$$

and

$$\eta = \frac{M(R,y)}{F(R,y)} - \frac{(1-y)M(R,0)}{F(R,0)} \ . \qquad \text{(VII.17)}$$

The "ß effect" thus arises from the increase in F with increasing y, while η is a measure of the change in the total fuel cycle cost exclusive of feed costs, normalized to unit feed, when U-236 is introduced into the feed. It should be noted that M includes any credit realized from the sale of Np-237.

Table VII.1 lists information required in this analysis for a representative sampling of cases. Results for F(R,y) and M(R,y) are given for both y=0 and y = 0.01 and at values of R sufficiently near R* to insure that $\delta_3(R,y)$ is reasonably close to $\bar{\delta}$ for each case. Using this information, the results for ß, $24LPC_E^*\beta$, η, and $\delta_3(R,0.01)$ which are given in Table VII.2 were obtained.

TABLE VII.1

Effect of y on F(R,y) and M(R,y) near R*

Recycle to	L_F	Unit Costs	R	$C_{U_3O_8}$ ($/lb)	F(R,0) (kgU/day)	F(R,0.01) (kgU/day)	C_N ($/gNp)	$24LPC^*_E$ ($/day)	M(R,0) ($/day)	M(R,0.01) ($/day)
Fabrication	0.01	High	0.55	8	2.536	2.630	0	16744	6300	6698
							60	11643	1203	650
							100	8225	-2195	-3381
				6	2.536	2.630	0	15382	6020	6406
		Low	0.50	8	2.704	2.804	0	14958	4525	4848
	0.002	High	0.70	8	2.182	2.259	0	16942	6448	6854
Diffusion Plant	0.01	High	0.03	8	29.66	34.33	0	13325	6074	8589
							60	11798	4559	3229
							100	10777	3549	-345
				6	29.86	34.45	0	12133	5792	8160
		Low	0.03	8	29.66	34.33	0	11702	4526	6269

TABLE VII.2

Items Which Govern U-236 Penalty Changes

Recycle to	L_F	Unit Costs	R	$C_{U_3O_8}$ (\$/lb)	β	C_N (\$/gNp)	$24LPC_E^*\beta$ (\$/kgU)	η (\$/kgU)	$\delta_3(R,0.01)$ (\$/gU-236)
Fabrication	0.01	High	0.55	8	0.01003	0	167.94	88.16	25.61
						60	116.78	-222.37	-10.56
						100	82.50	-429.00	-34.65
				6	0.01003	0	154.28	86.40	24.07
		Low	0.50	8	0.00956	0	142.92	71.94	21.49
	0.002	High	0.70	8	0.01097	0	185.85	108.95	29.48
Diffusion Plant	0.01	High	0.03	8	0.00425	0	56.63	47.45	10.41
						60	50.14	-58.12	- 0.80
						100	45.80	-128.51	- 8.27
				6	0.00413	0	50.13	44.81	9.49
		Low	0.03	8	0.00425	0	49.73	31.54	8.13

The value for ß is governed predominantly by the feed rate level, with ß increasing as the general level of F decreases. Consequently, ß is larger when recycling to fabrication than for recycle to a diffusion plant. Also, for recycle to fabrication, reduction of L_F leads to lower feed rates and higher ß.

As C_N increases, C_E^* decreases and the $24LPC_E^*ß$ contribution to the penalty becomes smaller. Obviously, any change in conditions which reduces C_E^* without significantly affecting ß will decrease the $24LPC_E^*ß$ contribution. Such changes are the lowering of either unit costs or U_3O_8 price. Conversely, $24LPC_E^*ß$ is increased by any change which increases ß but which does not affect C_E^*, a condition approximated by reducing L_F for recycle to fabrication.

The major terms in M/F, such as F_R/F and N/F, were shown in Table IV.2 to increase with increasing y. Thus, at C_N = \$0/g, the η contribution to the penalty is positive and important, although not as large as $24LPC_E^*ß$. As C_N becomes larger, the Np-237 credit increases faster for y = 0.01 than for y=0, which leads to decreasing η values. At C_N = \$60/g and \$100/g, η is strongly negative and provides the dominant contribution to the penalty. Since both $24LPC_E^*ß$ and η decrease with increasing C_N, the penalty also decreases, but becomes negative at a higher C_N than does η.

When $C_{U_3O_8}$ changes, η is affected only slightly; however, a decrease of $C_{U_3O_8}$ reduces C_E^*, thereby reducing the penalty. Conversely, an increase of $C_{U_3O_8}$ results in a penalty increase.

When unit costs are lowered, C_E^* decreases, and since the increase of F_R/F caused by an increase of y has less of an economic effect under these conditions, η also decreases. The effect is to decrease the penalty below that obtained for the high unit cost case.

For recycle to fabrication, reduction of L_F leads to a higher β, as mentioned above, but also leads to increased η since the effect of increasing y on burnup is greater near R* when the lower L_F is used (see Figure IV.7). The cumulative effect is an increase in the penalty.

At C_N = \$0/g, the penalty level is about \$15/g larger for the recycle-to-fabrication scheme than for recycle to a diffusion plant. About \$11/g of this differential results from the higher β and the higher C_E^* for recycle to fabrication. The remaining \$4/g results from the difference between η values caused by the higher sensitivity of $y_R F_R/F$, F_R/F, etc., to changes of y in the case of recycle to fabrication.

However, as C_N increases, the more rapid decrease of C_E^* and the greater sensitivity of N/F to changes of y (see Table IV.2) serve to reduce both $24LPC_E^*\beta$ and η at a faster rate for recycle to fabrication. The penalty is therefore more sensitive to C_N for that scheme than for recycle to a diffusion plant.

The preceding discussion indicates that the penalty level exhibits the following general characteristics:

a. $\bar{\delta}$ increases as the feed rate requirement decreases;

b. $\bar{\delta}$ decreases as C_E^* decreases; and

c. $\bar{\delta}$ decreases as C_N increases.

The reduction of U-236 penalty with unit increase of C_N has been calculated at a number of (R,y) points for both recycle schemes. Detailed results are given in Appendix J and a sampling of these calculated coefficients is given in Table VII.3. For the $C_{U_3O_8}$ = \$8/lb, high unit cost case,average coefficients were calculated over the interval C_N = \$0/g to \$60/g as well as the interval C_N = \$0/g to \$100/g. At each (R,y) point considered, the coefficients for these two C_N intervals were virtually the same, and it can be concluded that the U-236 penalty for a given feed composition R,y varies linearly with Np-237 price. Coefficients for the recycle-to-fabrication cases are larger than for recycle-to-diffusion plant, for the reasons mentioned above.

The linear variation of $\delta(R,y)$ with C_N also implies linear variation of $V_m(R,y)$ with C_N. It was

TABLE VII.3

Change of U-236 Penalty with Neptunium Price

($C_{U_3O_8}$ = \$8/lb; L_F = 0.01; high unit costs)

			$-\frac{\Delta\delta(R,y)}{\Delta C_N}$, $\frac{\$/g\ U\text{-}236}{\$/g\ Np\text{-}237}$					
Recycle to	C_N Range (\$/g Np-237)	$y \diagdown R$	0.01	0.03	0.06	0.5	2	15
Fabrication	0,60	0.01		0.333	0.422	0.600	0.621	0.624
		0.04				0.555	0.589	0.599
		0.15					0.512	0.546
	0,100	0.01		0.332	0.421	0.600	0.622	0.627
		0.04				0.555	0.589	0.600
		0.15					0.512	0.545
Diffusion Plant	0,60	0.005	0.121	0.190	0.200	0.194	0.194	0.193
		0.02		0.177	0.205	0.197	0.195	0.195
		0.15					0.205	0.204
	0,100	0.005	0.121	0.190	0.201	0.195	0.195	0.194
		0.02		0.178	0.207	0.198	0.196	0.195
		0.15					0.207	0.205

mentioned in Part C of Section VI that for fixed U_3O_8 price, unit cost condition, loss fractions, and recycle scheme, results for $V_m(R,0)$ are very nearly independent of C_N for C_N up to \$100/g. For fixed R and y, the derivative of $\delta(R,y)$ with respect to C_N is constant and if $V_m(R,0)$ is assumed invariant with C_N we can use Equation VII.1 to get

$$\frac{d\delta}{dC_N} = -\frac{1}{1000y}\frac{dV_m}{dC_N} = \text{constant} . \qquad \text{(VII.18)}$$

Hence, $V_m(R,y)$ for other Np-237 prices can be obtained by linear interpolation or extrapolation (to at least C_N = \$100/g) of the results obtained at two C_N values.

The non-linear behavior of the AEC price scale with changes in $C_{U_3O_8}$ will generally introduce the same non-linearity into any quantity which is either directly or indirectly dependent upon it. Although the values for $\bar{\delta}$ given above indicate a linear variation of penalty with $C_{U_3O_8}$, $\bar{\delta}$ values have been selected in a rather crude manner for the purpose of indicating the broad trends which occur and cannot be used to prove that linearity does or does not exist. When examined in detail, the actual non-linear variation of $\delta(R,y)$ with $C_{U_3O_8}$ can be ascertained and is indicated in Table VII.4, where the average change in $\delta(R,y)$ per unit change of $C_{U_3O_8}$ is given for the interval $C_{U_3O_8}$ = \$6/lb to \$8/lb as well as for the interval $C_{U_3O_8}$ = \$8/lb to \$10/lb. Coefficients are given for y = 0.01 at

TABLE VII.4

Change of U-236 Penalty with U_3O_8 Price

($y=0.01$; $C_N=\$0/g$; $L_F=0.01$; high unit costs)

Recycle to	$C_{U_3O_8}$ Range (\$/lbU_3O_8)	$\frac{\Delta\delta(R,y)}{\Delta C_{U_3O_8}}$, $\frac{\$/g\ U\text{-}236}{\$/lb\ U_3O_8}$					
		R = 0.01	0.03	0.06	0.5	2	15
Fabrication	6,8		0.660	0.785	0.845	0.820	0.825
	8,10		0.625	0.705	0.785	0.785	0.785
Diffusion Plant	6,8	0.380	0.480	0.495	0.490	0.485	0.480
	8,10	0.365	0.430	0.465	0.445	0.440	0.460

various R values. For both recycle schemes, the coefficients for the two $C_{U_3O_8}$ intervals differ significantly at each R value, which is sufficient proof of the aforementioned non-linearity.

D. Indifference Prices for Np-237

The "indifference price" for Np-237, $C_N^o(R,y)$, is defined as the price at which the U-236 penalty $\delta(R,y)$ is zero. At this neptunium price the value of uranium feed containing a given amount of U-235 and U-238 is the same whether or not the uranium contains U-236; therefore, it is a matter of indifference in purchasing uranium containing U-235 and U-238 at a given price whether the uranium contains U-236 or not.

Results for $C_N^o(R,y)$ are given in Table VII.5 for representative (R,y) points, for both recycle schemes, and for various economic conditions. $C_N^o(R,y)$ is a measure of the relative economic importance of U-236 as a neutron poison and as a target material for the production of Np-237, and is the ratio of the penalty at $C_N = \$0/g$ to the rate of decrease of the penalty with increasing C_N. By comparing $C_N^o(R,y)$ results, it is possible to judge the relative strengths of the poisoning and Np-237 effects under different conditions. As an example, $C_N^o(R,y)$ results for the recycle-to-diffusion-plant case are higher than for recycle to fabrication, despite the fact that the penalty level

TABLE VII.5

Indifference Prices of Np-237

(L_F = 0.01)

Unit Costs	$C_{U_3O_8}$ ($/lb)	Recycle to	y \ R	$C_N^o(R,y)$, $/g Np-237						
				0.01	0.03	0.06	0.2	0.5	2	15
High	6	Diff Pl	0.01	46.84	52.25	45.61	48.35	49.13	49.46	49.52
			0.02		49.56	43.68	47.00	48.41	49.13	49.28
		Fab	0.01		42.30	42.06	40.58	39.49	37.66	37.21
			0.02			42.32	41.85	40.67	38.93	38.18
	8	Diff Pl	0.01	50.55	55.71	49.16	52.18	53.03	53.36	53.54
			0.02		53.72	47.15	50.68	52.23	53.02	53.12
			0.15						48.20	49.39
		Fab	0.01		45.61	45.30	43.25	42.28	40.07	39.72
			0.02			45.97	45.00	43.43	41.41	40.69
			0.15						45.21	44.94
	10	Diff Pl	0.01	54.10	58.29	52.52	55.67	56.38	56.91	57.11
			0.02		57.52	50.36	54.15	55.67	56.57	56.87
		Fab	0.01		48.80	48.30	45.75	44.88	42.49	42.07
			0.02			49.32	47.90	46.04	43.82	43.07
Low	8	Diff Pl	0.01	45.27	43.81	42.89	42.65	42.50	42.19	42.36
			0.02		48.01	41.61	42.92	42.65	42.38	42.42
		Fab	0.01		40.33	39.34	36.57	35.13	34.25	34.02
			0.02			40.75	38.59	36.62	35.11	34.61

at C_N = \$0/g is significantly higher in the latter case. The rate at which $\delta(R,y)$ decreases with increasing C_N is sufficiently greater for the recycle-to-fabrication case that $\delta(R,y)$ becomes zero at a lower C_N. This is illustrated in Figure VII.11, where the variation of the penalty level, $\bar{\delta}$, with C_N is shown for both recycle schemes.

All $C_N^o(R,y)$ results, regardless of the recycle scheme considered, fall within the rather narrow range of \$34/g to \$59/g; furthermore, all results for recycle to fabrication are between \$34/g and \$50/g, while the range of \$41/g to \$59/g includes all results for recycle to a diffusion plant.

E. Alternative U-236 Penalty Definition

In an attempt to remove some of the extreme variation of the $\delta(R,y)$ curves at low R values, an alternative U-236 penalty was investigated. Equation VII.9 suggests that, if the requisite assumptions are valid for a particular case, $\delta(R,y)$ will vary directly with α over the δ_1 portion of the penalty curve. A logical step is to define an "adjusted U-236 penalty", $\delta_{ADJ}(R,y)$, as follows:

$$\delta_{ADJ}(R,y) = \frac{1}{\alpha}\delta(R,y) \quad . \qquad \text{(VII.19)}$$

This effectively changes the penalty basis from one gram of U-236 in the feed purchased to one gram of U-236 which is fed to fabrication. When $V_m(R,y)$ is

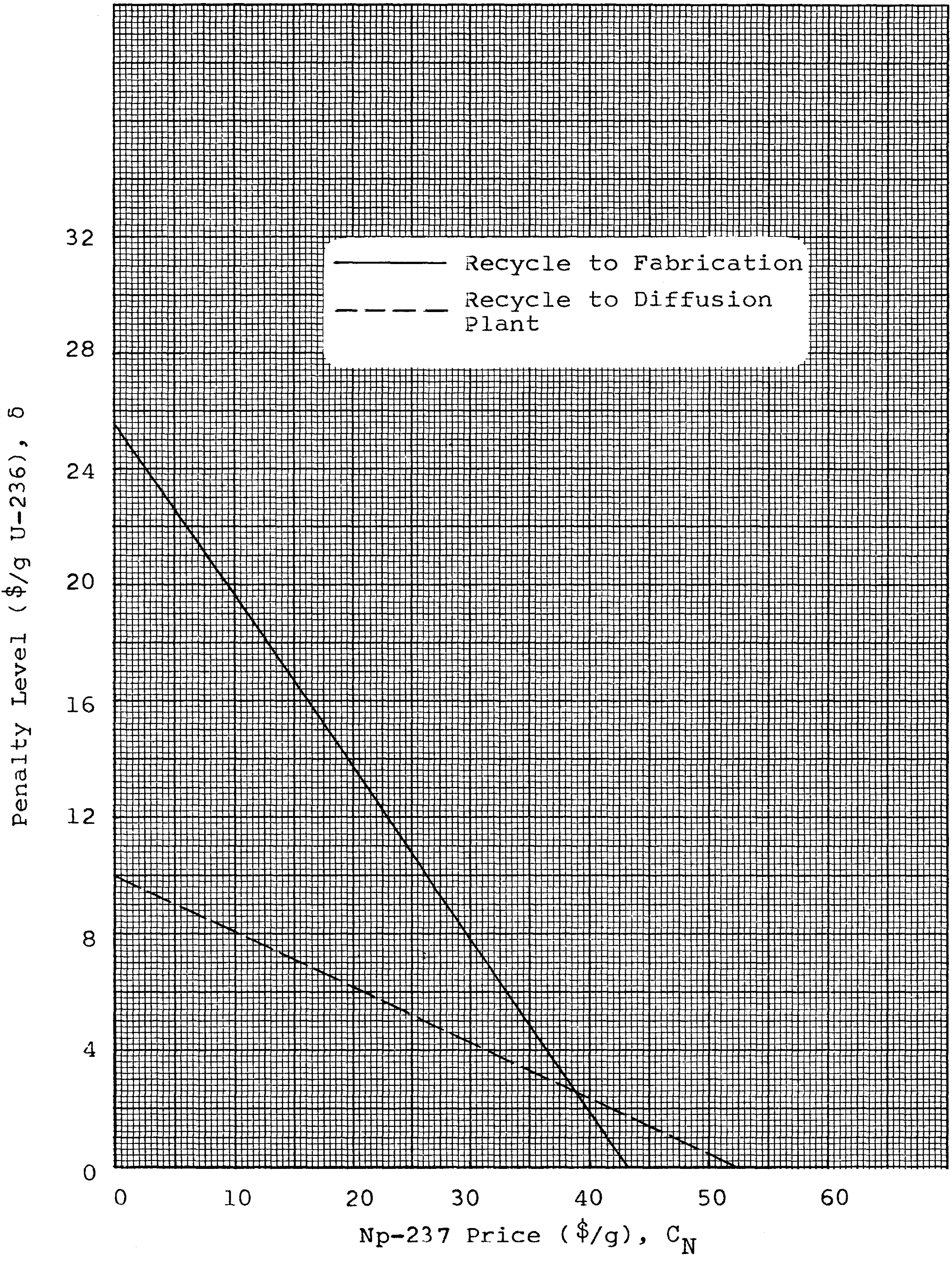


FIGURE VII.11 Variation of Penalty Level with Np-237 Price: $C_{U_3O_8}$ = \$8/lb, High Costs, L_F = 0.01

obtained by either blending with natural uranium or by basic recycle scheme operation, α can be defined as unity and $\delta(R,y) = \delta_{ADJ}(R,y)$. Results for $\delta_{ADJ}(R,y)$ were calculated for all (R,y) points at which $\alpha < 1.0$ and are listed, along with the values of α, in the tables of Appendix I.

Figures VII.12 and VII.13 show the results for $\delta_{ADJ}(R,y)$ for recycle to fabrication and to a diffusion plant, respectively, for $C_{U_3O_8} = \$8/\text{lb}$, $L_F = 0.01$, and high unit costs. Comparison with the $\delta(R,y)$ results shown in Figures VII.2 and VII.7 indicates the improvement made in "flattening" the penalty curves. For the recycle-to-fabrication scheme, substantial variation of $\delta_{ADJ}(R,y)$ with both R and y still exists for $R < R^*$, although the variation is noticeably less than for $\delta(R,y)$. However, dependence upon R and y for $R < R^*$ is significantly weaker for $\delta_{ADJ}(R,y)$ than for $\delta(R,y)$ in the case of recycle to a diffusion plant. The assumptions leading to Equation VII.9 are certainly more valid in the latter case. Figure VII.13 gives surprisingly uniform $\delta_{ADJ}(R,y)$ results at each C_N, particularly when one considers the extremely complex interactions between modes of operation which govern the $V_m(R,y)$ results.

The degree of "flattening" achieved by the use of $\delta_{ADJ}(R,y)$ does not affect the values of $\bar{\delta}$ given earlier,

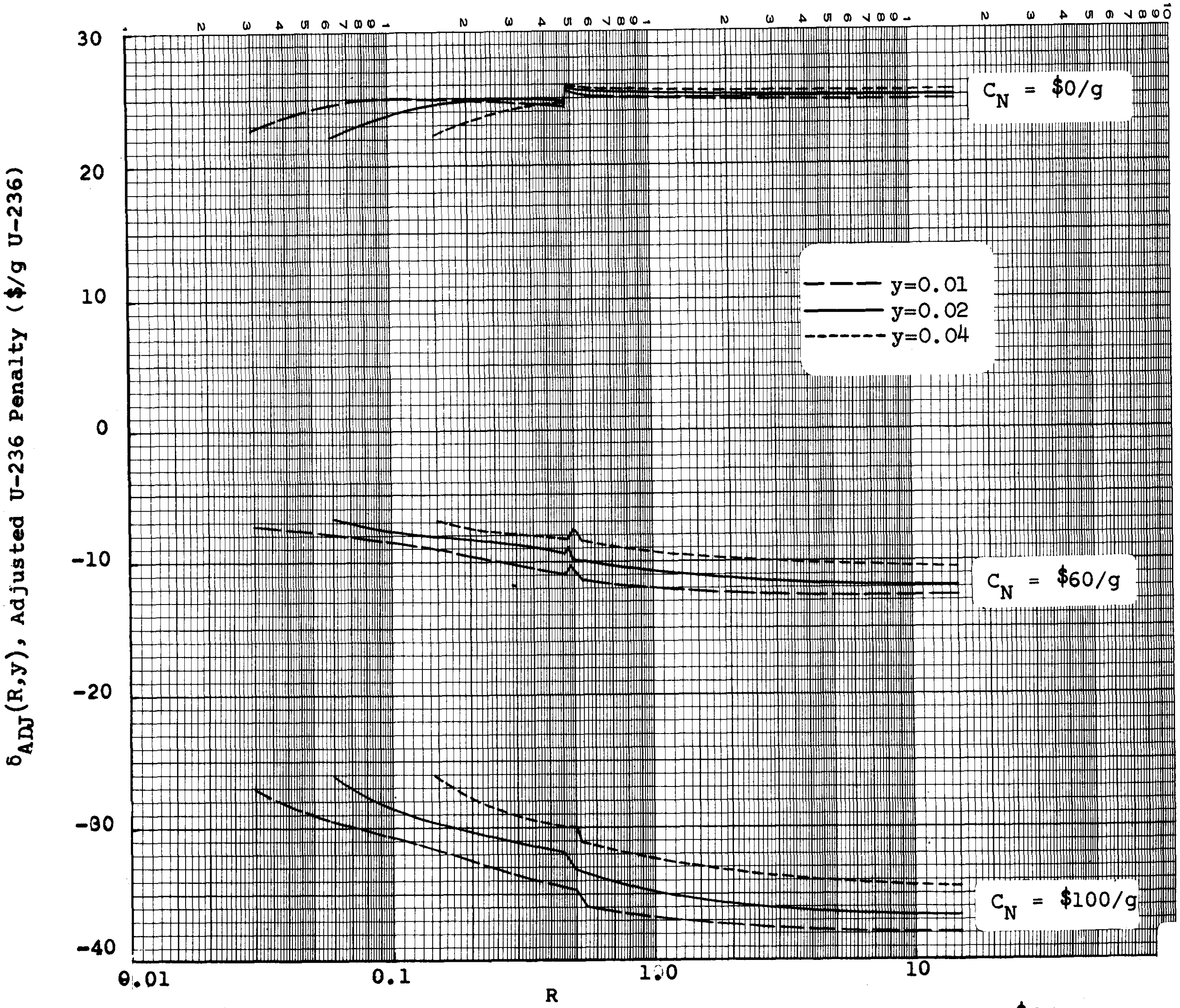


FIGURE VII.12 Adjusted U-236 Penalty - Recycle to Fabrication: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

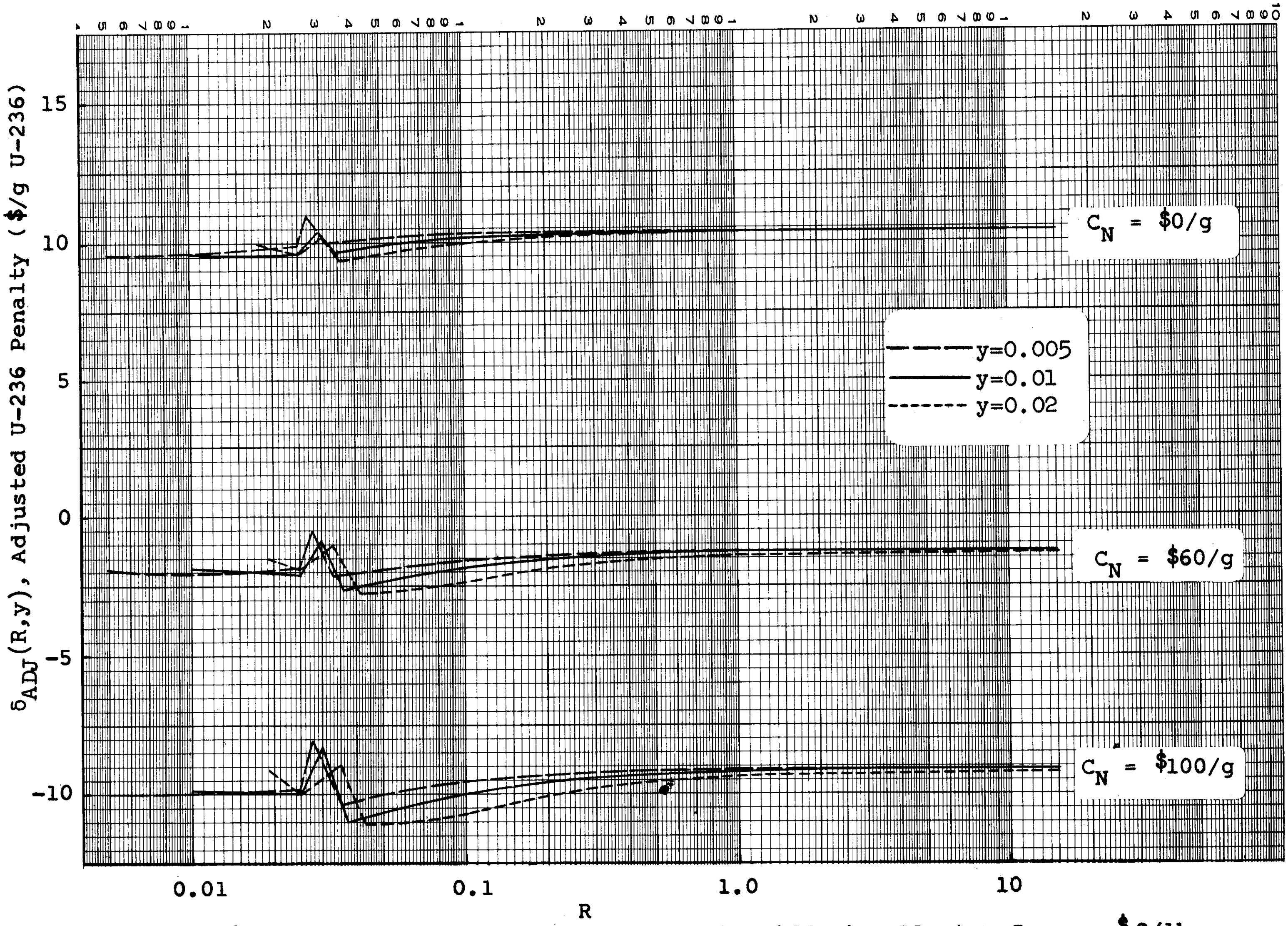


FIGURE VII.13 Adjusted U-236 Penalty - Recycle to Diffusion Plant: $C_{U_3O_8}$ = $8/lb, High Costs, L_F = 0.01

but it becomes more meaningful to use a single $\bar{\delta}$ value to characterize a set of $\delta_{ADJ}(R,y)$ results. In such a case, $\bar{\delta}$ would have units of \$/g of U-236 reaching fabrication, rather than \$/g of U-236 contained in feed.

Although $\delta_{ADJ}(R,y)$ has advantages over $\delta(R,y)$ under certain conditions and despite the insight gained by examining $\delta_{ADJ}(R,y)$, it is desirable to base the U-236 penalty on U-236 contained in the feed uranium purchased. As a result, the major emphasis has been placed on the U-236 penalty defined as $\delta(R,y)$.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The results of this study clearly indicate that operators of PWR systems must be prepared to account for the significant effects of U-236 on their fuel cycle economics when they consider the purchase of previously irradiated uranium. It has also been shown that the price at which the Np-237 produced during irradiation is sold can strongly influence the cost of power, the value of uranium containing U-236, and the selection of an optimum fuel-flow scheme.

When uranium containing no U-236 is purchased on the AEC price scale, the minimum fuel cycle cost will vary strongly with the unit price of Np-237 and the fuel flow scheme used. In general, when the Np-237 price is low, it is economically preferable to select a fuel flow scheme which minimizes the buildup of U-236 in reactor feed uranium; conversely, when the Np-237 price is high, the flow scheme which maximizes the concentration of U-236 in reactor feed uranium gives the lowest fuel cycle cost. The present work shows that, if the Np-237 price is less than about $55/g, it is economically advantageous to recycle uranium to a gaseous diffusion plant and permit the discharge of some U-236 with the tails stream; however, for Np-237 prices above about $55/g, it is preferable to maximize

U-236 retention and Np-237 production by recycling uranium directly to fabrication.

When no credit is received for the Np-237 produced during irradiation, U-236 acts only as a neutron poison and its presence in feed uranium causes the maximum unit value of feed to be less than the unit value of feed having the same U-235 to U-238 weight ratio but containing no U-236. However, as the price of Np-237 increases, the additional production of Np-237 which results from the presence of U-236 causes the unit value of any feed uranium containing U-236 to increase. For Np-237 prices above $60/g, the presence of U-236 results in a unit feed value which is higher than the corresponding value of feed containing no U-236, for any U-235 to U-238 weight ratio in the feed (R).

Except for a narrow range of R near the optimum ratio R^*, the maximum unit feed value is obtained by properly adjusting the isotopic composition of the feed prior to using it as makeup material for the basic fuel flow scheme. This is true whether the feed does or does not contain U-236 and whether the price of Np-237 is low or high. When feed has R significantly lower than R^*, its maximum unit value is obtained by pre-enriching it in a gaseous diffusion plant to a ratio nearer R^*; on the other hand, if R is significantly greater than R^*, the maximum unit feed value is obtained by blending the feed with natural uranium to give a ratio near R*.

Feed value results and the effects of U-236 and Np-237 can be effectively correlated by defining a U-236 penalty $\delta(R,y)$ as the reduction in total value per gram of U-236 when y kg of U-236 are added to 1-y kg of U-235 + U-238 at a constant U-235 to U-238 ratio. The value of the penalty at $R = R^*$, $\bar{\delta}$, provides a meaningful estimate of all $\delta(R,y)$ results calculated for a particular case. Results for $\bar{\delta}$ may be used in rough estimates of the effect of U-236 on the value of uranium feed for PWR's. Typical values for $\bar{\delta}$ at Np-237 prices of $0, $60, and $100/g, respectively, are $10, -$1.5, and -$9/g U-236 when recycling to a diffusion plant and $25.5, -$10, and -$33.5/g U-236 when recycling to fabrication, all based on a U_3O_8 price of $8/lb. The change in $\bar{\delta}$ from one set of conditions to another can be characterized as follows:

a. $\bar{\delta}$ increases as the feed rate requirement decreases;

b. $\bar{\delta}$ decreases as the minimum fuel cycle cost decreases; and

c. $\bar{\delta}$ decreases as the price of Np-237 increases.

When no credit is received for Np-237, $\bar{\delta}$ is about $15/g U-236 higher for recycle to fabrication than for recycle to a diffusion plant, due primarily to the lower feed rate requirement and higher minimum fuel cycle cost of the former scheme. However, the Np-237 production rate per unit of feed is much more sensitive to changes of the U-236 feed content in the case of recycle to fabrication, so that $\bar{\delta}$ decreases with increasing Np-237 price more rapidly than for recycle to a diffusion plant.

At a Np-237 price of C_N^o the presence or absence of U-236 is without effect on the value of a given quantity of U-235 plus U-238. All results for C_N^o fall within the range \$30/g to \$60/g Np-237. C_N^o is a measure of the relative economic importance of U-236 in feed uranium as a neutron poison and as a target material for the production of Np-237. Typically, a C_N^o value of \$43/g Np-237 for recycle to fabrication corresponds to C_N^o = \$52/g Np-237 for recycle to a diffusion plant. It can be concluded that the economic effect of feed U-236 as a poison relative to its economic effect as a Np-237 precursor is greater for recycle to a diffusion plant than for recycle to fabrication.

B. Recommendations

It is recommended that a limited study be made of how U-236 would affect uranium feed value if the unit cost of separative work were substantially different from the value of \$30/kgU used in this work.

Additional work on correlating the feed value results obtained in this study could lead to even more useful and meaningful parameters than the U-236 penalties defined herein. Many other definitions of a "U-236 penalty" could be examined in an attempt to present the effects of U-236 and Np-237 in a form which has little or no significant dependence on feed isotopic composition. Careful consideration of the factors which govern the change of $\bar{\delta}$ from case to case might lead to a penalty definition which also eliminates the strong dependence on the fuel flow scheme used and the economics parameters selected.

It would be of interest to estimate the effect on the results presented herein if other diffusion plant feed and product streams were assumed to be present during the toll enrichment operations encountered in the present study. The choice of a composition and size for each extraneous stream would be extremely arbitrary and would negate the uniqueness of results obtained. However, if procedures could be developed to simulate the dilution of U-236 in the product stream without detailed specification of these extraneous streams and without incurring excessive error in estimating separative work costs, the arbitrariness of the results might be minimized.

Another complex, but useful, study would be the determination of unit feed value throughout the period of transient flowsheet operation prior to the attainment of a steady-state recycling condition. A simple, yet tedious, procedure for including transient cycle effects would be to require that the levelized fuel cycle costs over the plant life be the same whether feed of optimum enrichment containing no U-236 is purchased on the AEC price scale for all cycles or feed having a specified isotopic composition is purchased for all cycles. However, when the same feed composition is specified for all cycles, the recycle of U-236 would result in significant differences in average burnup between transient and steady-state cycles, whether feed does or does not contain U-236. An alternative procedure might be to calculate the value of feed having composition R and y on a batch-to-batch basis by forcing the fuel cycle cost for each batch, when formed from the use of such feed, to equal the minimum fuel cycle cost which could be obtained if the same batch were formed instead from feed containing no U-236 and priced on the AEC price scale. A considerable amount of thought would be required before a procedure giving meaningful, consistent, and non-arbitrary transient-cycle feed values could be established.

Operators of other reactor types would find it advantageous to carry out studies similar to the present one when considering the use of uranium feed containing U-236, before deciding on the price they could afford to pay for such uranium. The procedures described herein can easily be adapted to other fuel flow schemes and reactor types.

Considerable effort should be expended in an attempt to forecast the market price for Np-237 before specifying a fuel flow scheme and before establishing limits on the price which can be afforded for feed uranium.

Appendices A through L, pages 236-363, are bound in Volume 2.

MIT-2073-6
MITNE-90
Vol. 2

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF NUCLEAR ENGINEERING
Cambridge, Massachusetts 02139

THE EFFECT OF URANIUM-236 AND NEPTUNIUM-237 ON THE VALUE OF URANIUM AS FEED FOR PRESSURIZED WATER POWER REACTORS
APPENDICES

by

D.A. Goellner, M. Benedict and E.A. Mason

December, 1967

For the
U.S. Atomic Energy Commission
Under Contract AT(30-1)-2073

MIT-2073-6
MITNE-90
Vol. 2

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DEPARTMENT OF NUCLEAR ENGINEERING

Cambridge, Massachusetts 02139

THE EFFECT OF URANIUM-236 AND NEPTUNIUM-237 ON THE VALUE OF URANIUM AS FEED FOR PRESSURIZED WATER POWER REACTORS

APPENDICES

by

D. A. Goellner, M. Benedict and E. A. Mason

December, 1967

For the
U. S. Atomic Energy Commission
Under Contract AT(30-1)-2073

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

APPENDIX A

REFERENCE REACTOR DESIGN CHARACTERISTICS

With few exceptions, the characteristics of the San Onofre PWR are listed below exactly as they are given in the reference design report(10), which presents detailed information only on the initial core loading. Since the initial loading utilizes SS-304 cladding, it was necessary to adjust certain design characteristics in order to represent correctly the core design for subsequent cycles when Zircaloy-4 cladding is used. When SS-304 is replaced by Zircaloy-4, the same fuel pin outer diameter (0.422 in.) is maintained, but the cladding thickness is increased from 0.0165 in. to 0.0243 in.(17) With the same diametral gap (0.0055 in.) for both claddings, the use of Zircaloy-4 leads to a pellet diameter of 0.3685 in., while the pellet diameter with SS-304 cladding is specified as 0.3835 in. Since no other changes in core design were noted(17) when Zircaloy-4 is used in place of SS-304, the volume fractions of coolant and structural material in the core remain unchanged. The volume fractions of cladding, void, and UO_2 were adjusted for the changes in dimensions mentioned above. The total core loading is reduced from 57,400 kgU to 53,000 kgU when Zircaloy-4 is used in place of SS-304 as cladding.

The listing of reference characteristics is given below.

Plant Capacity:	
Total heat output, MW	1346
Net plant efficiency, %	31.9
Net electrical output, MW	430
General Characteristics:	
Total core area (inside core baffle), ft^2	66.4
Equivalent core diameter, ft	9.2
Active core length, ft	10
Length-to-diameter ratio of core	1.09
Fuel weight, kgU	53,000
Core power density	
KW/liter of core	71.6
KW/kg of U	25.3
Number of fuel assemblies	157
Number of rod-cluster-control rods	45
Control rod material	Ag-In-Cd
Coolant Conditions:	
Nominal system pressure, psia	2100
Pressure drop, psi	
Across core	18.8
Across vessel, including nozzles	33
Flow rate, lbs/hr	
Total	76.9×10^6
Through active core	70×10^6
Flow area for active core, ft^2	33.2
Average velocity along fuel rods, ft/sec	13.1

Temperatures, $^{\circ}$F	
Inlet	552.8
Outlet, core average	601.6
Outlet, vessel average	597.6
Average film coefficient, BTU/hr-ft^2-$^{\circ}$F	5080
Average film temperature difference, $^{\circ}$F	28
Heat transfer surface area, ft^2	31,200
Average heat flux, BTU/hr-ft^2	143,400
Average linear power generation, kW/ft	4.64

Fuel Rod Specifications (cold dimensions):

Outside diameter, inches	0.422
Cladding material	Zircaloy-4
Cladding thickness, inches	0.0243
Diametral gap, inches	0.0055
Pellet diameter, inches	0.3685
Rod array in assembly	14 x 14
Lattice pitch, inches	0.556
Fuel rods per assembly	180
Number of rod-cluster-control pin positions per assembly	16
Total number fuel rods in core	28,260
Hydraulic diameter of unit cell, ft	0.0426
Additional water gap between assemblies, inches	0.019

Core Volume Fractions:

Fuel (UO_2)	0.3119
Zircaloy-4	0.0878
Water	0.5807
Inconel	0.0044
SS-304	0.0057
Void	0.0095
	1.0000

APPENDIX B

EQUATION FOR CALCULATING Np-237 BUILDUP

The production of Np-237 during irradiation results from the following reactions:

$$\begin{tikzcd}
\text{U-235} \arrow[r, "n{,}\gamma"] & \text{U-236} \arrow[r, "n{,}\gamma"] & \text{U-237} \arrow[d, "\beta^-(6.75\text{d})"] & \text{U-238} \arrow[l, "n{,}2n"'] \\
 & & \text{Np-237} &
\end{tikzcd}$$

The CELL code(13) considers the production of Np-237 from captures in U-236 alone, and neglects the contribution from (n,2n) reactions on U-238. However, other studies(32) have shown that the (n,2n) reaction on U-238 can be a significant source of Np-237; therefore, a modification of the Np-237 buildup equation used in CELL was made in order to account for this additional source. The resulting equation, which is discussed in detail below, was incorporated into the version of CELL used in the present study and in the studies performed by T. Golden(4) and D. Bauhs(5).

When the delay in the decay of U-237 to Np-237 is neglected, the differential equation for the Np-237 atom density N_{13} as a function of thermal flux-time θ can be written as:

$$\frac{dN_{13}}{d\theta} = N_6\bar{\sigma}_{a,6} - N_{13}\bar{\sigma}_{a,13} + \frac{qP_1}{\phi}[\langle 1-p_6\rangle - \langle 1-p_{13}\rangle] + \Phi\ . \tag{B.1}$$

Terms in this equation are defined as follows.

N_6	atom density of U-236
$\bar{\sigma}_{a,6}$, $\bar{\sigma}_{a,13}$	spectrum-averaged thermal absorption cross-sections for U-236 and Np-237, respectively
q/ϕ	slowing down density per unit thermal flux
P_1	fast non-leakage probability
$\langle 1-p_6 \rangle, \langle 1-p_{13} \rangle$	resonance absorption probabilities for U-236 and Np-237, respectively
Φ	the number of (n,2n) reactions on U-238 per unit volume per unit time per unit thermal flux.

When Φ is omitted in Equation B.1, the resulting equation is the one used in Reference 13 and the terms defined above are calculated as described therein. Determination of Φ is described below.

The following expression can be established:

$$\frac{\text{fissions in U-238}}{\text{cc-sec-unit thermal flux}} = \left(\frac{q}{\phi}\right)\frac{\epsilon - 1}{\epsilon(\eta_8 - 1)(1+\alpha_8)}\,, \qquad \text{(B.2)}$$

where ϵ is the fast fission factor, η_8 is the number of fast neutrons produced per fast neutron absorbed in U-238, and α_8 is the capture-to-fission ratio of U-238 for fast neutrons. If the flux per unit energy is given by $\phi(E)$, and if energy-dependent (n,2n) and fission cross-sections for U-238 are given by $\sigma^{28}_{n,2n}(E)$

and $\sigma_F^{28}(E)$, respectively, then the ratio of (n,2n) reactions on U-238 to fissions in U-238 can be written:

$$\frac{\text{U-238(n,2n)reactions}}{\text{fissions in U-238}} = \frac{\int_0^{\infty} \sigma_{n,2n}^{28}(E)\phi(E)dE}{\int_0^{\infty} \sigma_F^{28}(E)\phi(E)dE} = \frac{\bar{\sigma}_{n,2n}^{28}}{\bar{\sigma}_F^{28}} , \tag{B.3}$$

where $\bar{\sigma}_{n,2n}^{28}$ and $\bar{\sigma}_F^{28}$ are the spectrum-averaged cross-sections. By taking the product of Equations B.2 and B.3, the following expression for Φ is obtained:

$$\Phi = (\frac{q}{\phi}) \frac{(\epsilon-1)\bar{\sigma}_{n,2n}^{28}}{\epsilon(\eta_8-1)(1+\alpha_8)\bar{\sigma}_F^{28}} . \tag{B.4}$$

Pearlstein$^{(33)}$ has calculated $\bar{\sigma}_{n,2n}^{28}$ by weighting $\sigma_{n,2n}^{28}(E)$ with the following fission spectrum approximation suggested by Cranberg$^{(34)}$:

$$N(E) = 0.454e^{-\frac{E(MeV)}{0.965}} \sinh\sqrt{2.29E(MeV)} , \tag{B.5}$$

where N(E) has units of neutrons per unit energy. His assumption that the flux energy distribution $\phi(E)$ is proportional to the source energy distribution N(E) is warranted in this application since threshold energies of the (n,2n) and fission reactions in U-238 are about 6 MeV and 1 MeV, respectively. Pearlstein obtained the following result:

$$\bar{\sigma}^{28}_{n,2n} = \frac{\int_o^\infty \sigma^{28}_{n,2n}(E)N(E)dE}{\int_o^\infty N(E)dE} = 0.015 \text{ barns.} \qquad (B.6)$$

Data for $\sigma_F^{28}(E)$ were taken from Reference 35 and were similarly weighted by N(E) in order to calculate the corresponding $\bar{\sigma}_F^{28}$ value. The result obtained is as follows:

$$\bar{\sigma}_F^{28} = \frac{\int_o^\infty \sigma_F^{28}(E)N(E)dE}{\int_o^\infty N(E)dE} = 0.29685 \text{ barns.} \qquad (B.7)$$

Parabolic integration was used to evaluate the integrals in this equation.

The following result is then obtained:

$$\frac{\bar{\sigma}^{28}_{n,2n}}{\bar{\sigma}^{28}_F} = \frac{0.015}{0.29685} = 0.05053, \qquad (B.8)$$

so that the number of (n,2n) reactions in U-238 is equal to about 5% of the number of fast fissions in U-238.

By combining Equations B.8 and B.4 with Equation B.1, the Np-237 buildup equation can be written as:

$$\frac{dN_{13}}{d\theta} = N_6\bar{\sigma}_{a,6} - N_{13}\bar{\sigma}_{a,13} + \frac{g}{\phi}[P_1(<1-p_6>-<1-p_{13}>) + \frac{0.05053(\epsilon-1)}{\epsilon(\eta_8-1)(1+\alpha_8)}] \qquad (B.9)$$

which is the expression used in all CELL calculations performed for the present study.

APPENDIX C

MOVE CODE - SCATTER REFUELING VERSION

1. Description

The MOVE code(14) utilizes CELL output in order to calculate reactivity and flux distribution changes during fuel irradiation. Lattice characteristics are transferred to MOVE as functions of thermal flux-time either by means of cards punched by CELL or by magnetic tape records written by CELL. The thermal flux distribution is calculated using a two-dimensional, modified 2-group diffusion theory calculation performed in R-Z geometry. As irradiation proceeds, a record is kept of the thermal flux-time at each point, thereby permitting the rapid determination of fuel composition and macroscopic lattice characteristics using the functions generated by CELL. Thus, knowledge of the flux-time at a given space point implies knowledge of the lattice characteristics at that point as well. The code provides a number of options on the type of scheme used to control excess reactivity throughout core lifetime. When the end-of-life point is reached, the reactor may be refueled according to one of several standard fuel shuffling schemes. The code also provides for the repetition of irradiation cycles a sufficient number of times to achieve steady-state refueling. A fuel cycle cost calculation can be performed, if desired. The assumptions, analytical techniques, and operating procedures for MOVE are described in considerable detail in report NYO-9715(14). MOVE is written in Fortran II and requires a 32,000-location memory.

In order to use MOVE for the present study, two major changes were required. First, a provision for 4-batch modified scatter refueling was incorporated and second, the point-wise calculation of lattice characteristics was adjusted to simulate the "mixing" of different fuel batches throughout the region refueled scatterwise. As discussed in Section III, fresh fuel is charged to an outer radial annulus which occupies one-fourth the core volume. After irradiation for one cycle in this annulus, the fuel is placed uniformly throughout the inner three-quarters of the core, occupying positions left vacant by the discharge of fuel elements irradiated for a total of four cycles in the core. After they are placed in the inner, "scatter" portion of the core, fuel elements remain in place for three subsequent cycles before being discharged from the reactor.

Since the "revised" MOVE requires that the fuel charged to the outer annulus must have the same isotopic composition for all cycles leading to steady-state refueling, only a single value of thermal flux-time is needed at each point in the outer annulus in order to calculate lattice characteristics. However, within the "scatter" region of the core, three batches of fuel elements are present, each characterized by its period of residence within the core. Due to the coarse mesh point specification permitted by MOVE (10 points radially and 15 points axially), it is convenient to assume that, at any point within the "scatter" region, lattice characteristics can be taken as the arithmetic average of the lattice characteristics at that mesh point for the three batches of fuel. It is necessary, therefore, to retain three thermal flux-times at each mesh point in the scatter region, each flux-time enabling the calculation of lattice characteristics for the fuel batch to which it corresponds. What is done, in effect, is to assume that each batch of fuel fed to the inner core region is "scattered" in a sufficiently uniform manner to permit local homogenization of lattice properties at each mesh point. The validity of such an assumption depends upon the relative sizes of the core and the fuel elements, but such a procedure is necessary to simulate scatter refueling in MOVE. This homogenization is discussed analytically later in this appendix.

At the end of each irradiation period, refueling can easily be simulated by setting the flux-time equal to zero (fresh fuel) at all points in the outer annulus and by properly adjusting the three flux-time values at each point in the scatter region, using a procedure to be described.

The refueling procedure can be terminated after a specified number of cycles or can be continued until a sufficient number of cycles have been examined that the flux-times characterizing two successive discharged fuel batches are all within a specified tolerance, i.e., until steady-state refueling is attained. For the steady-state refueling conditions, the code will calculate all characteristics for the basic uranium-recycle flowsheets shown in Figures IV.1 and IV.2, using the analytical procedures described in Section IV.

It is not necessary to start a MOVE run with fresh fuel throughout the core, i.e., with zero flux-time at all mesh points. The attainment of steady-state refueling can be expedited by specifying a starting flux-time distribution which more closely approximates that of the steady-state cycle.

In its revised form, the MOVE code is highly problem-oriented, in that many options available in the original version are excluded when they are not necessary for the present study. In particular, no other refueling procedures are available except the modified scatter scheme described above. Also, the fuel cycle cost calculation is not included in the revised version since the economics analysis for this study is not performed until data from all steady-state refueling calculations are obtained. The input data requirement has been modified and is described in detail at the end of this appendix.

Despite these modifications, very little of the theory and analysis and none of the basic philosophy of the original version of MOVE has been affected.

Figure C.1 shows the broad logical flow of control in the revised MOVE. Items of particular interest are marked by underscored numbers and are discussed in more detail in Part 2 of this appendix.

2. Methods Used

The underscored numbers in Figure C.1 mark steps where major deviations from the description of MOVE in NYO-9715(14) occur. The steps so indicated are discussed below.

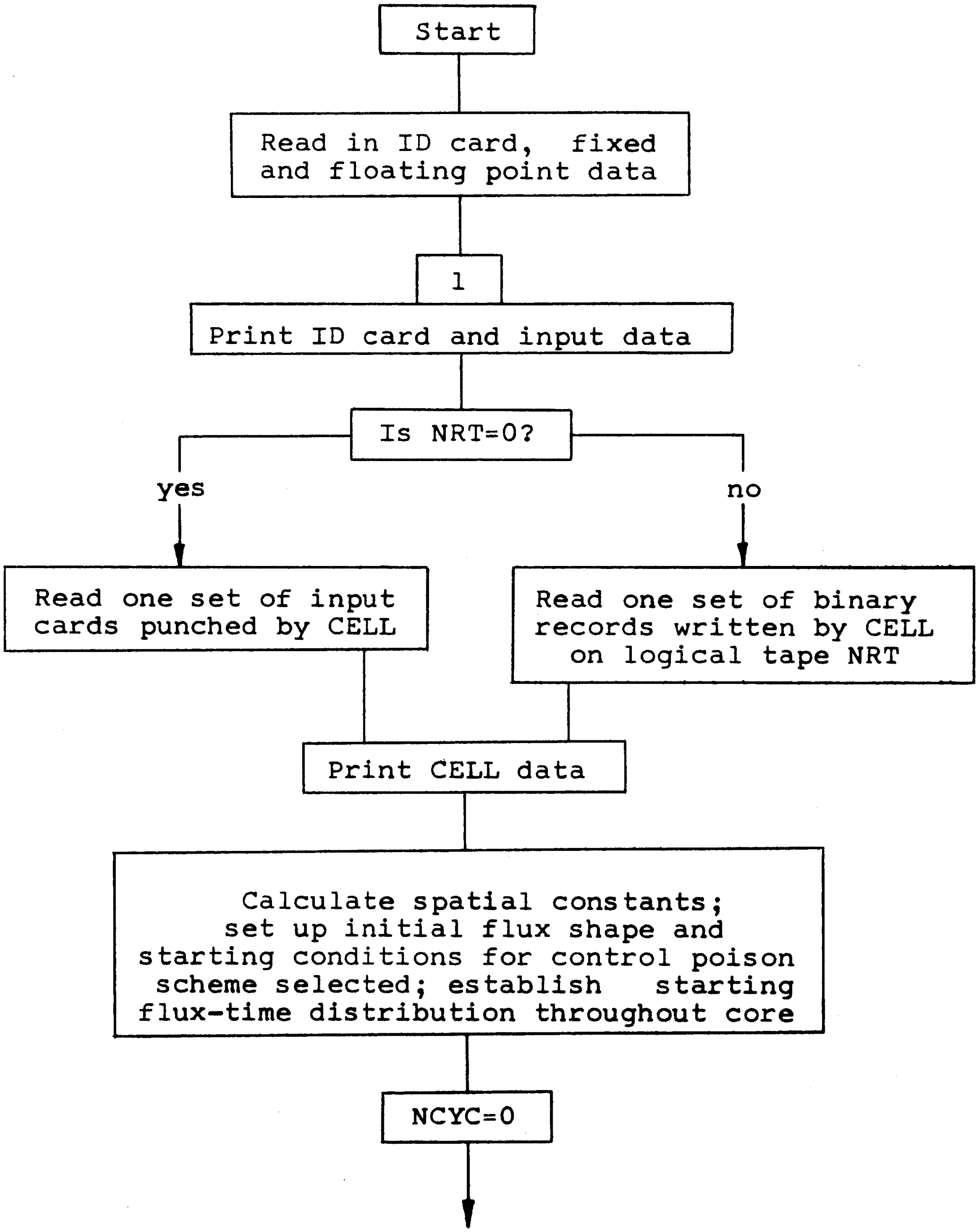
1. Consider the calculation of a lattice property, denoted by $\bar{P}$, for a general mesh point at which thermal flux-times of $\theta_{(1)}$, $\theta_{(2)}$, and $\theta_{(3)}$ are known. These flux-times correspond to fuel irradiated in the core for 1, 2, and 3 cycles prior to the start of the cycle being considered. If the value of the lattice property for a flux-time of θ is given by $P(\theta)$, then the data supplied by CELL is in the form $P(\theta_1)$, $P(\theta_2)$,----,$P(\theta_L)$ corresponding to flux-time values of θ_1, θ_2,----,θ_L.

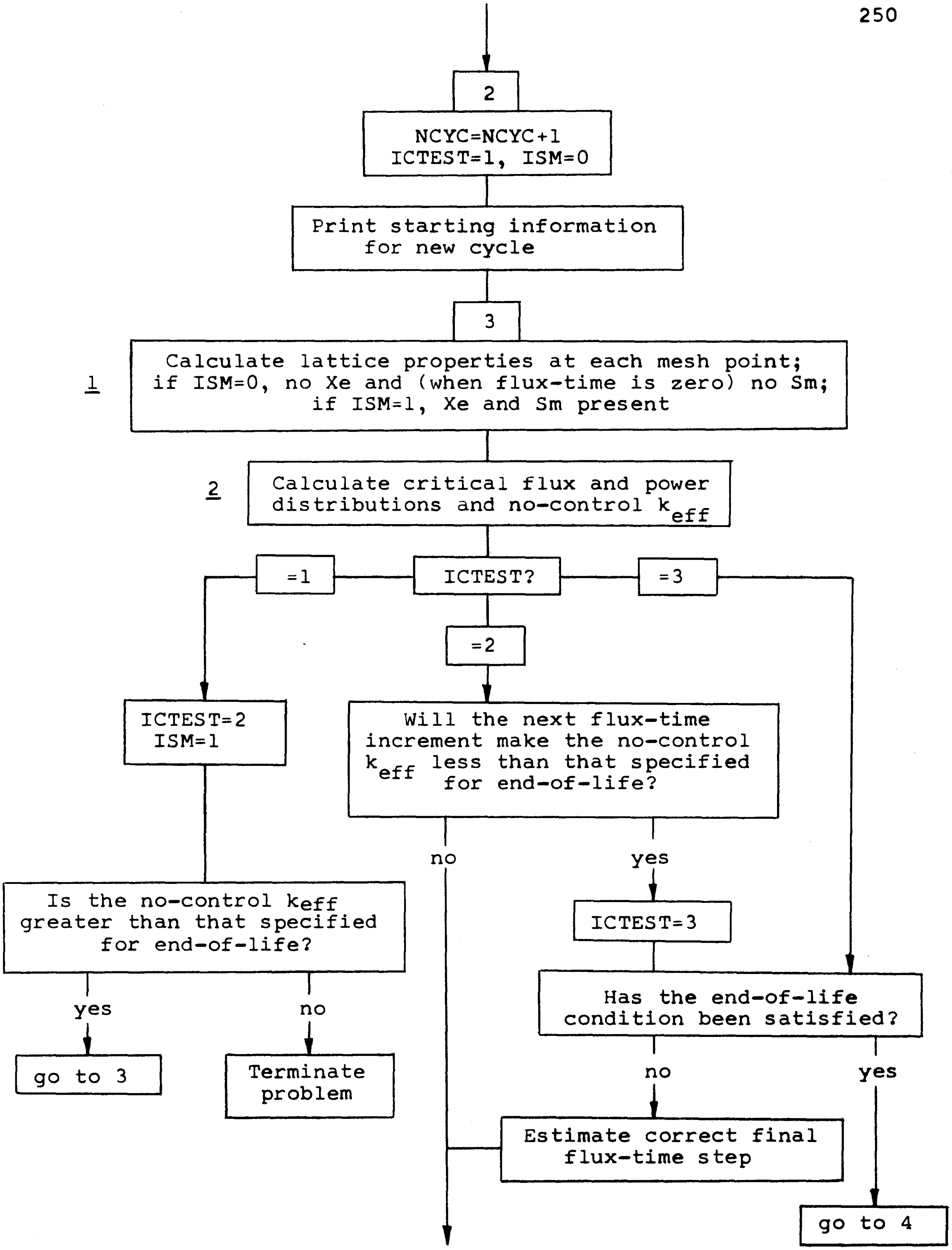
Using Lagrangian interpolation(26), the value for P at some flux-time θ can be determined from

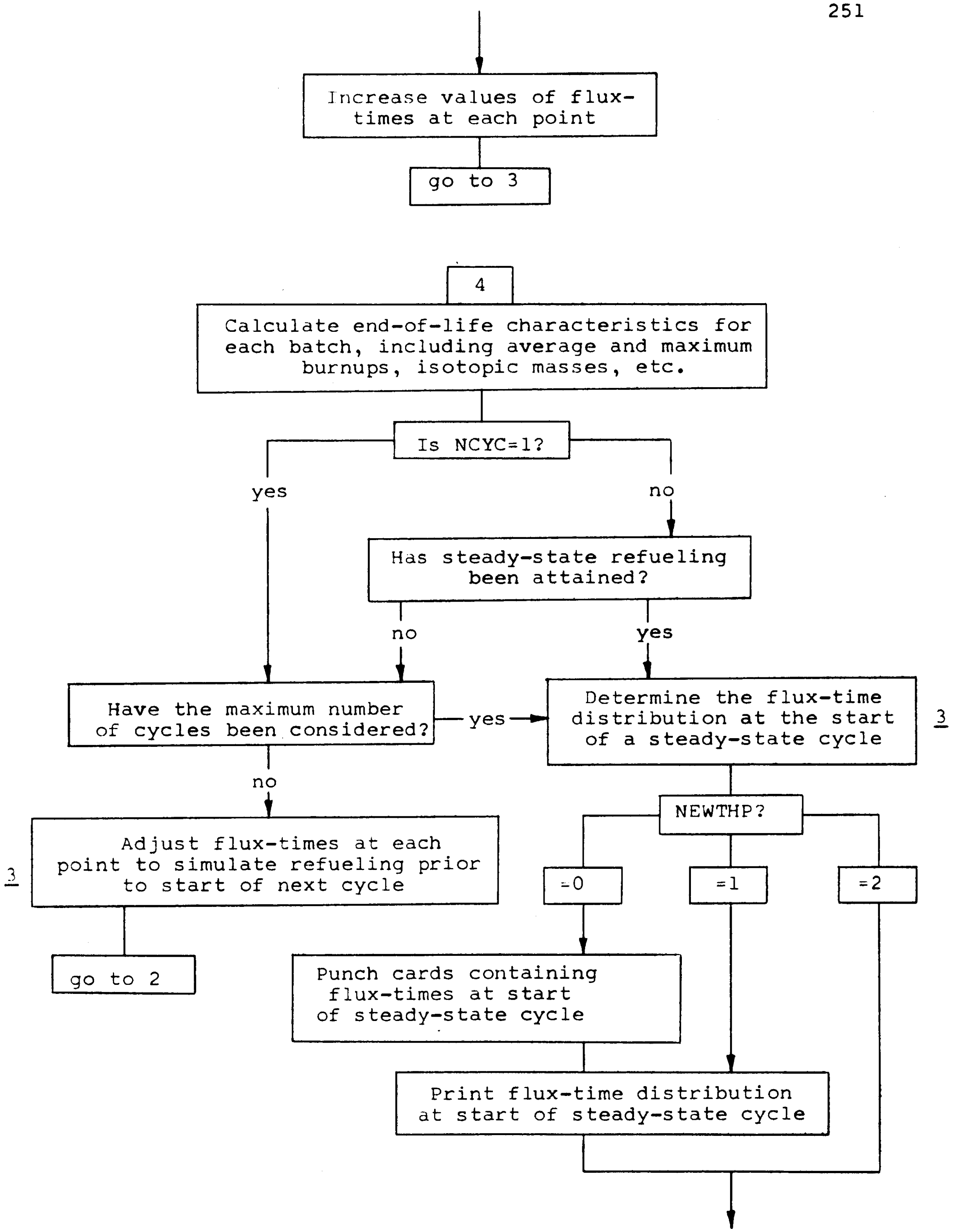
$$P(\theta) = \sum_{i=1}^{L} L_i(\theta) P(\theta_i) \ , \qquad \text{(C.1)}$$

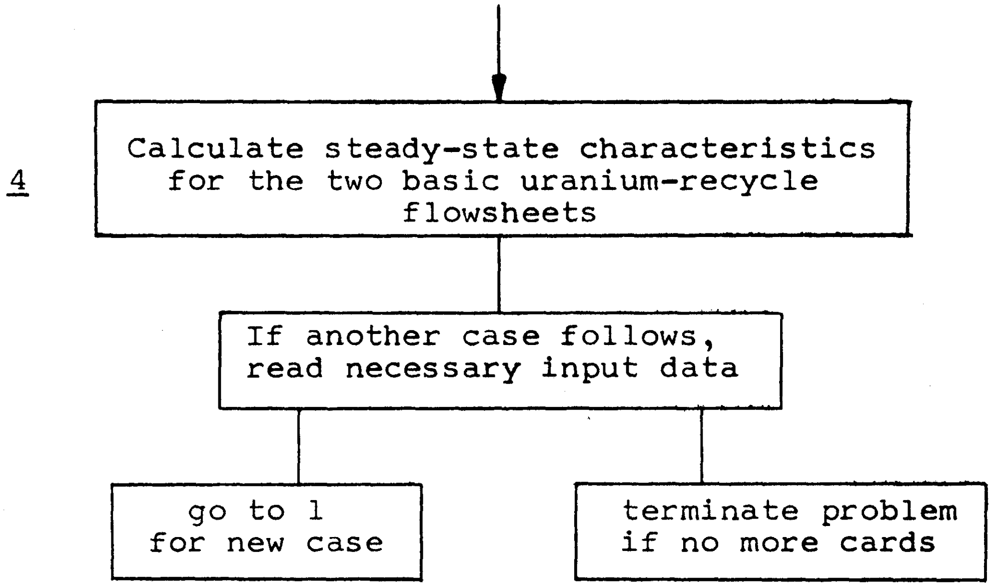
where the Lagrangian coefficient $L_i(\theta)$ is given by

FIGURE C.1 Flow Diagram for Scatter-Refueling Version of MOVE




2
NCYC=NCYC+1
ICTEST=1, ISM=0
Print starting information for new cycle
3
1
Calculate lattice properties at each mesh point; if ISM=0, no Xe and (when flux-time is zero) no Sm; if ISM=1, Xe and Sm present
2
Calculate critical flux and power distributions and no-control k_{eff}
=1
ICTEST?
=3
=2
ICTEST=2
ISM=1
Will the next flux-time increment make the no-control k_{eff} less than that specified for end-of-life?
no
yes
Is the no-control k_{eff} greater than that specified for end-of-life?
ICTEST=3
Has the end-of-life condition been satisfied?
yes
no
go to 3
Terminate problem
no
yes
Estimate correct final flux-time step
go to 4


Increase values of flux-times at each point
go to 3
4
Calculate end-of-life characteristics for each batch, including average and maximum burnups, isotopic masses, etc.
Is NCYC=1?
yes
no
Has steady-state refueling been attained?
no
yes
Have the maximum number of cycles been considered?
yes
Determine the flux-time distribution at the start of a steady-state cycle
3
no
NEWTHP?
3
Adjust flux-times at each point to simulate refueling prior to start of next cycle
=0
=1
=2
go to 2
Punch cards containing flux-times at start of steady-state cycle
Print flux-time distribution at start of steady-state cycle


4
Calculate steady-state characteristics for the two basic uranium-recycle flowsheets
If another case follows, read necessary input data
go to 1 for new case
terminate problem if no more cards

$$L_i(\theta) = \frac{(\theta_1-\theta)(\theta_2-\theta)\text{---}(\theta_{i-1}-\theta)(\theta_{i+1}-\theta)\text{---}(\theta_L-\theta)}{(\theta_1-\theta_i)(\theta_2-\theta_i)\text{---}(\theta_{i-1}-\theta_i)(\theta_{i+1}-\theta_i)\text{---}(\theta_L-\theta_i)} \cdot \tag{C.2}$$

Equation C.1 can be used to evaluate P at each of the flux-times $\theta_{(1)}$, $\theta_{(2)}$, and $\theta_{(3)}$ and $\bar{P}$ can then be determined by simple arithmetic averaging since all fuel batches in the core have equal volume.

$$\bar{P} = \tfrac{1}{3}[P(\theta_{(1)}) + P(\theta_{(2)}) + P(\theta_{(3)})] \tag{C.3}$$

If Equations C.1 and C.2 are combined with Equation C.3, the following expression for $\bar{P}$ is obtained:

$$\bar{P} = \sum_{i=1}^{L} \bar{L}_i P(\theta_i) \ , \tag{C.4}$$

where the modified Lagrangian coefficient $\bar{L}_i$ is given by

$$\bar{L}_i = \frac{\sum_{k=1}^{3}(\theta_1-\theta_{(k)})(\theta_2-\theta_{(k)})\text{---}(\theta_{i-1}-\theta_{(k)})(\theta_{i+1}-\theta_{(k)})\text{---}(\theta_L-\theta_{(k)})}{3(\theta_1-\theta_i)(\theta_2-\theta_i)\text{---}(\theta_{i-1}-\theta_i)(\theta_{i+1}-\theta_i)\text{---}(\theta_L-\theta_i)} \tag{C.5}$$

Equations C.4 and C.5 can be used at any point in the core, if values for $\theta_{(1)}$, $\theta_{(2)}$, and $\theta_{(3)}$ are properly assigned. For points within the "scatter" region, these values will generally be different due to the different residence time of the three batches of fuel present. However, in the outer annulus only fresh fuel is irradiated so that lattice properties could be determined by retaining only a single flux-time value at each point. This is done in effect by maintaining the condition that $\theta_{(1)} = \theta_{(2)} = \theta_{(3)}$, so that Equations C.4 and C.5 yield the correct result at points throughout the outer annulus, as well.

2. In the original version of MOVE(14), the procedure for calculating the pointwise flux distribution includes the solution of a system of difference equations by means of a modified Crout reduction scheme described by Shanstrom.(27) However, Richardson(28) has modified the solution of the difference equations by using the "extrapolated Liebmann" method(29), rather than the Crout reduction scheme. Although results given by the two procedures are the same, the Liebmann version was used in the scatter-refueling version of MOVE.

3. To describe the preparation of starting flux-times for the next cycle from the flux-times at the end of the previous cycle the following nomenclature is used:

IRL,	the total number of radial mesh points;
JZL,	the total number of axial mesh points;
A_i,	area of annual ring associated with radial mesh point i;
NSRB,	the number of the outermost mesh point in the scatter region;
$\theta^{i,j}_{(k)}$,	flux-time at start of next cycle at radial point i and axial point j where k=1 denotes least-exposed fuel, k=2 denotes fuel of intermediate exposure, and k=3 denotes fuel of highest previous exposure; and

$\gamma^{i,j}_{(k)}$, flux-time at end of previous cycle, with same notation as above.

The inner scatter region includes radial mesh points from i=1 to i=NSRB, while the outer annulus includes points from i=NSRB+1 to i=IRL. As mentioned in the discussion of 1 above, the condition that $\gamma^{i,j}_{(1)} = \gamma^{i,j}_{(2)} = \gamma^{i,j}_{(3)}$ is true for all points in the outer annulus.

The batch of fuel discharged from the reactor during refueling is characterized by the flux-times $\gamma^{i,j}_{(3)}$ with i ranging from 1 to NSRB and j ranging from 1 to JZL. The first steps in simulating the refueling are as follows:

$$\theta^{i,j}_{(3)} = \gamma^{i,j}_{(2)} ,$$

and $\theta^{i,j}_{(2)} = \gamma^{i,j}_{(1)}$,

for i=1 through i=NSRB and for j=1 through JZL. In simulating the transfer of fuel from the outer annulus to the scatter region, the area-averaged flux-time at a given axial mesh point number (j) in the outer annulus is transferred to all points in the scatter region at that same axial mesh point number. This is indicated symbolically as follows:

$$\theta^{i,j}_{(1)} = \frac{\sum\limits_{n=NSRB+1}^{IRL} A_n \gamma^{n,j}_{(1)}}{\sum\limits_{n=NSRB+1}^{IRL} A_n} ,$$

where i ranges from 1 to NSRB and j ranges from 1 to JZL. The refueling simulation is completed by setting $\theta^{i,j}_{(1)} = \theta^{i,j}_{(2)} = \theta^{i,j}_{(3)} = 0$ for i=NSRB+1 through i=IRL and for j=1 through j=JZL, since fresh fuel is added to the outer annulus for the start of the next cycle.

4. After steady-state refueling has been attained, the isotopic compositions and time-averaged flow rates throughout the two basic recycle flowsheets, shown in Figures IV.1 and IV.2, are calculated by using the equations developed in Part A of Section IV. One has the option to read in up to 10 values for the optimum tails U-235 to U-238 weight ratio and the code will calculate a separate set of characteristics for each value, in the case of recycle to a diffusion plant.

3. Input Description

The nine basic types of input data used for the scatter-refueling version of MOVE are described below. Definitions of all variables are given along with the limitations on their size and the format in which they are to be punched on cards. Reference 14 contains more elaborate definitions for many of the variables. Some definitions refer to the variable ZETA, which is used in CELL as the size of the flux-time step, in neutrons/barn, for the step-wise solution of the nuclide concentration equations. The input data described below must be supplied exactly in the order given.

a. Title card:

All 72 columns are available for use.

b. Floating point data:

This data is punched on four cards in 6E12.8 format.

R(I), I=1,10	outer radii for each radial mesh area, cm; even if less than 10 radial mesh points are used, 10 data fields should be allotted.
H	active height of core, cm
DELR	radial reflector savings, cm
DELH	axial reflector savings, cm
ZSYM	axial symmetry control; if = 0.0, core is assumed to be axially symmetric around midplane; if $\neq 0$, full core height calculation is performed
DBSQU	initial thermal leakage estimate, cm^{-1}
PFAST	initial fast non-leakage probability estimate
PDENAV	core average power density, kW/l
ERROR	flux iteration convergence criterion; when $\|\Delta\phi\|/\phi <$ ERROR at all points, flux iteration has converged
DELCRT	end-of-life convergence criterion; when k_{eff} with no control poison is within CRIT ± DELCRT, the cycle is terminated and the reactor refueled (CRIT is defined next).

CRIT	the no-control k_{eff} desired at the end of each cycle, normally 1.0
ZET2	the central flux-time step taken during the irradiation, neutrons/barn
F	over-relaxation parameter in extrapolated Liebmann method; must be between 1.0 and 2.0, with 1.5 generally a good choice
TIGG	maximum number of iterations permitted for flux calculation; a number >50 is usually satisfactory
SSCVG	convergence criterion for attainment of steady-state refueling; when $\lvert\Delta\theta\rvert/\theta <$ SSCVG for all points of two successive discharged fuel batches, steady-state is attained.

c. Fixed point data:

The following data is punched in 24I3 format.

LOCPRP(1)	relative location on binary tape of the CELL code output which is to be used by MOVE; if NRT=0 (see below), this field can be left blank
NSRB	the number of the outermost radial meshpoint in the scatter region; must be $\leqslant 9$
IRL	total number of radial mesh points; must be >NSRB but $\leqslant 10$
JZL	total number of axial mesh points; must be $\leqslant 15$
NCYCM	maximum number of cycles to be run in an attempt to attain steady-state refueling
NTHETP	=0, print out flux-time distribution at start and end of each cycle; $\neq 0$, bypass printout

NCP	>0, punch starting flux-time distribution for (NCP+1)st cycle at end of NCPth cycle; = 0, bypass punching of cards.
NRT	logical number of the binary tape containing CELL code results; if = 0, data is read in from cards punched by CELL
IPOIS	poison management control parameter; =1, uniform poison removal =2, radial zone poison removal =3, axial bank poison removal
NPOISR	number of radial mesh points, starting at the outer edge of core, containing no control poison
NP0ISZ	number of axial mesh points, starting at the end, containing no control poison
ITRATE	maximum number of iterations permitted in obtaining the correct amount of control poison to give a poisoned k_{eff} within 1.0 ± 0.005
IPRT1	$\neq 0$, print out flux and power distributions at each flux-time step; = 0, bypass printout but see IPRT3 below
IPRT2	$\neq 0$, print out detailed results from all subroutines; = 0, bypass printout; generally = 0
IPRT3	$\neq 0$, print out flux and power distributions at start and end of each cycle; = 0, bypass printout
IPSPPR	$\neq 0$, print out values of lattice properties at each mesh point whenever they are calculated; = 0, bypass print out; generally = 0

IPSGMW	≠ 0, print out control poison macroscopic absorption cross-section at each mesh point; = 0, bypass print out
INORMP	> 0, normalized control poison absorption cross-section read in for each mesh point; = 0, set to 1.0 at each point; < 0, current values go unaltered
IABSP	> 0, absolute (fixed) poison macroscopic absorption cross-section read in for each mesh point; = 0, set equal to zero at each point; < 0, current values go unaltered
ITHET	> 0, flux-times normalized to the CELL value for ZETA are read in at each point to start the calculation; = 0, flux-times set equal to zero at each point; > 0, current values go unaltered
NEWTHP	= 0, print out flux-time distribution at start of steady-state cycle and punch flux-times on cards suitable for subsequent input to MOVE; = 1, print only; = 2, bypass both printout and punching

d. CELL data:

If NRT = 0, read in a block of cards containing CELL punched output, including the heading card punched by CELL.

If NRT > 0, skip this part and go on to "e".

e. Normalized control poison data:

If INORMP > 0, read in pointwise values for the control poison macroscopic absorption cross-section arbitrarily normalized, i.e., in relative units. These are read in as ((SIGMWN(I,J),I=1,10),J=1,JZL) in 6E12.8 format.

If INORMP $\leqslant 0$, skip this part and go on to "f".

f. Absolute poison data:

If IABSP > 0, read in pointwise values for the fixed-poison macroscopic absorption cross-section as ((SIGMWA(I,J), I=1,10), J=1,JZL) in 6E12.8 format.

If IABSP $\leqslant 0$, skip this part and go on to "g".

g. Starting flux-time data:

If ITHET > 0, read in three flux-times for each mesh point as (((THETA(I,J),I=1,10),J=1,15),K=1,3) in 6E12.8 format. These flux-times are normalized to the CELL value for ZETA. The THETA block is preceded by a heading card as punched by MOVE. Note that THETA(I,J,K) corresponds to $\theta_{(k)}^{i,j}$ as defined in Part 2 of this appendix.

If ITHET $\leqslant 0$, skip this part and go on to "h".

h. Data for recycle calculations:

The first card contains the following six items in 6E12.8 format.

PTH	reactor thermal power output, MW
PF	average plant load factor
FRLFB	fraction of fuel lost during fabrication, based on fabricated product
FRLC	fraction of fuel lost during conversion of UO_3 to UF_6, based on converted product

FRLRU	fraction of uranium lost during reprocessing, based on uranium fed to reprocessing plant
FRLRP	fraction of Np + Pu lost during reprocessing, based on Np and Pu fed to reprocessing plant

The second card contains the following single item in I2 format.

NTAR	the number of tails U-235 to U-238 weight ratios to be considered for the recycle-to-diffusion-plant flowsheet; must be ≤ 10

The third and, if necessary, fourth cards contain the following in 6E12.8 format.

RW(N),N=1,NTAR	the tails U-235 to U-238 weight ratio values to be considered

i. Data for a subsequent case:

If only one case is to be run, the input cards are complete after "h" . Any number of cases can be run consecutively. If a second or subsequent case is to be run, the following cards are required:

(1) title card - all 72 columns available;

(2) one card with format 7I3, containing LOCPRP(1), NRT, NCP, NCYCM, ITHET, INORMP, and IABSP, all as defined previously in "c" . Other fixed-point input and all floating-point input remains unchanged in storage.

(3) Repeat "d" through "h" for the new case.

APPENDIX D

INPUT DATA FOR CELL AND MOVE CODES

Input data for typical CELL and MOVE cases are listed in Tables D.1 and D.2, respectively. For symbol definitions, refer to Reference 13 for CELL and to Appendix C of this work for MOVE (scatter refueling version). Sources used for obtaining many of the input data are noted in the tables, while comments regarding several of the input values are given below. Unless otherwise specified, input data describing the reactor and its operation were obtained from the information given in Reference 10.

The input data listed corresponds to the use of reactor feed uranium having a U-235 to U-238 weight ratio of 0.03 and a weight fraction of U-236 equal to 0.01. Atom densities for uranium isotopes were calculated using a mass density of 10.2 g/cc for UO_2.(10)

The following microscopic cross-section information is required by CELL:

SAO(K)	absorption cross-section, 2200 m/sec;
STR(K)	$(1-\bar{\mu})\sigma_S$ for thermal neutrons;
ESSR(K)	slowing-down power, $\xi\sigma_S^{RES}$; and
RINT(K)	resonance integral, infinite dilution.

For these items, the following subscript designations were made:

K = 1 UO_2
2 Zircaloy-4

3 H_2O
4 H_2O
5 Inconel
6 SS-304
7 Void
8 Not Used

The thermal and resonance cross-section libraries used by CELL are described in Reference 13.

The nine radial mesh points for MOVE were specified in such a way that the outer annulus loaded with fresh fuel has one-fourth of the total core volume and the inner scatter region has three-fourths of the core volume.

Uniform poison removal was selected as the control scheme in MOVE, since this procedure is a good representation of the actual soluble poison control method to be used for the San Onofre reactor.(10)

For MOVE, the radial (δR) and axial (δH) reflector savings were assumed to be equal and were determined from the following equation:

$$B_g^2 = \left(\frac{2.405}{R + \delta R}\right)^2 + \left(\frac{\pi}{H + 2\delta H}\right)^2 ,$$

where the geometric buckling B_g^2, the equivalent core radius R, and the active core height H are given in Reference 10 as 0.000362 cm^{-2}, 140.13 cm, and 304.8 cm, respectively. The result obtained is $\delta R = \delta H = 7.5$ cm.

TABLE D.1

Input Data for CELL Code

<u>NOTE</u>: Numbers in parentheses after input values refer to source references.

ANIN(5) = 0.00066796 atoms/barn-cm

ANIN(6) = 0.00023067

ANIN(7) = 0.0

ANIN(8) = 0.021984

ANIN(9) = 0.0

ANIN(10) = 0.0

ANIN(11) = 0.0

ANIN(12) = 0.0

ANIN(13) = 0.0

ACLD = 0.04326 atoms/barn-cm (39)

ACOL = 0.02399 atoms/barn-cm

RAD = 0.4680 cm

R1 = 0.7968 cm

R2 = 0.5359 cm

TC = 0.06096 cm

ZLAT = 0.0

VFF = 0.31190

VFVD = 0.00938

VFCLD = 0.08776

VFCOL = 0.49502

VFEX = 0.09594

VEM(1) = 0.89286

VEM(2) = 0.04634
VEM(3) = 0.05984
VEM(4) = 0.00096
VEM(5) = 0.0
ANN(1) = 0.02399 atoms/barn-cm
ANN(2) = 0.0837
ANN(3) = 0.0881 (39)
ANN(4) = 0.0
ANN(5) = 0.0
DIFAC(1) = 1.0
DIFAC(2) = 1.0
DIFAC(3) = 1.0
DIFAC(4) = 1.0
DIFAC(5) = 1.0
SAO(1) = 0.0 barns (not used) (13)
SAO(2) = 0.18 (39)
SAO(3) = 0.664 (36)
SAO(4) = 0.664 (36)
SAO(5) = 4.21 (37)
SAO(6) = 2.99 (39)
SAO(7) = 0.0
SAO(8) = 0.0
STR(1) = 16.5 barns (37)
STR(2) = 7.88 (37)
STR(3) = 50.5 (38)
STR(4) = 50.5 (38)
STR(5) = 13.8 (37)

STR(6) = 9.8 (37,39)

STR(7) = 0.0

STR(8) = 0.0

SCRTA = 7.6 barns (39)

SSRCL = 6.1 barns (39)

SSRCO = 44.8 barns (39)

ESSR(1) = 0.97 barns (39)

ESSR(2) = 0.1328 (39)

ESSR(3) = 41.44 (39)

ESSR(4) = 41.44 (39)

ESSR(5) = 0.484 (37,39)

ESSR(6) = 0.387 (39)

ESSR(7) = 0.0

ESSR(8) = 0.0

RINT(1) = 0.0 barns (not used) (13)

RINT(2) = 1.56 (37,40)

RINT(3) = 0.2676 (13)

RINT(4) = 0.2676 (13)

RINT(5) = 2.57 (37,40)

RINT(6) = 2.20 (37,40)

RINT(7) = 0.0

RINT(8) = 0.0

RIUFP = 181.0 barns (13)

RIPFP = 264.0 barns (13)

TMOD = 302.8 degrees C (10)

TEFF = 1089.0 degrees K (17)

TAU = 52.2 cm^2 (10)

P1IN = 0.9815
POWERD = 71.6 kw/l
PDNLIM = 400.0 kw/l
ENNFIS(1) = 201.0 MeV/fission (13)
ENNFIS(2) = 203.0 (13)
ENNFIS(3) = 211.0 (13)
ENNFIS(4) = 213.0 (13)
SFAC(1) = 0.79808 (13)
SFAC(2) = 0.76846 (13)
XEADJ = 1.0
SMADJ = 1.0
FPFCTR = 1.0
ZETA = 0.0002 neutrons/barn
EVCUT = 0.625 eV
B22 = 0.000362 cm^{-2} (10)
EPSI = 0.0
RI8CHK = 0.0
IL = 63
NRES = 68
NUMPOZ = 30
NUMSPA = 2
NWILK = 1
NPOICK = 1
NPT = 3
NWT = 9
ISKIP = 0
INPUT = 1

IPRNT = 1

IPRTI = 0

IPRT2 = 0

IPRWLK = 0

POISON(I) = 0.018514 cm^{-1}, I = 1,30

Thermal cross-section data (13)

Lethargy increments (13)

Resonance cross-section data (13)

Wigner-Wilkins startup data (13)

TABLE D.2

Input Data for MOVE Code - Scatter Refueling Version

R(1) = 15.168 cm

R(2) = 30.336

R(3) = 45.504

R(4) = 60.672

R(5) = 75.839

R(6) = 91.007

R(7) = 106.175

R(8) = 121.343

R(9) = 140.130

R(10) = 0.0

H = 304.8 cm

DELR = 7.5 cm

DELH = 7.5 cm

ZSYM = 0.0

DBSQU = 0.0001267 cm^{-1}

PFAST = 0.9815

PDENAV = 71.6 kw/l

ERROR = 0.005

DELCRT = 0.001

CRIT = 1.0

ZET2 = 0.0002 neutrons/barn

F = 1.5

TIGG = 200.0

SSCVG = 0.015

LOCPRP(1) = 1

NSRB = 8

IRL = 9

JZL = 15

NCYCM = 12

NTHETP = 0

NCP = 8

NRT = 9

IPOIS = 1

NPOISR = 0

NPOISZ = 0

ITRATE = 20

IPRT1 = 0

IPRT2 = 0

IPRT3 = 1

IPSPPR = 0

IPSGMW = 0

INORMP = 0

IABSP = 0

ITHET = 0

NEWTHP = 0

PTH = 1346.0 MW

PF = 0.8

FRLFB = 0.01

FRLC = 0.003

FRLRU = 0.01

FRLRP = 0.01

NTAR = 3

RW(1) = 0.0023173

RW(2) = 0.0025372

RW(3) = 0.0028195

APPENDIX E

FLOWSHEET CHARACTERISTICS AS FUNCTIONS OF EXTERNAL FEED COMPOSITION R AND y

The tables included in this appendix give the major steady-state characteristics of the two basic recycle flowsheets at all (R,y) points considered, where R is the weight ratio of U-235 to U-238 in the feed uranium for the basic recycle scheme and y is the weight fraction of U-236 in the feed uranium. For recycle to fabrication, results for the weight ratio of U-235 to U-238 in reactor feed uranium R_R (Table E.1), weight fraction of U-236 in reactor feed uranium y_R (Table E.2), average discharge burnup B (Table E.3), feed uranium flowrate F (Table E.4), and Np-237 production rate N (Table E.5), are presented. For each of these characteristics, results are given for fabrication loss fractions, L_F, of 0.01 and 0.002.

For recycle to a diffusion plant, results are given for y_R (Table E.6), B (Table E.7), F (Table E.8), N (Table E.9), and for the separative work expended in re-enriching recycled spent uranium (Table E.10). Results for each of these characteristics are given for three U_3O_8 prices, $C_{U_3O_8}$ - \$6/lb, \$8/lb, and \$10/lb. At $C_{U_3O_8}$ = \$8/lb, results for y_R are given for both $L_F = 0.01$ and $L_F = 0.002$. Other characteristics are given only for $L_F = 0.01$. Since the condition $R_R = R$ is imposed for this recycle scheme, results for R_R are not given explicitly.

TABLE E.1 Weight Ratio of U-235 to U-238 in Reactor Feed Uranium, R_R - Recycle to Fabrication

Fabrication Loss = 0.01

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	.02645	.02985	.03370	.03810	.04289	.04793	.05324	.05921	.06563	.07940	.09480
.01	.02748	.03089	.03472	.03877	.04318	.04810	.05361	.05942	.06554	.07917	.09467
.02	.02863	.03198	.03562	.03946	.04386	.04871	.05395	.05959	.06561	.07922	.09438
.04	.03073	.03387	.03724	.04107	.04546	.05026	.05548	.06108	.06695	.07977	.09443
.06	.03350	.03655	.04001	.04416	.04813	.05256	.05752	.06277	.06845	.08132	.09548
.08	.03709	.04009	.04376	.04775	.05152	.05537	.06049	.06619	.07199	.08278	.09585
.10	.03910	.04270	.04646	.05053	.05506	.06015	.06578	.07167	.07513	.08469	.09823

Fabrication Loss = 0.002

Y	R= .50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
0.	.02575	.02867	.03207	.03595	.04027	.04479	.04947	.05454	.06048	.07330	.08777
.01	.02646	.02935	.03270	.03628	.04003	.04417	.04898	.05447	.05984	.07220	.08664
.02	.02744	.03022	.03333	.03659	.04010	.04431	.04890	.05390	.05931	.07148	.08560
.04	.02908	.03190	.03468	.03766	.04111	.04518	.04974	.05475	.06017	.07087	.08388
.06	.03234	.03479	.03747	.04064	.04453	.04754	.05104	.05563	.06044	.07150	.08461
.08	.03375	.03779	.04111	.04405	.04695	.05015	.05399	.05867	.06408	.07416	.08289
.10	.03886	.04165	.04452	.04763	.05114	.05523	.06004	.06543	.07114	.07610	.08435

TABLE E.2 Weight Fraction of U-236 in Reactor Feed

Uranium, y_R - Recycle to Fabrication

Fabrication Loss = 0.01

R=	.40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
Y											
0.	.0242	.0262	.0283	.0307	.0332	.0358	.0386	.0416	.0446	.0514	.0600
.01	.0317	.0337	.0358	.0380	.0405	.0432	.0461	.0492	.0526	.0600	.0695
.02	.0400	.0419	.0439	.0461	.0486	.0515	.0545	.0579	.0614	.0696	.0792
.04	.0573	.0593	.0615	.0641	.0671	.0704	.0740	.0780	.0820	.0908	.1008
.06	.0777	.0801	.0829	.0862	.0890	.0922	.0959	.0999	.1044	.1143	.1252
.08	.1015	.1036	.1066	.1099	.1129	.1159	.1203	.1251	.1300	.1390	.1499
.10	.1222	.1257	.1294	.1334	.1378	.1425	.1476	.1527	.1559	.1648	.1766

Fabrication Loss = 0.002

R=	.50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
Y											
0.	.0274	.0291	.0311	.0332	.0354	.0379	.0403	.0431	.0459	.0523	.0606
.01	.0347	.0364	.0383	.0402	.0423	.0447	.0472	.0503	.0534	.0607	.0696
.02	.0428	.0445	.0462	.0480	.0501	.0527	.0555	.0586	.0621	.0699	.0793
.04	.0603	.0619	.0638	.0659	.0685	.0715	.0749	.0787	.0828	.0907	.1004
.06	.0814	.0835	.0859	.0888	.0921	.0943	.0969	.1007	.1048	.1143	.1254
.08	.1037	.1074	.1104	.1131	.1158	.1187	.1223	.1267	.1318	.1410	.1493
.10	.1276	.1308	.1343	.1381	.1422	.1467	.1515	.1567	.1621	.1680	.1769

TABLE E.3 Average Discharge Burnup, B (MWD/T) - Recycle to Fabrication

Fabrication Loss = 0.01

R=	.40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
Y											
0.	14348	17418	20675	24172	27696	31076	34355	37974	41748	48946	55111
.01	13477	16419	19544	22612	25698	28884	32236	35670	39048	45847	52038
.02	12764	15532	18373	21122	24015	27009	30083	33223	36415	42886	48946
.04	11321	13680	15990	18368	20899	23580	26379	29248	32012	37481	43136
.06	10402	12352	14369	16598	18663	20906	23300	25666	28075	33094	37918
.08	9968	11508	13358	15307	17058	18723	20897	23198	25415	29029	32990
.10	8750	10421	12068	13765	15583	17571	19698	21838	22849	25533	29357

Fabrication Loss = 0.002

R=	.50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
Y											
0.	12697	15367	18311	21466	24728	27855	30821	33861	37486	44523	50873
.01	11727	14238	17041	19855	22561	25347	28361	31637	34677	41084	47342
.02	11006	13316	15814	18267	20687	23328	26077	28933	31881	37944	43890
.04	9344	11534	13535	15489	17550	19821	22293	24919	27620	32361	37501
.06	8965	10567	12165	13908	15917	17425	19127	21301	23421	27893	32576
.08	7642	9590	11211	12635	13994	15419	17047	18953	21072	24700	27264
.10	8160	9360	10527	11736	13064	14584	16360	18306	20296	21534	23591

TABLE E.4 Uranium Feed Rate to Basic Recycle Flowsheet.

F (kgU/day) - Recycle to Fabrication

Fabrication Loss = 0.01

Y \ R=	.40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3.2137	2.9212	2.7039	2.5364	2.4079	2.3093	2.2317	2.1638	2.1067	2.0224	1.9710
.01	3.3454	3.0355	2.8044	2.6296	2.4946	2.3880	2.3015	2.2283	2.1680	2.0773	2.0188
.02	3.4730	3.1480	2.9070	2.7252	2.5826	2.4687	2.3754	2.2980	2.2330	2.1353	2.0689
.04	3.7378	3.3860	3.1235	2.9245	2.7665	2.6371	2.5299	2.4407	2.3679	2.2565	2.1745
.06	3.9812	3.6099	3.3353	3.1173	2.9467	2.8053	2.6866	2.5893	2.5076	2.3802	2.2879
.08	4.1893	3.8253	3.5333	3.3016	3.1196	2.9730	2.8444	2.7371	2.6475	2.5090	2.4055
.10	4.4805	4.0632	3.7432	3.4953	3.2956	3.1313	2.9948	2.8796	2.7882	2.6414	2.5242

Fabrication Loss = 0.002

Y \ R=	.50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
0.	2.7693	2.5648	2.4049	2.2803	2.1825	2.1068	2.0477	1.9991	1.9536	1.8878	1.8477
.01	2.8798	2.6643	2.4940	2.3616	2.2592	2.1771	2.1105	2.0554	2.0087	1.9377	1.8923
.02	2.9866	2.7618	2.5844	2.4460	2.3378	2.2508	2.1788	2.1188	2.0682	1.9901	1.9393
.04	3.2132	2.9662	2.7731	2.6227	2.5031	2.4044	2.3213	2.2510	2.1916	2.1023	2.0381
.06	3.3989	3.1457	2.9489	2.7921	2.6606	2.5565	2.4680	2.3885	2.3225	2.2191	2.1441
.08	3.5699	3.3257	3.1243	2.9591	2.8230	2.7093	2.6107	2.5257	2.4529	2.3385	2.2546
.10	3.7708	3.5053	3.2899	3.1150	2.9708	2.8489	2.7447	2.6553	2.5780	2.4605	2.3695

TABLE E.5 Np-237 Production Rate, N (kg Np/day) - Recycle to Fabrication

Fabrication Loss = 0.01

Y \ R=	.40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	.1045	.1059	.1073	.1086	.1101	.1116	.1132	.1148	.1160	.1192	.1248
.01	.1270	.1271	.1270	.1271	.1275	.1282	.1291	.1300	.1313	.1342	.1394
.02	.1492	.1481	.1468	.1461	.1457	.1458	.1462	.1468	.1477	.1503	.1544
.04	.1910	.1883	.1863	.1849	.1839	.1831	.1826	.1825	.1827	.1840	.1860
.06	.2322	.2292	.2268	.2248	.2228	.2210	.2197	.2189	.2185	.2187	.2201
.08	.2715	.2684	.2654	.2626	.2602	.2583	.2567	.2553	.2543	.2539	.2544
.10	.3063	.3034	.3009	.2985	.2962	.2938	.2916	.2896	.2893	.2891	.2884

Fabrication Loss = 0.002

Y \ R=	.50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
0.	.1167	.1171	.1175	.1180	.1186	.1195	.1207	.1217	.1226	.1249	.1298
.01	.1383	.1379	.1370	.1362	.1360	.1360	.1365	.1371	.1380	.1406	.1449
.02	.1602	.1587	.1568	.1553	.1545	.1543	.1544	.1546	.1552	.1574	.1609
.04	.2029	.1996	.1972	.1956	.1944	.1936	.1928	.1924	.1924	.1929	.1949
.06	.2441	.2414	.2393	.2375	.2358	.2340	.2325	.2314	.2307	.2303	.2315
.08	.2845	.2820	.2796	.2773	.2752	.2734	.2719	.2705	.2693	.2681	.2690
.10	.3169	.3156	.3146	.3136	.3124	.3108	.3088	.3067	.3049	.3057	.3069

TABLE E.6 WEIGHT FRACTION OF U-236 IN REACTOR FEED URANIUM, y_R - RECYCLE TO DIFFUSION PLANT

CASE	y R	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
$C_{U_3O_8}$ = \$6/LB L_F = 0.01	0	0.00323	0.00384	0.00461	0.00550	0.00647	0.00748	0.00854	0.00967	0.0109	0.0117	0.0132	0.0148	0.0165		
	0.005	0.0132	0.0136	0.0144	0.0155	0.0165	0.0177	0.0189	0.0202	0.0216	0.0230	0.0245	0.0261	0.0277		
	0.01	0.0243	0.0248	0.0256	0.0267	0.0279	0.0292	0.0305	0.0320	0.0335	0.0350	0.0366	0.0382	0.0398	0.0431	0.0472
	0.015	0.0358	0.0368	0.0378	0.0389	0.0402	0.0417	0.0432	0.0447	0.0462	0.0478	0.0494	0.0510	0.0526	0.0563	0.0601
	0.02	0.0461	0.0492	0.0505	0.0517	0.0531	0.0547	0.0563	0.0579	0.0594	0.0612	0.0629	0.0645	0.0663	0.0700	0.0736
	0.03			0.0763	0.0782	0.0803	0.0823	0.0842	0.0860	0.0877	0.0895	0.0914	0.0933	0.0952	0.0985	0.1020
	0.04			0.0993	0.1038	0.1071	0.1097	0.1122	0.1144	0.1164	0.1184	0.1204	0.1223	0.1242	0.1281	0.1323
$C_{U_3O_8}$ = \$8/LB L_F = 0.01	0	0.00352	0.00419	0.00501	0.00594	0.00695	0.00800	0.00910	0.0103	0.0116	0.0124	0.0140	0.0156	0.0173		
	0.005	0.0139	0.0144	0.0152	0.0163	0.0174	0.0185	0.0198	0.0211	0.0226	0.0240	0.0256	0.0272	0.0288		
	0.01	0.0255	0.0260	0.0269	0.0280	0.0292	0.0305	0.0319	0.0334	0.0349	0.0364	0.0380	0.0396	0.0412	0.0447	0.0487
	0.015	0.0372	0.0385	0.0396	0.0407	0.0420	0.0434	0.0450	0.0465	0.0480	0.0496	0.0512	0.0528	0.0545	0.0582	0.0620
	0.02	0.0473	0.0513	0.0526	0.0539	0.0553	0.0568	0.0584	0.0600	0.0616	0.0635	0.0651	0.0668	0.0685	0.0722	0.0758
	0.03			0.0791	0.0812	0.0833	0.0854	0.0873	0.0890	0.0908	0.0926	0.0945	0.0964	0.0983	0.1016	0.1051
	0.04			0.1019	0.1071	0.1106	0.1134	0.1159	0.1181	0.1202	0.1222	0.1241	0.1260	0.1279	0.1318	0.1361
$C_{U_3O_8}$ = \$8/LB L_F = 0.002	0	0.00361	0.00428	0.00511	0.00607	0.00709	0.00817	0.00929	0.0105	0.0118	0.0127	0.0143	0.0160	0.0177		
	0.005	0.0142	0.0147	0.0155	0.0166	0.0177	0.0189	0.0202	0.0216	0.0230	0.0246	0.0262	0.0278	0.0295		
	0.01	0.0264	0.0267	0.0275	0.0286	0.0298	0.0312	0.0326	0.0341	0.0357	0.0373	0.0389	0.0406	0.0423	0.0459	0.0501
	0.015	0.0390	0.0398	0.0407	0.0418	0.0431	0.0445	0.0461	0.0477	0.0493	0.0509	0.0526	0.0542	0.0560	0.0599	0.0638
	0.02	0.0498	0.0536	0.0544	0.0555	0.0569	0.0585	0.0601	0.0617	0.0634	0.0653	0.0671	0.0688	0.0706	0.0744	0.0781
	0.03			0.0828	0.0846	0.0866	0.0886	0.0905	0.0923	0.0941	0.0959	0.0979	0.0998	0.1019	0.1052	0.1089
	0.04			0.1073	0.1127	0.1161	0.1187	0.1210	0.1232	0.1253	0.1273	0.1292	0.1312	0.1331	0.1373	0.1420
$C_{U_3O_8}$ = \$10/LB L_F = 0.01	0	0.00378	0.00448	0.00534	0.00631	0.00735	0.00844	0.00957	0.0108	0.0121	0.0130	0.0146	0.0162	0.0179		
	0.005	0.0145	0.0150	0.0159	0.0170	0.0181	0.0193	0.0206	0.0220	0.0234	0.0249	0.0265	0.0281	0.0298		
	0.01	0.0265	0.0271	0.0280	0.0291	0.0303	0.0316	0.0331	0.0345	0.0360	0.0376	0.0392	0.0408	0.0425	0.0460	0.0500
	0.015	0.0384	0.0400	0.0411	0.0422	0.0435	0.0450	0.0465	0.0480	0.0496	0.0511	0.0528	0.0544	0.0561	0.0598	0.0636
	0.02	0.0482	0.0531	0.0545	0.0558	0.0572	0.0587	0.0603	0.0619	0.0635	0.0654	0.0671	0.0688	0.0705	0.0742	0.0777
	0.03			0.0814	0.0838	0.0860	0.0880	0.0899	0.0917	0.0935	0.0953	0.0971	0.0990	0.1010	0.1042	0.1077
	0.04			0.1039	0.1098	0.1136	0.1165	0.1191	0.1213	0.1234	0.1254	0.1273	0.1292	0.1311	0.1350	0.1394

TABLE E.7 AVERAGE DISCHARGE BURNUP, B (MWD/T) - RECYCLE TO DIFFUSION PLANT

($L_F = 0.01$)

Cu_3O_8	y \ R	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
$6/LB	0	13508	20332	26245	31533	36395	40973	45307	49304	52733	56011	58908	61510	63880		
	0.005	9677	16093	21625	26516	31215	35656	39786	43573	47015	50218	53211	56018	58678		
	0.01	6686	12555	17740	22405	26801	30903	34718	38286	41685	44932	47966	50869	53662	58351	61791
	0.015	4357	9761	14564	19011	23084	26840	30356	33724	37040	40205	43211	46104	48881	53631	57801
	0.02	2633	7429	11934	16102	19900	23424	26762	29988	33157	36042	38957	41746	44390	49204	53780
	0.03			7758	11478	14770	17774	20751	23674	26513	29243	31839	34278	36547	41290	45810
	0.04			5059	8132	10981	13686	16187	18747	21228	23640	25992	28281	30501	34676	38336
$8/LB	0	13370	20160	26034	31283	36113	40667	44981	48958	52365	55625	58511	61114	63496		
	0.005	9449	15815	21312	26173	30840	35248	39345	43104	46532	49728	52716	55526	58196		
	0.01	6423	12227	17370	22010	26368	30426	34201	37740	41128	44370	47398	50300	53092	57778	61312
	0.015	4103	9421	14169	18584	22616	26333	29818	33164	36464	39598	42594	45476	48238	52990	57231
	0.02	2447	7052	11526	15642	19405	22907	26230	29440	32582	35416	38311	41077	43693	48512	53122
	0.03			7392	11047	14292	17264	20213	23106	25915	28611	31173	33581	35826	40542	45007
	0.04			4792	7741	10512	13176	15675	18192	20639	23028	25360	27630	29827	33934	37469
$10/LB	0	13252	20014	25855	31072	35876	40410	44707	48667	52055	55298	58177	60781	63172		
	0.005	9257	15579	21047	25884	30525	34904	38973	42709	46125	49315	52300	55112	57789		
	0.01	6204	11953	17058	21678	26003	30026	33766	37282	40661	43897	46921	49821	52612	57294	60906
	0.015	3897	9136	13839	18224	22223	25909	29371	32700	35984	39090	42076	44947	47695	52451	56747
	0.02	2308	6732	11185	15255	18989	22475	25786	28980	32099	34892	37771	40516	43107	47931	52564
	0.03			7098	10693	13898	16843	19767	22635	25415	28083	30616	32999	35230	39917	44328
	0.04			4582	7417	10116	12741	15258	17736	20156	22525	24840	27093	29271	33319	36748

TABLE E.8 URANIUM FEED RATE TO BASIC RECYCLE FLOWSHEET, F (KG U/DAY) - RECYCLE TO DIFFUSION PLANT

(L_F= 0.01)

$C_{U_3O_8}$	y \ R	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
$6/LB	0	49.2422	36.7584	29.8555	25.4126	22.2777	19.9257	18.0908	16.6317	15.4732	14.5407	13.7041	12.9922	12.3771		
	0.005	54.9106	40.0665	32.1992	27.2324	23.7066	21.0844	19.0690	17.4803	16.2005	15.1385	14.2329	13.4572	12.7832		
	0.01	60.6966	43.3632	34.4501	28.8978	25.0465	22.2188	20.0538	18.3381	16.9350	15.7573	14.7767	13.9348	13.2029	12.0220	11.1213
	0.015	67.0804	46.5455	36.5598	30.4363	26.3024	23.2946	20.9888	19.1487	17.6329	16.3748	15.3190	14.4141	13.6305	12.3649	11.3786
	0.02	75.1281	49.8679	38.7120	32.0279	27.5692	24.3282	21.8434	19.8708	18.2701	16.9674	15.8427	14.8835	14.0586	12.7112	11.6456
	0.03			43.0532	35.0199	29.9152	26.2751	23.4867	21.2816	19.4968	18.0266	16.7991	15.7635	14.8825	13.3943	12.2108
	0.04			47.1061	37.8080	32.0747	28.0077	25.0684	22.6438	20.6996	19.1004	17.7591	16.6174	15.6343	14.0352	12.8104
$8/LB	0	48.6582	36.4269	29.6594	25.2846	22.1889	19.8606	18.0411	16.5933	15.4436	14.5130	13.6818	12.9734	12.3605		
	0.005	54.4464	39.8149	32.0467	27.1325	23.6390	21.0384	19.0377	17.4586	16.1840	15.1231	14.2207	13.4468	12.7738		
	0.01	60.3504	43.1676	34.3290	28.8156	24.9950	22.1888	20.0378	18.3297	16.9291	15.7530	14.7736	13.9323	13.2007	12.0198	11.1160
	0.015	66.9739	46.4059	36.4727	30.3799	26.2708	23.2781	20.9804	19.1443	17.6317	16.3787	15.3230	14.4183	13.6352	12.3684	11.3779
	0.02	75.2314	49.8528	38.6956	32.0275	27.5715	24.3271	21.8389	19.8668	18.2715	16.9755	15.8511	14.8926	14.0690	12.7197	11.6500
	0.03			43.0563	35.0138	29.9142	26.2759	23.4898	21.2873	19.5052	18.0377	16.8128	15.7792	14.8993	13.4096	12.2263
	0.04			47.1568	37.8708	32.1419	28.0669	25.0887	22.6658	20.7211	19.1201	17.7770	16.6336	15.6498	14.0525	12.8358
$10/LB	0	48.2294	36.2008	29.5162	25.1919	22.1252	19.8144	18.0063	16.5667	15.4234	14.4940	13.6667	12.9608	12.3494		
	0.005	54.1246	39.6408	31.9418	27.0643	23.5939	21.0089	19.0188	17.4465	16.1752	15.1146	14.2142	13.4414	12.7688		
	0.01	60.1369	43.0426	34.2519	28.7633	24.9641	22.1733	20.0319	18.3286	16.9292	15.7539	14.7750	13.9336	13.2019	12.0205	11.1136
	0.015	66.9732	46.3357	36.4281	30.3529	26.2588	23.2746	20.9806	19.1462	17.6355	16.3864	15.3304	14.4254	13.6423	12.3739	11.3795
	0.02	75.3568	49.9006	38.7165	32.0516	27.5898	24.3372	21.8433	19.8699	18.2783	16.9866	15.8619	14.9037	14.0810	12.7294	11.6560
	0.03			43.0821	35.0258	29.9262	26.2863	23.5003	21.2989	19.5183	18.0524	16.8290	15.7964	14.9163	13.4248	12.2420
	0.04			47.2344	37.9608	32.2327	28.1458	25.1118	22.6896	20.7436	19.1405	17.7951	16.6500	15.6652	14.0693	12.8594

TABLE E.9 NP-237 PRODUCTION RATE, N (KG NP/DAY) – RECYCLE TO DIFFUSION PLANT

(L_F = 0.01)

$C_{U_3O_8}$	y R	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
$6/LB	0	0.0264	0.0287	0.0313	0.0340	0.0365	0.0389	0.0412	0.0434	0.0459	0.0469	0.0497	0.0526	0.0552		
	0.005	0.0722	0.0683	0.0668	0.0668	0.0670	0.0674	0.0682	0.0693	0.0706	0.0719	0.0735	0.0751	0.0765		
	0.01	0.1179	0.1090	0.1039	0.1010	0.0990	0.0978	0.0971	0.0969	0.0969	0.0972	0.0976	0.0981	0.0985	0.1002	0.1033
	0.015	0.1598	0.1483	0.1405	0.1350	0.1310	0.1282	0.1263	0.1249	0.1235	0.1226	0.1219	0.1214	0.1210	0.1216	0.1226
	0.02	0.1944	0.1853	0.1750	0.1673	0.1616	0.1575	0.1544	0.1519	0.1494	0.1480	0.1464	0.1452	0.1441	0.1432	0.1423
	0.03			0.2395	0.2292	0.2214	0.2155	0.2102	0.2055	0.2015	0.1981	0.1952	0.1928	0.1907	0.1866	0.1832
	0.04			0.2923	0.2840	0.2757	0.2684	0.2622	0.2563	0.2510	0.2463	0.2421	0.2384	0.2351	0.2297	0.2257
$8/LB	0	0.0279	0.0302	0.0328	0.0355	0.0380	0.0404	0.0427	0.0449	0.0474	0.0485	0.0513	0.0541	0.0568		
	0.005	0.0754	0.0712	0.0696	0.0694	0.0694	0.0698	0.0706	0.0716	0.0728	0.0742	0.0757	0.0772	0.0786		
	0.01	0.1224	0.1133	0.1079	0.1047	0.1025	0.1011	0.1004	0.1000	0.0999	0.1001	0.1004	0.1007	0.1011	0.1028	0.1056
	0.015	0.1647	0.1535	0.1455	0.1396	0.1353	0.1324	0.1303	0.1287	0.1271	0.1261	0.1253	0.1247	0.1242	0.1247	0.1253
	0.02	0.1985	0.1914	0.1806	0.1726	0.1667	0.1623	0.1589	0.1562	0.1535	0.1521	0.1504	0.1490	0.1478	0.1467	0.1456
	0.03			0.2461	0.2358	0.2278	0.2217	0.2160	0.2111	0.2069	0.2033	0.2003	0.1978	0.1955	0.1911	0.1876
	0.04			0.2980	0.2909	0.2828	0.2754	0.2689	0.2628	0.2573	0.2524	0.2480	0.2441	0.2406	0.2350	0.2310
$10/LB	0	0.0291	0.0314	0.0341	0.0367	0.0393	0.0417	0.0439	0.0462	0.0487	0.0499	0.0527	0.0554	0.0581		
	0.005	0.0781	0.0737	0.0719	0.0716	0.0716	0.0719	0.0726	0.0735	0.0747	0.0761	0.0775	0.0790	0.0803		
	0.01	0.1262	0.1169	0.1113	0.1079	0.1055	0.1040	0.1031	0.1027	0.1024	0.1025	0.1027	0.1030	0.1033	0.1049	0.1076
	0.015	0.1687	0.1579	0.1497	0.1435	0.1390	0.1359	0.1336	0.1319	0.1302	0.1291	0.1282	0.1275	0.1269	0.1272	0.1277
	0.02	0.2016	0.1966	0.1854	0.1771	0.1709	0.1663	0.1628	0.1598	0.1570	0.1556	0.1538	0.1523	0.1511	0.1497	0.1484
	0.03			0.2514	0.2413	0.2332	0.2268	0.2210	0.2159	0.2115	0.2078	0.2047	0.2020	0.1996	0.1949	0.1912
	0.04			0.3026	0.2966	0.2888	0.2813	0.2745	0.2683	0.2626	0.2575	0.2529	0.2489	0.2453	0.2396	0.2355

TABLE E.10 SEPARATIVE WORK FOR RE-ENRICHING SPENT URANIUM, Δ (KG U/DAY) - RECYCLE TO DIFFUSION PLANT

(L_F= 0.01)

$C_{U_3O_8}$	y \ R	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
$6/LB	0	34.6897	28.3484	25.2361	23.4012	22.1448	21.1736	20.3871	19.7845	19.4133	19.0675	18.8153	18.6124	18.4348		
	0.005	43.7794	34.9079	30.5395	27.9545	26.0009	24.5083	23.3646	22.4865	21.8047	21.2343	20.7381	20.3020	19.9070		
	0.01	52.2366	41.1224	35.4673	32.0054	29.5320	27.6906	26.2690	25.1247	24.1544	23.3047	22.5945	21.9623	21.3915	20.5385	19.9658
	0.015	60.0948	46.7206	39.9056	35.6282	32.7391	30.6160	28.9467	27.5530	26.3299	25.2816	24.3844	23.5896	22.8813	21.7859	20.9128
	0.02	67.5348	52.0607	44.1006	39.1283	35.7917	33.3053	31.3224	29.6718	28.2672	27.1452	26.0907	25.1681	24.3600	23.0269	21.9039
	0.03			51.8197	45.3926	41.2770	38.2420	35.7546	33.6814	31.9339	30.4501	29.1845	28.1023	27.1757	25.4561	24.0068
	0.04			57.3875	50.4942	45.8785	42.3262	39.7751	37.3702	35.3640	33.6471	32.1526	30.8376	29.6735	27.7266	26.2244
$8/LB	0	38.3147	31.2279	27.6819	25.5514	24.0709	22.9203	21.9879	21.2671	20.8004	20.3767	20.0485	19.7770	19.5373		
	0.005	48.0734	38.2365	33.3117	30.3550	28.1285	26.4284	25.1210	24.1083	23.3105	22.6385	22.0554	21.5420	21.0780		
	0.01	57.0921	44.8372	38.5216	34.6136	31.8365	29.7698	28.1690	26.8731	25.7689	24.8024	23.9954	23.2783	22.6330	21.6584	20.9739
	0.015	65.4540	50.7638	43.2034	38.4296	35.2076	32.8328	30.9595	29.3950	28.0287	26.8679	25.8654	24.9800	24.1936	22.9631	21.9710
	0.02	73.0919	56.4827	47.6879	42.1773	38.4481	35.6545	33.4277	31.5865	30.0372	28.8093	27.6440	26.6276	25.7402	24.2608	23.0143
	0.03			55.6822	48.6623	44.1372	40.7815	38.0417	35.7665	33.8551	32.2363	30.8577	29.6790	28.6679	26.7945	25.2269
	0.04			61.2957	53.9815	48.9987	45.1188	42.2384	39.6225	37.4352	35.5619	33.9327	32.5025	31.2407	29.1453	27.5518
$10/LB	0	41.4839	33.7406	29.8128	27.4222	25.7448	24.4372	23.3773	22.5532	22.0030	21.5108	21.1163	20.7853	20.4916		
	0.005	51.8393	41.1491	35.7319	32.4468	29.9804	28.0982	26.6475	25.5168	24.6174	23.8560	23.1970	22.6163	22.0923		
	0.01	61.3496	48.0886	41.1895	36.8874	33.8436	31.5792	29.8208	28.3918	27.1701	26.1021	25.2104	24.4194	23.7092	22.6282	21.8469
	0.015	70.1485	54.3077	46.0885	40.8780	37.3614	34.7629.	32.7082	30.9929	29.5020	28.2451	27.1505	26.1861	25.3319	23.9832	22.8878
	0.02	77.8543	60.3642	50.8415	44.8551	40.7724	37.7025	35.2586	33.2498	31.5748	30.2533	28.9915	27.8937	26.9376	25.3304	23.9769
	0.03			59.0278	51.5015	46.6217	42.9857	40.0265	37.5764	35.5231	33.7872	32.3101	31.0470	29.9065	27.9541	26.2854
	0.04			64.6880	57.0459	51.7590	47.5963	44.3685	41.5713	39.2269	37.2176	35.4714	33.9412	32.5950	30.3723	28.7024

APPENDIX F

CALCULATION OF AEC PRICE SCALES AND PLUTONIUM VALUES

This appendix contains four parts, presented in logical sequence. In order, these deal with the effects of U_3O_8 price on the cost of natural UF_6, the optimum tails composition, the AEC price scale, and the unit value of fissile plutonium.

1. Cost of natural uranium as UF_6

The price of natural U_3O_8, $C_{U_3O_8}$, is in units of \$/lb U_3O_8. It is more convenient to work with C_{NAT}, the cost of natural uranium as UF_6 in \$/kgU. The current value of C_{NAT} is \$23.46/kgU(1) and corresponds to a U_3O_8 price of \$8/lb. With this information and an assumed economics model, C_{NAT} can be determined for other values of $C_{U_3O_8}$.

Let t_C be the period of time between the purchase of U_3O_8 and the completion of conversion to UF_6, in years, and define C'_{CT} as the total of all unit costs incurred during t_C, in \$/kgU. If L'_C is the fractional loss of uranium during conversion of U_3O_8 to UF_6, based on the product from conversion, then $(1+L'_C)$ kgU must be purchased in U_3O_8 form per kgU obtained as UF_6. If i is the annual fixed charge on working capital, then the following equation can be written for C_{NAT}:

$$C_{NAT} = (1+L'_C)[2.5998(1+it_C)C_{U_3O_8} + C'_{CT}] \quad , \qquad (F.1)$$

where 2.5998 represents the ratio of lbs U_3O_8 to kgU. Using C_{NAT} = \$23.46/kgU and $C_{U_3O_8}$ = \$8/lb along with the following assumed values

$i = 0.1$/year

$t_C = 30/365$ years

$L_C' = 0.01$,

a value of \$2.26/kgU can be calculated for C_{CT}' from Equation F.1. Equation F.1 can be reduced to the form

$$C_{NAT} = 2.647 C_{U_3O_8} + 2.281 \; . \qquad (F.2)$$

Using this equation, the following results are obtained:

$C_{U_3O_8}$	C_{NAT}
\$6/lb	\$18.17/kgU
8	23.46
10	28.75

2. Optimum tails composition

Let x_W represent the weight fraction of U-235 in tails uranium from the diffusion plant and define C_Δ as the unit cost of separative work in \$/kgU. The weight fraction of U-235 in natural uranium is x_F. The optimum value of x_W, x_W^o, is determined by trial-and-error from the following equation(15):

$$\frac{C_{NAT}}{C_\Delta} = (2x_F - 1)\ln\frac{x_F(1-x_W^o)}{x_W^o(1-x_F)} + \frac{(x_F - x_W^o)(1-2x_W^o)}{x_W^o(1-x_W^o)} \; . \qquad (F.3)$$

The weight ratio of U-235 to U-238 corresponding to x_W^o is found from

$$R_W^o = \frac{x_W^o}{1 - x_W^o} \,. \qquad \text{(F.4)}$$

Using C_Δ = \$30/kgU and x_F = 0.00711 together with the values of C_{NAT} given in Part 1, the following results are obtained using Equations F.3 and F.4:

$C_{U_3O_8}$	x_W^o	R_W^o
\$6/lb	0.0028116	0.0028195
8	0.0025308	0.0025372
10	0.0023119	0.0023173

3. AEC price scale

Let x represent the weight fraction of U-235 in uranium and denote the unit price of UF_6 on the AEC price scale by $C_{AEC}(x)$, in \$/kgU. For this study, the AEC price scale is assumed to change according to the equation(15)

$$C_{AEC}(x) = C_\Delta\left[(2x-1)\ln\frac{x(1-x_W^o)}{x_W^o(1-x)} + \frac{(x-x_W^o)(1-2x_W^o)}{x_W^o(1-x_W^o)}\right] \qquad \text{(F.5)}$$

when changes in U_3O_8 price, hence changes in x_W^o, are made. Equation F.5 can be rewritten in the equivalent form

$$C_{AEC}(x) = C_\Delta[(2x-1)\ln\frac{x}{1-x} + A_1x - A_2] \,, \qquad \text{(F.6)}$$

where

$$A_1 = 2\ln\frac{1-x_W^o}{x_W^o} + \frac{1-2x_W^o}{x_W^o(1-x_W^o)} \qquad \text{(F.7)}$$

and

$$A_2 = \ln\frac{1-x_W^o}{x_W^o} + \frac{1-2x_W^o}{1-x_W^o} \,. \qquad \text{(F.8)}$$

When C_Δ = \$30/kgU, the following results for A_1 and A_2 are obtained by using the x_W^o values reported in Part 2:

$C_{U_3O_8}$	A_1	A_2
\$6/lb	366.409	6.86840
8	406.083	6.97415
10	443.677	7.06505

4. Unit value of fissile plutonium

At present, the AEC(21) values one gram of fissile Pu in nitrate form at 10/12 of the price of one gram of U-235 contained in 90% - enriched uranium (x=0.9) based on the AEC price scale. For this study, it has been assumed that the unit value of fissile Pu, C_K, in \$/g, is given by the following equation:

$$C_K = \frac{10}{12} \times \frac{C_{AEC}(0.9)}{0.9} \times \frac{1}{1000} . \tag{F.9}$$

Using this equation and the expressions for $C_{AEC}(x)$ given in Part 3, the following results are obtained for C_Δ = \$30/kgU:

$C_{U_3O_8}$	$C_{AEC}(0.9)$	C_K
\$6/lb	\$9740/kgU	\$9.01/gPu
8	10808	10.00
10	11820	10.94

A summary of the results obtained in this appendix is given in Table F.1.

TABLE F.1

Effect of U_3O_8 Price on AEC Price Scale and Plutonium Value

C_Δ = \$30/kgU $\qquad$ $C_{AEC}(x) = 30[(2x-1)\ln\frac{x}{1-x} + A_1x - A_2]$, \$/kgU

$C_{U_3O_8}$ (\$/lb)	C_{NAT} (\$/kgU)	x_W^o	R_W^o	A_1	A_2	C_K (\$/gPu)
6	18.17	0.0028116	0.0028195	366.409	6.86840	9.01
8	23.46	0.0025308	0.0025372	406.083	6.97415	10.00
10	28.75	0.0023119	0.0023173	443.677	7.06505	10.94

APPENDIX G

MINIMUM FUEL CYCLE COST RESULTS

All minimum fuel cycle costs and corresponding optimum operating conditions calculated for the two basic recycle flowsheets are given in the three tables of this appendix. The minimum fuel cycle cost C_E^* is based upon the use of feed uranium which contains no U-236 and which is purchased as UF_6 on the AEC price scale.

Table G.1 gives results for both recycle schemes when the high unit cost condition is imposed and for a fabrication loss fraction L_F equal to 0.01. Table G.2 gives results for low unit costs and $L_F = 0.01$. Finally, Table G.3 gives results for the high unit cost condition when $L_F = 0.002$. Each table presents results for U_3O_8 prices, $C_{U_3O_8}$, of \$10, \$8, and \$6/lb and for Np-237 prices, C_N, ranging from \$0/g to \$100/g in steps of \$20/g. In each table and for each U_3O_8 price, results are also given at one non-integral value of C_N, which represents the Np-237 price at which C_E^* is the same (within a reasonable tolerance) for both recycle schemes. Since these non-integral values of C_N were obtained by linear interpolation of C_E^* vs C_N results, the results for C_E^* for the two recycle schemes are not exactly the same.

In addition to C_E^*, the optimum weight ratio of U-235 to U-238 in the UF_6 feed purchased, R^*, is given, as are the corresponding values for the weight ratio of U-235 to U-238 in the uranium fed to the reactor R_R, the weight fraction of U-236 in the uranium fed to the reactor y_R, and the average discharge burnup B (MWD/T). For recycle to a diffusion plant, R_R is not given explicitly in the tables, but operation according to this recycle scheme is such that $R_R = R^*$ at the optimum condition, so that results for R_R are given implicitly.

TABLE G.1 MINIMUM FUEL CYCLE COSTS, C_E^* (MILLS/KWHR) - HIGH UNIT COSTS, $L_F = 0.01$

		RECYCLE TO FABRICATION					RECYCLE TO DIFFUSION PLANT			
$C_{U_3O_8}$ (#/LB)	C_N (#/GNP)	C_E^*	R^*	R_R	y_R	BURNUP	C_E^*	R^*	y_R	BURNUP
10	0	2.183050	0.545488	0.03768	0.030462	23850.5	1.750193	0.03000	0.005340	25855.0
	20	1.976703	0.539577	0.03714	0.030179	23431.6	1.686461	0.03032	0.005400	26205.2
	40	1.769934	0.534043	0.03664	0.029916	23040.5	1.622690	0.03048	0.005429	26379.7
	60	1.562758	0.528668	0.03616	0.029663	22662.1	1.558856	0.03070	0.005471	26617.5
	60.53	1.557262	0.528442	0.03614	0.029652	22646.3	1.557162	0.03072	0.005474	26639.4
	80	1.355191	0.523456	0.03570	0.029419	22296.8	1.494966	0.03100	0.005527	26941.2
	100	1.147251	0.518180	0.03524	0.029175	21928.9	1.430997	0.03126	0.005577	27219.3
8	0	2.028046	0.557334	0.03878	0.031038	24692.4	1.613926	0.03086	0.005159	26975.6
	20	1.822566	0.551118	0.03820	0.030734	24250.4	1.552394	0.03106	0.005196	27191.2
	40	1.616631	0.545052	0.03764	0.030441	23819.6	1.490752	0.03128	0.005235	27428.9
	57.41	1.437004	0.540018	0.03718	0.030200	23462.8	1.437035	0.03146	0.005268	27621.9
	60	1.410254	0.539137	0.03710	0.030158	23400.4	1.429039	0.03150	0.005275	27664.7
	80	1.203448	0.533597	0.03660	0.029895	23009.1	1.367227	0.03172	0.005316	27898.8
	100	0.996229	0.527991	0.03610	0.029631	22614.6	1.305330	0.03194	0.005357	28132.5
6	0	1.863146	0.571264	0.04010	0.031726	25682.0	1.469579	0.03182	0.004925	28232.2
	20	1.658677	0.564545	0.03946	0.031393	25205.0	1.410500	0.03202	0.004960	28445.9
	40	1.453721	0.558186	0.03886	0.031079	24753.0	1.351322	0.03224	0.004999	28679.9
	54.01	1.309862	0.553483	0.03842	0.030849	24418.5	1.309801	0.03244	0.005036	28890.7
	60	1.248285	0.551549	0.03824	0.030755	24281.0	1.292032	0.03252	0.005050	28975.2
	80	1.042380	0.545487	0.03768	0.030462	23850.5	1.232630	0.03274	0.005090	29206.9
	100	0.836020	0.539357	0.03712	0.030168	23416.0	1.173123	0.03296	0.005129	29437.6

TABLE G.2 MINIMUM FUEL CYCLE COSTS, C_E^* (MILLS/KWHR) – LOW UNIT COSTS, $L_F = 0.01$

		RECYCLE TO FABRICATION					RECYCLE TO DIFFUSION PLANT			
$C_{U_3O_8}$ (\$/LB)	C_N (\$/G NP)	C_E^*	R^*	R_R	y_R	BURNUP	C_E^*	R^*	y_R	BURNUP
10	0	1.958708	0.485672	0.03254	0.027716	19717.2	1.547046	0.02650	0.004726	21845.5
	20	1.748188	0.480085	0.03210	0.027473	19348.1	1.484663	0.02676	0.004769	22155.8
	40	1.537345	0.475186	0.03172	0.027262	19027.3	1.422286	0.02688	0.004790	22297.7
	55.48	1.373953	0.471794	0.03146	0.027117	18806.8	1.373966	0.02702	0.004814	22463.2
	60	1.326213	0.470743	0.03138	0.027072	18738.7	1.359850	0.02702	0.004814	22463.2
	80	1.114815	0.466509	0.03106	0.026892	18465.6	1.297374	0.02722	0.004848	22698.7
	100	0.903181	0.462491	0.03076	0.026723	18208.3	1.234860	0.02742	0.004882	22933.1
8	0	1.811838	0.497074	0.03346	0.028218	20480.9	1.417422	0.02700	0.004499	22598.6
	20	1.602026	0.490674	0.03294	0.027935	20050.5	1.357377	0.02722	0.004534	22859.6
	40	1.391826	0.485168	0.03250	0.027694	19683.7	1.297298	0.02738	0.004561	23047.8
	52.58	1.259429	0.481618	0.03222	0.027539	19449.0	1.259472	0.02748	0.004578	23164.9
	60	1.181275	0.479829	0.03208	0.027462	19331.2	1.237148	0.02754	0.004588	23235.3
	80	0.970409	0.474926	0.03170	0.027251	19010.4	1.176940	0.02774	0.004621	23469.0
	100	0.759259	0.470480	0.03136	0.027061	18721.6	1.116669	0.02794	0.004654	23701.6
6	0	1.655897	0.510724	0.03460	0.028833	21412.8	1.280762	0.02750	0.004212	23380.0
	20	1.446980	0.503602	0.03400	0.028510	20924.3	1.223386	0.02772	0.004246	23639.1
	40	1.237594	0.496829	0.03344	0.028207	20464.4	1.165936	0.02800	0.004291	23966.5
	49.41	1.138928	0.493888	0.03320	0.028077	20266.2	1.138883	0.02808	0.004303	24059.8
	60	1.027782	0.490674	0.03294	0.027935	20050.5	1.108415	0.02820	0.004322	24199.3
	80	0.817586	0.485167	0.03250	0.027694	19683.7	1.050811	0.02840	0.004354	24430.9
	100	0.607045	0.479829	0.03208	0.027462	19331.2	0.993137	0.02846	0.004364	24500.1

TABLE G.3 MINIMUM FUEL CYCLE COSTS, C_E^* (MILLS/KWHR) - HIGH UNIT COSTS, $L_F = 0.002$

		RECYCLE TO FABRICATION					RECYCLE TO DIFFUSION PLANT			
$C_{U_3O_8}$ ($/LB)	C_N ($/G NP)	C_E^*	R^*	R_R	y_R	BURNUP	C_E^*	R^*	y_R	BURNUP
10	0	2.208383	0.682903	0.03876	0.034640	23620.8	1.739199	0.03020	0.005499	26009.4
	20	1.982520	0.674625	0.03804	0.034261	23079.7	1.674596	0.03038	0.005533	26205.3
	40	1.755831	0.666720	0.03736	0.033904	22561.7	1.609922	0.03054	0.005562	26379.4
	57.93	1.551898	0.659427	0.03674	0.033578	22083.7	1.551893	0.03072	0.005598	26573.2
	60	1.528312	0.658480	0.03666	0.033536	22021.6	1.545193	0.03078	0.005609	26638.1
	80	1.299965	0.650597	0.03600	0.033188	21506.1	1.480403	0.03106	0.005662	26938.6
	100	1.070806	0.643076	0.03538	0.032861	21016.2	1.415533	0.03132	0.005713	27215.7
8	0	2.052099	0.694272	0.03976	0.035167	24359.9	1.604126	0.03070	0.005241	26741.6
	20	1.827376	0.686100	0.03904	0.034787	23829.2	1.541725	0.03112	0.005319	27195.0
	40	1.601804	0.677393	0.03828	0.034388	23260.9	1.479270	0.03134	0.005358	27431.7
	54.94	1.432741	0.671148	0.03774	0.034104	22852.0	1.432571	0.03150	0.005388	27602.7
	60	1.375372	0.669055	0.03756	0.034009	22714.7	1.416743	0.03156	0.005399	27666.7
	80	1.148073	0.660610	0.03684	0.033631	22161.2	1.354114	0.03178	0.005442	27899.9
	100	0.919913	0.652279	0.03614	0.033262	21616.0	1.291397	0.03202	0.005487	28153.8
6	0	1.885967	0.708657	0.04104	0.035844	25284.5	1.460902	0.03170	0.005005	28047.5
	20	1.662549	0.699462	0.04022	0.035410	24694.9	1.401083	0.03208	0.005072	28453.2
	40	1.438264	0.690422	0.03942	0.034988	24110.2	1.341182	0.03230	0.005112	28686.4
	51.75	1.306081	0.684960	0.03894	0.034735	23754.9	1.305937	0.03248	0.005146	28875.4
	60	1.213087	0.681070	0.03860	0.034556	23501.2	1.281165	0.03258	0.005164	28980.7
	80	0.987006	0.672077	0.03782	0.034146	22912.8	1.221034	0.03280	0.005204	29211.5
	100	0.760014	0.663438	0.03708	0.033757	22346.5	1.160793	0.03304	0.005248	29462.2

APPENDIX H

URANIUM VALUES FOR BASIC RECYCLE SCHEMES

The unit value of uranium used as feed for basic recycle scheme operation, V(R,y), is given in the tables of this appendix for all sets of economic conditions considered. Results are given for both recycle schemes over ranges of R and y, where R is the weight ratio of U-235 to U-238 in feed uranium and y is the weight fraction of U-236. The units for V(R,y) are $/kgU.

Results for recycle to fabrication are given in Tables H.1 through H.5. For the high unit cost condition ("high costs") and a fabrication loss fraction L_F of 0.01, Tables H.1, H.2, and H.3 give results which correspond to U_3O_8 prices ($C_{U_3O_8}$) of \$10, 8, and \$6/lb, respectively. For $C_{U_3O_8}$ = \$8/lb, results are given by Table H.4 for the low unit cost condition ("low costs") with L_F = 0.01, and by Table H.5 for high unit costs with L_F = 0.002. In each table, uranium values are listed at more than one Np-237 price C_N.

Tables H.6 through H.10 give V(R,y) results for recycle to a diffusion plant for economic conditions which correspond, in the same order, to those of Tables H.1 through H.5.

TABLE H.1 Uranium Value, V(R,y) - Recycle to Fabrication:

$C_{U_3O_8}$ = \$10/lb, High Costs, L_F = 0.01

(\$/kgU)

C_N = \$0/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3161.66	3744.80	4190.09	4515.58	4722.87	4820.33	4826.82	4777.56	4666.58	4261.03	3621.52
.01	2835.39	3419.83	3878.64	4199.90	4412.26	4531.24	4567.18	4537.87	4445.48	4076.80	3480.31
.02	2532.08	3113.26	3566.31	3883.40	4104.77	4236.85	4292.32	4281.51	4211.43	3874.05	3342.77
.04	1923.17	2497.16	2928.39	3247.61	3480.75	3638.69	3726.75	3749.40	3703.16	3452.98	3028.20
.06	1430.30	1946.26	2343.78	2664.36	2895.23	3066.73	3178.24	3220.32	3205.31	3018.44	2664.30
.08	1012.86	1469.27	1849.17	2151.70	2371.95	2523.95	2642.30	2695.72	2699.13	2589.65	2320.75
.10	485.19	965.64	1342.44	1636.92	1868.68	2042.49	2157.39	2215.49	2234.18	2154.68	1941.51

C_N = \$20/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3183.47	3762.00	4199.42	4513.79	4708.64	4793.73	4787.42	4721.32	4588.71	4143.49	3483.95
.01	2975.24	3557.37	4007.97	4318.66	4518.59	4623.57	4643.60	4595.46	4485.17	4078.53	3457.62
.02	2730.35	3362.52	3809.96	4119.08	4329.18	4448.21	4488.79	4461.61	4374.27	3999.52	3437.67
.04	2355.63	2942.77	3381.63	3703.35	3934.02	4084.35	4161.15	4170.29	4109.36	3827.32	3364.60
.06	2023.29	2568.67	2986.88	3319.65	3555.73	3726.50	3833.29	3868.02	3843.04	3629.38	3246.06
.08	1741.21	2241.63	2651.97	2975.14	3210.88	3373.94	3494.77	3544.51	3542.26	3427.37	3141.22
.10	1315.96	1853.05	2275.76	2605.48	2861.87	3049.76	3170.22	3228.98	3264.92	3202.13	2974.21

C_N = \$60/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3223.87	3792.87	4214.27	4506.13	4675.89	4736.06	4704.00	4604.04	4428.05	3903.30	3203.56
.01	3251.83	3829.04	4262.96	4552.24	4727.12	4803.90	4791.96	4706.01	4559.78	4077.02	3407.14
.02	3273.89	3857.76	4293.69	4586.64	4773.99	4866.76	4877.38	4817.31	4695.33	4245.63	3622.47
.04	3217.80	3830.95	4284.81	4611.28	4836.82	4971.73	5025.84	5007.84	4917.41	4571.42	4032.67
.06	3206.66	3810.62	4269.98	4626.93	4873.25	5042.37	5139.57	5159.42	5114.39	4846.92	4405.06
.08	3195.41	3783.66	4254.65	4618.91	4885.43	5070.46	5196.07	5238.30	5224.59	5098.70	4777.86
.10	2975.19	3625.35	4139.66	4539.65	4845.12	5061.01	5192.45	5252.40	5322.73	5293.12	5035.52

C_N = \$100/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3260.24	3819.32	4224.36	4493.39	4637.78	4672.81	4614.81	4480.82	4261.29	3656.75	2916.63
.01	3524.56	4096.47	4513.35	4780.92	4930.47	4978.83	4934.72	4810.59	4628.33	4069.30	3350.27
.02	3763.74	4348.91	4772.99	5049.47	5213.82	5280.08	5260.54	5167.40	5010.62	4485.70	3801.05
.04	4076.51	4715.32	5183.86	5514.81	5734.95	5854.23	5885.45	5840.11	5720.01	5309.80	4694.81
.06	4386.80	5049.01	5549.20	5930.08	6186.39	6353.63	6441.05	6445.85	6380.60	6059.05	5558.42
.08	4646.56	5322.31	5853.68	6258.75	6555.84	6762.63	6892.85	6927.39	6902.07	6764.88	6409.14
.10	4631.56	5394.46	6000.11	6470.14	6824.47	7068.14	7210.37	7271.33	7375.90	7379.23	7091.73

TABLE H.2 Uranium Value, V(R,y) - Recycle to Fabrication:

$C_{U_3O_8}$ = \$8/lb, High Costs, L_F = 0.01

($/kgU)

C_N = \$0/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2797.17	3361.09	3795.42	4117.49	4328.08	4434.76	4455.78	4425.33	4337.21	3988.04	3419.06
.01	2491.60	3056.75	3503.72	3820.21	4034.17	4160.85	4210.18	4198.18	4126.68	3811.64	3283.03
.02	2207.93	2769.72	3210.31	3521.80	3744.14	3882.96	3949.94	3964.73	3903.89	3618.13	3149.93
.04	1635.34	2189.67	2608.34	2921.74	3155.16	3318.25	3415.83	3451.89	3422.87	3216.58	2847.16
.06	1175.74	1673.94	2060.38	2376.03	2605.35	2779.50	2898.09	2951.14	2950.82	2803.68	2498.83
.08	790.59	1230.97	1600.88	1898.12	2116.00	2268.84	2494.01	2458.57	2475.47	2394.97	2167.49
.10	292.75	757.67	1124.26	1417.43	1644.42	1821.88	1944.38	2012.95	2037.07	1980.49	1805.96

C_N = \$20/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2821.21	3380.74	3807.40	4118.52	4316.82	4411.26	4419.59	4372.39	4262.73	3874.03	3285.11
.01	2633.58	3196.64	3635.60	3941.68	4143.37	4256.18	4289.71	4258.98	4169.66	3816.82	3263.89
.02	2458.26	3021.25	3456.41	3760.10	3971.32	4097.23	4149.42	4137.94	4069.93	3746.95	3248.28
.04	2069.72	2637.40	3063.87	3379.92	3611.01	3766.62	3853.06	3875.71	3832.09	3594.08	3186.86
.06	1770.52	2298.32	2705.62	3033.63	3268.29	3441.83	3555.83	3601.61	3591.40	3417.63	3083.72
.08	1520.65	2005.21	2405.70	2723.73	2957.23	3121.25	3249.00	3309.98	3321.29	3235.55	2990.94
.10	1125.12	1646.84	2059.49	2384.05	2639.79	2831.43	2959.81	3028.94	3070.39	3030.65	2841.50

C_N = \$60/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2865.80	3416.23	3827.23	4116.17	4289.67	4359.44	4342.22	4261.35	4108.48	3640.51	3011.57
.01	2914.20	3472.76	3895.40	4180.40	4357.30	4442.15	4443.93	4376.58	4250.49	3821.80	3220.09
.02	2955.69	3520.78	3944.79	4232.62	4421.35	4521.23	4543.68	4499.51	4397.03	3999.37	3439.61
.04	2935.50	3529.56	3971.36	4292.46	4518.69	4659.11	4723.08	4718.80	4645.84	4344.15	3861.13
.06	2957.29	3544.01	3992.76	4345.23	4590.38	4762.50	4867.12	4898.22	4868.13	4640.84	4248.62
.08	2978.09	3550.76	4012.20	4371.57	4636.09	4822.29	4955.05	5008.70	5008.72	4912.26	4633.18
.10	2787.36	3422.45	3926.99	4322.08	4627.15	4846.99	4986.33	5067.04	5133.02	5126.75	4908.16

C_N = \$100/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2905.99	3446.87	3841.84	4108.25	4256.64	4301.48	4258.51	4143.78	3947.52	3400.00	2730.85
.01	3190.61	3744.23	4150.15	4417.72	4565.56	4622.21	4592.00	4485.83	4324.80	3819.97	3169.29
.02	3449.06	4015.81	4428.30	4699.93	4865.92	4939.51	4932.00	4854.92	4717.80	4245.17	3624.09
.04	3797.49	4417.54	4874.33	5200.18	5421.25	5546.25	5587.52	5556.08	5453.61	5087.96	4528.89
.06	4140.51	4785.79	5275.66	5652.30	5907.67	6078.13	6173.15	6189.38	6139.22	5858.11	5407.33
.08	4432.14	5092.61	5614.70	6015.13	6310.43	6518.58	6856.12	6702.26	6690.82	6583.31	6269.54
.10	4446.46	5194.57	5790.70	6256.07	6610.20	6858.02	7008.33	7080.22	7190.58	7217.48	6969.21

TABLE H.3 Uranium Value, V(R,y) - Recycle to Fabrication:

$C_{U_3O_8}$ = \$6/lb, High Costs, L_F = 0.01

($/kgU)

C_N = \$0/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2407.36	2950.58	3372.97	3691.11	3904.91	4021.10	4057.25	4046.45	3982.29	3692.35	3197.65
.01	2123.79	2668.20	3102.31	3413.45	3628.83	3763.40	3826.65	3832.74	3783.10	3524.42	3067.26
.02	1861.02	2401.95	2829.04	3134.31	3357.41	3503.12	3582.03	3603.08	3572.39	3340.84	2939.01
.04	1327.02	1860.24	2265.34	2577.30	2805.78	2974.07	3081.47	3131.52	3120.50	2960.23	2649.03
.06	902.74	1381.87	1756.32	2066.51	2293.96	2470.69	2596.56	2681.00	2675.98	2570.51	2317.46
.08	551.93	975.04	1334.12	1625.53	1840.68	1994.19	2126.37	2202.51	2233.46	2183.29	1999.29
.10	85.68	533.93	889.47	1172.82	1402.78	1583.87	1714.21	1793.67	1823.36	1790.70	1856.71

C_N = \$20/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2433.99	2973.09	3388.04	3695.43	3897.12	4001.22	4024.80	3997.37	3911.77	3582.49	3067.94
.01	2268.26	2810.84	3237.17	3538.10	3741.37	3862.22	3909.81	3897.28	3829.93	3533.82	3052.25
.02	2113.75	2656.14	3078.02	3375.68	3587.82	3720.75	3785.02	3789.93	3742.17	3473.57	3041.40
.04	1763.64	2310.44	2723.54	3032.33	3264.63	3425.60	3521.99	3558.76	3533.25	3341.44	2992.57
.06	1499.63	2008.58	2404.07	2726.79	2959.73	3135.99	3257.38	3314.68	3319.90	3187.97	2906.00
.08	1283.90	1751.45	2141.32	2452.67	2684.58	2849.40	2984.29	3056.96	3082.44	3027.19	2826.20
.10	919.92	1425.16	1826.94	2145.82	2400.68	2596.09	2732.22	2812.55	2859.67	2844.02	2695.56

C_N = \$60/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2483.53	3014.01	3413.74	3699.34	3876.55	3956.25	3954.54	3893.66	3765.04	3356.81	2802.43
.01	2553.63	3092.18	3502.63	3782.84	3961.66	4054.84	4070.92	4021.00	3918.08	3546.23	3016.30
.02	2615.74	3160.69	3571.85	3854.01	4044.00	4151.18	4185.96	4158.39	4076.37	3733.41	3240.39
.04	2633.66	3207.28	3636.11	3951.30	4178.04	4324.11	4398.28	4408.34	4353.69	4098.54	3674.13
.06	2690.38	3258.65	3695.96	4042.48	4287.20	4462.31	4574.58	4617.41	4602.95	4417.84	4077.82
.08	2745.09	3301.15	3752.30	4106.31	4368.53	4555.78	4695.91	4761.48	4775.86	4710.21	4475.04
.10	2585.69	3204.67	3698.67	4088.39	4392.85	4616.71	4764.24	4846.16	4927.99	4946.11	4768.49

C_N = \$100/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	2528.23	3049.62	3433.72	3697.15	3849.56	3904.59	3877.33	3782.80	3610.98	3123.48	2529.10
.01	2834.38	3368.43	3762.56	4021.69	4175.74	4240.98	4225.30	4137.77	3999.09	3551.40	2972.70
.02	3113.29	3660.34	4060.35	4326.67	4494.20	4575.34	4580.38	4520.13	4403.65	3986.02	3431.90
.04	3499.55	4099.56	4543.73	4863.98	5085.86	5216.76	5268.47	5251.58	5167.59	4848.78	4348.57
.06	3877.26	4504.46	4983.22	5355.21	5609.42	5783.12	5886.02	5914.17	5879.83	5641.21	5242.89
.08	4202.62	4846.80	5358.91	5754.27	6047.52	6256.96	6402.08	6460.35	6463.44	6387.07	6117.44
.10	4248.04	4980.37	5566.27	6026.54	6380.31	6632.38	6791.09	6874.38	6990.76	7042.36	6835.30

TABLE H.4 Uranium Value, V(R,y) - Recycle to Fabrication:
$C_{U_3O_8}$ = \$8/lb, Low Costs, $L_F = 0.01$

($/kgU)

C_N = \$0/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3119.41	3544.98	3858.54	4073.49	4193.28	4225.49	4183.72	4093.13	3950.49	3515.11	2887.34
.01	2853.97	3280.50	3605.13	3821.42	3949.48	3999.83	3979.98	3906.32	3781.58	3377.93	2785.18
.02	2605.69	3030.44	3353.25	3569.41	3705.10	3766.52	3764.62	3707.96	3602.28	3224.57	2687.65
.04	2115.73	2536.72	2846.13	3064.38	3209.50	3291.83	3316.34	3287.20	3202.72	2904.16	2458.14
.06	1706.79	2085.55	2369.23	2585.39	2734.59	2833.08	2879.79	2870.56	2813.56	2567.47	2185.19
.08	1346.54	1683.11	1952.32	2158.03	2303.04	2395.15	2446.82	2443.81	2401.98	2238.96	1935.44
.10	924.68	1274.54	1542.60	1743.41	1890.36	1986.77	2033.46	2035.26	2029.28	1904.74	1644.66

C_N = \$60/g Np-237

Y	R= .40	.45	.50	.55	.60	.65	.70	.75	.80	.90	1.00
0.	3155.22	3564.03	3851.35	4030.61	4111.09	4104.51	4022.91	3880.43	3671.72	3115.47	2426.37
.01	3245.04	3661.79	3959.22	4141.51	4230.35	4236.98	4167.92	4036.39	3856.76	3337.33	2670.01
.02	3323.08	3748.02	4051.46	4241.54	4341.49	4362.08	4313.97	4206.86	4048.21	3556.44	2926.37
.04	3387.66	3845.46	4175.42	4399.05	4534.91	4592.71	4581.92	4510.91	4381.16	3985.01	3423.63
.06	3461.84	3926.44	4270.00	4520.76	4683.84	4778.49	4809.56	4776.91	4688.83	4360.33	3888.89
.08	3508.91	3975.33	4333.80	4599.55	4789.34	4913.14	4970.77	4955.41	4895.41	4714.21	4357.30
10	3395.78	3913.37	4317.17	4621.89	4841.08	4978.22	5040.21	5042.74	5087.43	5011.08	4705.08

TABLE H.5 Uranium Value, V(R,y) - Recycle to Fabrication:

$C_{U_3O_8}$ = \$8/lb, High Costs, L_F = 0.002

(\$/kgU)

C_N = \$0/g Np-237

Y \ R=	.50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
0.	3003.46	3655.14	4167.21	4548.78	4808.36	4953.23	5005.47	4986.74	4927.47	4615.61	4074.49
.01	2600.79	3251.26	3800.59	4200.88	4465.21	4639.06	4730.07	4743.59	4701.36	4440.05	3945.54
.02	2233.53	2891.42	3431.62	3835.52	4114.02	4307.39	4421.64	4466.34	4449.34	4240.38	3800.73
.04	1392.18	2124.64	2673.36	3077.73	3379.93	3610.22	3770.53	3862.17	3888.82	3778.90	3474.19
.06	927.35	1549.47	2024.89	2403.77	2729.01	2944.16	3108.44	3246.06	3311.94	3276.89	3044.76
.08	401.59	972.05	1426.78	1785.55	2068.12	2294.65	2486.58	2631.35	2720.68	2749.10	2646.89
.10	146.46	589.75	961.29	1274.31	1543.37	1777.46	1972.23	2113.76	2193.46	2232.04	2156.03

C_N = \$60/g Np-237

Y \ R=	.50	.55	.60	.65	.70	.75	.80	.85	.90	1.00	1.10
0.	3160.49	3783.50	4253.76	4584.22	4788.22	4880.95	4884.12	4810.92	4675.20	4215.94	3589.38
.01	3158.55	3800.87	4295.88	4643.63	4857.32	4977.08	5008.47	4955.10	4851.84	4465.62	3868.83
.02	3166.94	3816.91	4322.39	4683.39	4918.68	5066.19	5127.22	5113.68	5035.72	4703.68	4151.38
.04	2995.70	3743.13	4301.75	4707.75	5000.02	5205.92	5325.73	5366.46	5337.88	5124.71	4705.21
.06	3096.89	3797.26	4332.10	4747.73	5084.40	5305.10	5457.80	5564.94	5597.33	5473.46	5139.87
.08	3104.94	3771.49	4307.78	4732.92	5066.02	5326.62	5535.85	5673.48	5734.33	5716.38	5618.42
.10	3151.10	3761.03	4277.83	4710.58	5069.69	5359.75	5572.47	5704.93	5761.43	5928.09	5907.51

TABLE H.6 URANIUM VALUE, V(R,y) - RECYCLE TO DIFFUSION PLANT: $C_{U_3O_8}$ = $10/LB, HIGH COSTS, L_F = 0.01 ($/KG U)

y	R C_N ($/G NP)	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
0	0	110.33	207.52	274.80	325.26	364.36	394.42	416.18	429.48	433.79	431.08	422.64	407.75	386.93		
	20	109.76	207.06	274.76	325.83	365.56	396.17	418.37	432.10	437.17	434.15	426.76	412.95	393.16		
	60	108.58	206.11	274.65	326.91	367.90	399.62	422.69	437.29	443.85	440.23	434.92	423.28	405.52		
	100	107.37	205.10	274.47	327.91	370.15	402.96	426.89	442.35	450.40	446.16	442.93	433.45	417.71		
0.005	0	22.25	143.61	217.56	270.52	312.24	344.15	367.05	381.40	387.51	387.39	381.28	369.49	352.37		
	20	38.00	161.57	237.24	291.85	334.79	367.69	391.46	406.65	413.57	414.24	408.91	397.75	381.05		
	60	69.47	197.46	276.57	334.48	379.85	414.70	440.22	457.09	465.62	467.86	464.07	454.19	438.32		
	100	100.90	233.29	315.84	377.03	424.82	461.61	488.87	507.41	517.53	521.34	519.09	510.47	495.43		
0.01	0	-94.90	72.97	159.49	218.78	262.61	294.97	318.07	333.32	341.62	344.45	340.70	331.59	317.29	271.01	202.83
	20	-65.74	107.71	198.07	260.43	306.60	340.89	365.67	382.35	391.73	395.52	392.53	383.91	369.81	324.78	258.96
	60	-7.43	177.17	275.20	343.68	394.53	432.68	460.81	480.37	491.89	497.61	496.10	488.47	474.76	432.22	371.11
	100	50.84	246.58	352.26	426.86	482.37	524.37	555.85	578.27	591.93	599.55	599.53	592.88	579.54	539.48	483.08
0.015	0	-275.04	-6.74	99.07	167.42	214.04	247.42	271.51	288.33	298.68	302.77	301.20	294.18	281.72	240.47	181.87
	20	-236.60	42.14	154.64	227.83	278.23	314.78	341.61	360.67	372.57	378.03	377.49	371.21	359.16	319.59	261.88
	60	-159.74	139.87	265.74	348.60	406.56	449.45	481.74	505.30	520.30	528.47	530.02	525.18	513.95	477.74	421.82
	100	-82.91	237.57	376.79	469.31	534.81	584.04	621.78	649.82	667.90	678.78	682.40	679.01	668.59	635.72	581.56
0.02	0	-562.21	-113.21	31.71	111.44	163.51	200.72	228.06	247.46	259.24	262.75	262.99	257.39	245.81	209.78	158.51
	20	-519.46	-52.84	101.41	188.11	245.69	287.55	318.92	341.61	355.68	361.85	363.75	359.46	348.90	314.75	263.76
	60	-433.96	67.87	240.77	341.42	409.99	461.18	500.57	529.84	548.50	559.98	565.19	563.53	554.98	524.62	474.17
	100	-348.49	188.54	380.08	494.65	574.22	634.72	682.13	717.98	741.21	757.99	766.50	767.46	760.92	734.32	684.40
0.03	0			-140.27	-12.09	56.89	102.13	135.99	160.63	177.31	186.78	189.45	185.49	174.96	147.79	103.98
	20			-47.74	93.18	172.02	225.65	266.32	296.59	318.04	331.63	337.88	337.02	329.09	304.92	262.94
	60			137.30	303.68	402.25	472.64	526.91	568.46	599.46	621.26	634.66	640.02	637.28	619.10	580.77
	100			322.29	514.12	632.40	719.55	787.42	840.23	880.76	910.77	931.32	942.88	945.33	933.12	898.42
0.04	0			-362.90	-169.58	-70.97	-6.79	36.15	67.65	89.29	103.22	110.67	112.33	108.58	85.25	39.73
	20			-256.89	-43.57	69.85	146.26	199.32	239.71	268.86	289.21	302.18	308.67	309.20	293.23	254.27
	60			-44.89	208.41	351.46	452.32	525.63	583.78	627.95	661.11	685.14	701.28	710.35	709.13	683.26
	100			167.06	460.34	633.01	758.31	851.85	927.75	986.94	1032.90	1067.98	1093.77	1111.38	1124.87	1112.08

TABLE H.7 URANIUM VALUE, V(R,y) - RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = $8/LB, HIGH COSTS, L_F = 0.01
($/KG U)

y	R C_N ($/G NP)	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
0	0	90.10	181.19	244.45	292.13	329.26	358.01	379.12	392.44	397.45	395.92	389.13	376.33	358.03		
	20	89.45	180.66	244.35	292.64	330.41	359.75	381.33	395.11	400.89	399.02	393.32	381.66	364.43		
	60	88.12	179.53	244.07	293.56	332.62	363.10	385.60	400.31	407.63	405.07	401.52	392.12	377.05		
	100	86.72	178.33	243.69	294.36	334.69	366.30	389.72	405.33	414.17	410.92	409.50	402.35	389.42		
0.005	0	9.15	122.41	191.67	241.48	281.00	311.52	333.73	348.00	354.61	355.39	350.71	340.74	325.85		
	20	24.23	139.64	210.61	262.07	302.83	334.35	357.45	372.59	380.04	381.62	377.76	368.50	354.10		
	60	54.34	174.03	248.42	303.17	346.38	379.88	404.76	421.62	430.74	433.91	431.69	423.83	410.40		
	100	84.40	208.34	286.14	344.16	389.81	425.28	451.92	470.49	481.26	486.00	485.43	478.94	466.48		
0.01	0	-97.74	57.29	137.96	193.43	234.92	265.88	288.27	303.33	311.90	315.43	312.89	305.40	293.16	252.27	190.59
	20	-69.57	90.80	175.20	233.71	277.53	310.43	334.50	351.01	360.70	365.25	363.51	356.57	344.58	305.00	245.95
	60	-13.27	157.76	249.63	314.20	362.67	399.41	426.83	446.24	458.16	464.73	464.59	458.75	447.26	410.26	356.45
	100	42.97	224.66	323.96	394.59	447.69	488.26	519.02	541.32	555.44	564.04	565.47	560.71	549.71	515.28	466.68
0.015	0	-260.40	-15.94	82.13	145.88	189.86	221.61	244.73	261.12	271.61	276.49	275.95	270.43	259.95	223.61	170.91
	20	-222.85	31.44	135.98	204.49	252.20	287.09	312.93	331.57	343.64	349.88	350.42	345.66	335.62	301.04	249.48
	60	-147.79	126.16	243.62	321.63	376.79	417.95	449.22	472.35	487.57	496.52	499.20	495.95	486.77	455.72	406.41
	100	-72.77	220.81	351.18	438.67	501.27	548.69	585.37	612.98	631.34	642.98	647.79	646.04	637.71	610.15	563.08
0.02	0	-523.85	-110.70	20.41	94.57	143.24	178.15	204.01	222.69	234.56	238.96	240.11	235.95	226.35	194.76	149.04
	20	-481.60	-51.94	88.26	169.21	223.26	262.75	292.57	314.51	328.67	335.62	338.43	335.58	326.98	297.41	252.13
	60	-397.13	65.51	223.90	318.41	383.22	431.86	469.59	498.03	516.75	528.79	534.91	534.67	528.07	502.52	458.12
	100	-312.69	182.91	359.46	467.52	543.07	600.84	646.46	681.40	704.68	721.78	731.20	733.57	728.95	707.41	663.85
0.03	0			-137.74	-19.91	44.08	86.25	118.15	141.68	157.97	167.67	171.11	168.42	159.60	136.36	98.10
	20			-47.20	82.83	156.38	206.75	245.32	274.39	295.37	309.10	316.05	316.42	310.20	289.96	253.45
	60			133.82	288.25	380.92	447.67	499.57	539.70	570.03	591.82	605.79	612.27	611.22	596.98	563.94
	100			314.77	493.59	605.36	688.47	753.68	804.87	844.55	874.38	895.36	907.93	912.06	903.77	874.20
0.04	0			-344.19	-163.59	-72.22	-13.12	25.33	55.25	75.94	89.47	97.03	99.32	96.71	75.22	37.89
	20			-239.58	-39.82	65.84	136.81	185.02	223.59	251.62	271.45	284.45	291.48	293.06	280.73	247.56
	60			-30.42	207.65	341.87	436.58	504.30	560.16	602.88	635.27	659.14	675.66	685.60	687.56	666.73
	100			178.68	455.05	617.82	736.25	823.46	896.61	953.99	998.95	1033.67	1059.66	1077.96	1094.18	1085.67

TABLE H.8 URANIUM VALUE, V(R,y) - RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$= $6/LB, HIGH COSTS, L_F= 0.01

($/KG U)

y	R / C_N ($/GNP)	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
0	0	69.03	153.48	212.39	257.05	292.02	319.35	339.71	353.00	358.69	358.37	353.30	342.68	327.00		
	20	68.29	152.84	212.18	257.45	293.08	321.01	341.87	355.66	362.15	361.44	357.48	348.06	333.52		
	60	66.75	151.50	211.67	258.14	295.09	324.20	346.05	360.82	368.89	367.42	365.67	358.60	346.36		
	100	65.15	150.06	211.04	258.69	296.93	327.21	350.03	365.77	375.40	373.14	373.59	368.87	358.90		
0.005	0	-4.28	100.18	164.36	210.76	247.89	276.87	298.29	312.44	319.53	321.23	318.01	309.94	297.37		
	20	9.99	116.53	182.41	230.45	268.83	298.82	321.15	336.19	344.15	346.65	344.31	337.02	325.03		
	60	38.49	149.15	218.42	269.74	310.59	342.60	366.73	383.54	393.24	397.32	396.75	390.99	380.13		
	100	66.92	181.68	254.31	308.90	352.20	386.20	412.13	430.68	442.11	447.75	448.93	444.69	434.95		
0.01	0	-100.24	40.98	115.32	166.67	205.60	235.02	256.61	271.43	280.25	284.45	283.15	277.35	267.23	232.00	177.14
	20	-73.30	73.00	150.97	205.32	246.56	277.91	301.18	317.47	327.45	332.73	332.28	327.10	317.30	283.42	231.50
	60	-19.46	136.99	222.19	282.53	328.40	363.57	390.18	409.39	421.68	429.12	430.38	426.42	417.25	386.07	339.99
	100	34.32	200.90	293.30	359.62	410.08	449.06	479.00	501.12	515.69	525.28	528.23	525.47	516.92	488.41	448.15
0.015	0	-244.23	-25.38	64.38	123.15	164.27	194.27	216.35	232.26	242.84	248.47	248.98	245.00	236.56	205.36	158.84
	20	-207.85	20.17	116.16	179.59	224.38	257.48	282.26	300.41	312.61	319.60	321.23	318.05	310.08	280.73	235.63
	60	-135.14	111.21	219.63	292.37	344.50	383.80	413.94	436.59	452.00	461.72	465.57	463.96	456.92	431.26	388.98
	100	-62.48	202.18	323.01	405.04	464.48	509.95	545.46	572.58	591.19	603.62	609.66	609.63	603.50	581.50	542.01
0.02	0	-479.87	-108.54	8.57	76.73	121.78	154.27	178.54	196.41	208.31	213.63	215.71	213.01	205.45	178.50	138.56
	20	-438.36	-51.79	74.15	148.89	199.20	236.17	264.33	285.42	299.61	307.35	311.09	309.71	303.14	278.34	239.04
	60	-355.36	61.67	205.24	293.14	353.94	399.87	435.80	463.32	482.07	494.64	501.69	502.92	498.32	477.81	439.79
	100	-272.42	175.05	336.23	437.28	508.55	563.41	607.10	641.04	664.33	681.72	692.06	695.89	693.25	677.00	640.23
0.03	0			-134.43	-27.88	30.73	69.62	99.36	121.65	137.46	147.34	151.56	150.20	143.22	124.00	91.47
	20			-46.41	71.77	139.60	186.46	222.73	250.44	270.83	284.66	292.31	293.94	289.53	273.36	242.50
	60			129.57	270.99	357.26	420.06	469.35	507.89	537.44	559.14	573.65	581.27	581.99	571.89	544.36
	100			305.46	470.12	574.80	653.52	715.82	765.17	803.86	833.42	854.78	868.37	874.21	870.14	845.92
0.04	0			-323.13	-157.36	-74.02	-20.34	14.16	42.30	61.93	75.00	82.65	85.56	84.11	68.59	35.67
	20			-220.43	-36.48	60.56	125.72	169.59	206.12	232.90	252.12	265.10	272.66	275.30	266.69	239.53
	60			-15.10	205.21	329.63	417.75	480.35	533.64	574.72	606.22	629.85	646.71	657.52	662.70	647.04
	100			190.16	446.81	598.59	709.64	790.96	861.00	916.36	960.14	994.40	1020.53	1039.51	1058.45	1054.26

TABLE H.9 URANIUM VALUE, V(R,y) - RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8} = \$8/\text{LB}$, LOW COSTS, $L_F = 0.01$

(\$/KG U)

y	C_N \ R (\$/G NP)	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
0	0	118.70	191.51	241.94	278.93	306.47	326.29	338.97	344.42	342.41	334.28	321.16	302.42	278.47		
	60	117.50	190.90	242.84	281.86	311.55	333.30	347.55	354.59	355.06	346.06	336.33	321.14	300.57		
0.005	0	57.70	145.66	200.04	238.43	267.66	288.78	302.37	308.71	308.00	301.87	290.58	274.30	253.33		
	60	103.60	198.23	257.98	301.52	334.65	358.96	375.41	384.53	386.49	382.89	374.24	360.22	340.86		
0.01	0	-20.60	96.06	158.27	200.66	231.15	252.47	266.14	273.13	274.03	270.20	260.76	246.64	227.97	175.61	104.12
	60	64.49	197.41	271.05	322.75	360.43	387.71	406.60	418.12	422.53	421.93	415.04	402.72	384.95	336.78	273.41
0.015	0	-137.84	41.31	115.62	163.83	195.91	217.65	231.82	239.87	242.32	239.64	231.91	219.50	202.39	154.15	90.51
	60	-24.66	184.23	278.16	340.84	384.30	415.63	438.13	453.09	460.44	462.00	457.65	447.66	432.01	389.34	329.35
0.02	0	-326.29	-28.56	68.86	124.35	159.71	183.77	200.07	209.93	213.48	210.46	204.19	192.98	176.70	132.69	75.13
	60	-199.06	148.42	273.33	349.38	401.07	439.04	467.38	487.19	497.76	502.53	501.39	494.26	481.13	443.45	387.49
0.03	0			-48.74	37.95	84.10	113.33	133.94	147.38	154.51	155.81	151.52	141.69	126.26	89.59	38.78
	60			223.70	347.21	422.21	476.20	516.98	547.18	568.62	582.07	588.47	587.95	580.43	553.05	507.74
0.04	0			-200.21	-68.94	-3.43	38.04	63.14	81.40	91.86	96.13	95.15	89.47	79.38	46.32	-4.64
	60			114.37	303.31	411.85	489.10	543.63	587.99	620.64	643.93	659.40	668.10	670.71	659.37	627.17

TABLE H.10 URANIUM VALUE, V(R, y) - RECYCLE TO DIFFUSION PLANT: $C_{U_3O_8}$ = \$8/LB, HIGH COSTS, L_F = 0.002

($/KG U)

y	C_N \ R ($/G NP)	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.09	0.10
0	0	89.16	180.92	244.44	292.25	329.46	358.28	379.42	392.73	397.69	396.12	389.25	376.38	358.01		
	60	87.21	179.23	244.01	293.66	332.86	363.45	386.05	400.83	408.22	405.82	402.35	393.03	378.04		
0.005	0	5.15	120.77	190.69	240.80	280.48	311.07	333.27	347.51	354.08	354.85	350.09	340.07	325.13		
	60	52.11	173.97	249.04	304.20	347.68	381.37	406.41	423.42	432.69	436.10	434.02	426.28	412.96		
0.01	0	-111.04	52.87	135.33	191.57	233.34	264.39	286.78	301.82	310.41	313.94	311.37	303.85	291.54	250.45	188.99
	60	-22.36	157.08	250.77	316.25	365.21	402.27	429.98	449.67	461.84	468.66	468.72	463.08	451.75	415.33	362.09
0.015	0	-305.83	-25.87	76.68	142.09	186.70	218.74	242.03	258.55	269.11	273.88	273.35	267.79	257.20	220.76	168.35
	60	-186.33	122.48	244.42	324.22	380.29	422.11	453.97	477.63	493.22	502.46	505.50	502.56	493.64	463.34	414.66
0.02	0	-663.04	-136.87	9.90	87.42	137.60	173.41	199.86	218.89	230.86	235.03	236.23	231.99	222.19	190.67	145.19
	60	-527.48	48.93	222.09	320.14	386.86	436.93	475.81	505.14	524.40	537.08	543.74	543.97	537.75	513.07	469.42
0.03	0			-171.67	-38.36	30.64	75.27	108.70	133.19	150.04	160.03	163.58	160.90	152.08	129.04	90.36
	60			115.66	285.87	384.24	454.32	508.53	550.37	582.07	605.00	619.99	627.39	627.16	614.37	582.69
0.04	0			-434.00	-213.82	-107.00	-39.45	6.42	38.42	60.76	75.63	84.23	87.28	85.12	65.51	24.27
	60			-99.67	180.12	331.12	435.46	512.23	571.52	617.05	651.84	677.77	696.10	707.66	712.42	694.13

APPENDIX I

MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS FOR DIFFERENT MODES OF OPERATION

The tables of this appendix list the maximum unit value of feed uranium over wide ranges of feed isotopic composition and also summarize the optimum operating conditions at those isotopic compositions for which the maximum unit values are given corresponding to either pre-enrichment by gaseous diffusion or blending with natural uranium. Where applicable, U-236 penalty results are also listed in the tables.

For both recycle schemes, the weight ratio of U-235 to U-238 in the feed uranium, R, was varied over the range from $R=0.005$ (depleted uranium) to $R=15$ (fully-enriched uranium). The weight fraction of U-236 in feed uranium, y, is varied between zero and 0.04 for recycle to fabrication and between zero and 0.02 for recycle to a diffusion plant. For each value of y considered, the range of R examined was terminated at the low end at a value of R below which it would be necessary to extrapolate tables for the unit value and flowrate of the diffusion plant product stream during pre-enrichment by gaseous diffusion. Results were also obtained for $y=0.15$ at $R=2$, 6, and 15, for both recycle schemes.

Table I.1 provides a summary of the conditions applicable to each of the remaining 22 tables of the appendix. In addition to the recycle scheme considered, each table is characterized by: a fabrication loss

TABLE I.1

Table Numbers for Maximum Uranium Value Results

Table	Recycle to	Fab. Loss Fraction, L_F	Unit Costs	Natural U_3O_8 Price, $C_{U_3O_8}$ (\$/lb)	Neptunium Price, C_N (\$/g Np)
I.2	Fabrication	0.01	High	8	0
I.3	Fabrication	0.01	High	8	60
I.4	Fabrication	0.01	High	8	100
I.5	Fabrication	0.01	High	6	0
I.6	Fabrication	0.01	High	6	60
I.7	Fabrication	0.01	High	10	0
I.8	Fabrication	0.01	High	10	60
I.9	Fabrication	0.01	Low	8	0
I.10	Fabrication	0.002	Low	8	60
I.11	Fabrication	0.002	High	8	0
I.12	Fabrication:	Pre-enrichment by gaseous diffusion, y=0 at low R, for cases described by I.2 to I.11 above.			
I.13	Fabrication:	Blending with natural uranium, y=0.15 at high R, for cases described by I.2 to I.11 above.			
I.14	Diffusion Plant	0.01	High	8	0
I.15	Diffusion Plant	0.01	High	8	60
I.16	Diffusion Plant	0.01	High	8	100
I.17	Diffusion Plant	0.01	High	6	0
I.18	Diffusion Plant	0.01	High	6	60
I.19	Diffusion Plant	0.01	High	10	0
I.20	Diffusion Plant	0.01	High	10	60
I.21	Diffusion Plant	0.01	Low	8	0
I.22	Diffusion Plant	0.01	Low	8	60
I.23	Diffusion Plant:	Blending with natural uranium, y=0.15 at high R, for cases described by I.14 to I.22 above.			

fraction L_F of either 0.01 or 0.002; a U_3O_8 price $C_{U_3O_8}$ of \$6, \$8, or \$10/lb; a Np-237 price C_N of \$0, \$60, or \$100/g; and the unit cost condition - either "high costs" or "low costs" - in effect.

The optimum value of R when feed contains no U-236 and is priced on the AEC scale, R*, is given for convenience on each table. At each (R,y) point considered, the "mode" of operation used is designated by D, B, or BL, where D denotes pre-enrichment by gaseous diffusion, B refers to basic recycle operation, and BL represents blending with natural uranium. For the indicated "mode", the maximum obtainable unit feed value, in \$/kgU, is listed next as "value". For some (R,y) points, results are given for more than one mode of operation in order to show the transition between the modes of operation which yield the highest unit feed value as R increases.

For the pre-enrichment and blending modes, the three items listed after "value" are the feed stream flowrate (denoted by "kgU/D") at the optimum operating condition, the weight ratio of U-235 to U-238 in the product stream from either the pre-enrichment or blending process (denoted by R_{PROD}), and the weight fraction of U-236 in the product stream (denoted by y_{PROD}). The results for R_{PROD} and y_{PROD} correspond to optimum flowsheet operation.

The final entry for y=0 points is the optimum ratio of natural uranium to product uranium (listed as ϵ) when the blending mode is examined. For points having $y > 0$, this entry is extended to "α or ϵ ", with ϵ listed wherever the blending mode is examined and with α, the fraction of U-236 contained in the feed which is discharged in the product stream from the diffusion plant, listed wherever the pre-enrichment mode is examined.

For points having $y > 0$, the final two entries are the U-236 penalty δ and the "adjusted" U-236 penalty δ_{ADJ}, both with units of $/g U-236.

TABLE I.2 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8} = \$8/\text{LB}$, $C_N = \$0/\text{G}$, HIGH COSTS, $L_F = 0.01$ ($R^* = 0.557$)

$y \backslash R$		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	←0.50→		←0.55→		0.6	0.8	1.0	2	6	15	
0	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	
	VALUE	229.37	528.56	913.87	1364.41	1780.74	2165.59	2522.00	2852.81	3160.59	3447.58	3715.80	3795.42	4117.49	4116.79	4357.06	5175.08	5829.50	7792.76	10036.45	10982.76	
	KGU/D	33.71	16.58	10.14	7.009	5.462	4.540	3.928	3.492	3.166	2.912	2.710			2.536	2.399	2.018	1.790	1.338	1.038	0.9483	
	R_{PROD}	0.556	0.556	0.556	0.556	0.556	0.556	0.556	0.556	0.556	0.556	0.556			0.548	0.561	0.561	0.560	0.560	0.562	0.558	
	y_{PROD}	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0	
	ϵ														0.0018	0.043	0.194	0.286	0.467	0.585	0.623	
0.01	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	
	VALUE	75.26	332.32	694.31	1129.57	1535.74	1912.75	2262.64	2587.81	2890.62	3173.16	3437.32	3503.72	3820.21	3824.04	4062.28	4873.01	5521.37	7466.14	9688.28	10625.24	
	KGU/D	41.13	18.97	11.17	7.545	5.807	4.789	4.122	3.6497	3.299	3.028	2.813			2.628	2.482	2.080	1.842	1.370	1.060	0.9670	
	R_{PROD}	0.594	0.585	0.576	0.568	0.565	0.562	0.562	0.559	0.559	0.559	0.559			0.549	0.561	0.561	0.563	0.559	0.561	0.558	
	y_{PROD}	0.0860	0.0506	0.0339	0.0247	0.0199	0.0169	0.0149	0.0134	0.0122	0.0114	0.0107			0.0100	0.0096	0.0081	0.0072	0.0054	0.0042	0.0038	
	α OR ϵ	0.6677	0.7762	0.8421	0.8872	0.9155	0.9358	0.9511	0.9636	0.9737	0.9822	0.9895			0.0013	0.042	0.193	0.282	0.464	0.583	0.621	
	δ	15.18	19.10	21.04	22.12	22.72	23.12	23.41	23.65	23.84	23.99		25.38		25.23	25.12	25.03	24.98	24.87	24.78	24.77	
	δ_{ADJ}	22.73	24.61	24.99	24.93	24.82	24.71	24.61	24.54	24.48	24.42											
0.02	MODE		D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	
	VALUE		174.54	496.16	901.45	1290.61	1656.29	1997.76	2316.23	2613.43	2891.09	3150.98	3210.31	3521.80	3521.57	3759.45	4563.07	5205.81	7133.20	9334.76	1026294	
	KGU/D		20.95	12.10	8.079	6.164	5.053	4.327	3.819	3.443	3.153	2.923			2.725	2.572	2.147	1.895	1.403	1.082	0.9870	
	R_{PROD}		0.656	0.591	0.585	0.579	0.576	0.571	0.571	0.568	0.568	0.565			0.549	0.566	0.564	0.562	0.564	0.561	0.564	
	y_{PROD}		0.1030	0.0670	0.0494	0.0399	0.0340	0.0298	0.0269	0.0247	0.0229	0.0215			0.0200	0.0193	0.0162	0.0144	0.0108	0.0084	0.0077	
	α OR ϵ		0.7706	0.8407	0.8855	0.9141	0.9343	0.9501	0.9622	0.9726	0.9811	0.9888			0.00068	0.036	0.189	0.280	0.459	0.581	0.615	
	δ		17.17	19.97	21.78	22.73	23.30	23.69	23.98	24.20	24.38		25.46	25.67		25.52	25.43	25.36	25.19	25.04	25.01	
	δ_{ADJ}		22.28	23.75	24.60	24.87	24.94	24.93	24.92	24.88	24.85											
0.04	MODE				D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	
	VALUE				523.74	869.44	1196.36	1507.95	1803.21	2081.80	2344.17	2591.15	2608.34	2921.74	2920.10	3159.53	3941.53	4569.39	6457.47	8616.87	9527.72	
	KGU/D				8.981	6.793	5.539	4.724	4.152	3.729	3.406	3.149			2.924	2.760	2.287	2.011	1.475	1.130	1.028	
	R_{PROD}				0.600	0.591	0.591	0.591	0.588	0.585	0.585	0.582			0.548	0.581	0.576	0.572	0.570	0.567	0.563	
	y_{PROD}				0.0971	0.0790	0.0679	0.0602	0.0544	0.0499	0.0465	0.0436			0.0399	0.0392	0.0330	0.0293	0.0220	0.0171	0.0156	
	α OR ϵ				0.8840	0.9128	0.9327	0.9479	0.9604	0.9708	0.9793	0.9869			0.0025	0.020	0.174	0.268	0.450	0.573	0.611	
	δ				19.65	21.00	22.07	22.83	23.39	23.81	24.14		25.88	25.78		25.58	25.66	25.67	25.59	25.45	25.39	
	δ_{ADJ}				22.23	23.01	23.66	24.08	24.35	24.53	24.65											

TABLE I.3 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$8/LB, C_N = \$60/G, HIGH COSTS, L_F = 0.01 (R^* = 0.539)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	← 0.50 →		← 0.55 →		0.6	0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	229.38	528.59	913.93	1364.50	1780.85	2165.72	2522.16	2852.99	3160.78	3447.79	3716.02	3827.23	4116.17	4117.26	4354.64	5172.18	5826.23	7788.29	10030.90	10976.78
	KGU/D	33.69	16.57	10.14	7.006	5.459	4.538	3.926	3.490	3.164	2.911	2.709			2.536	2.397	2.016	1.789	1.337	1.037	0.9478
	R_{PROD}	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.538			0.543	0.542	0.544	0.541	0.541	0.543	0.544
	y_{PROD}	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
	ε														0.0078	0.064	0.211	0.302	0.479	0.594	0.629
0.01	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	274.95	585.32	976.08	1431.48	1851.02	2237.64	2594.86	2925.90	3233.51	3520.07	3787.69	3895.40	4180.40	4190.28	4426.28	5238.53	5887.80	7834.10	10056.51	10993.56
	KGU/D	41.16	18.95	11.16	7.530	5.797	4.782	4.116	3.646	3.296	3.025	2.810			2.626	2.479	2.078	1.839	1.368	1.059	0.9663
	R_{PROD}	0.600	0.576	0.559	0.541	0.538	0.538	0.538	0.535	0.535	0.535	0.535			0.539	0.539	0.540	0.541	0.540	0.543	0.544
	y_{PROD}	0.0865	0.0502	0.0333	0.0240	0.0193	0.0164	0.0145	0.0130	0.0119	0.0111	0.0104			0.0099	0.0093	0.0079	0.0070	0.0052	0.0041	0.0037
	α OR ε	0.6673	0.7770	0.8437	0.8901	0.9185	0.9385	0.9538	0.9664	0.9765	0.9851	0.9924			0.013	0.066	0.212	0.300	0.476	0.592	0.627
	δ	-4.79	-6.20	-7.13	-8.06	-8.80	-9.36	-9.79	-10.14	-10.43	-10.68		-10.64		-11.42	-11.52	-11.81	-11.98	-12.37	-12.59	-12.65
	δ_{ADJ}	-7.18	-7.98	-8.45	-9.06	-9.58	-9.97	-10.26	-10.49	-10.68	-10.84										
0.02	MODE		D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE		622.71	1025.28	1479.98	1896.81	2281.45	2637.48	2968.05	3275.38	3561.73	3829.04	3944.79	4232.62	4233.30	4468.52	5277.67	5923.98	7858.73	10064.81	10994.68
	KGU/D		20.90	12.10	8.071	6.156	5.045	4.321	3.812	3.436	3.147	2.918			2.724	2.567	2.143	1.892	1.401	1.081	0.9854
	R_{PROD}		0.621	0.585	0.574	0.565	0.559	0.553	0.544	0.541	0.541	0.541			0.544	0.542	0.540	0.541	0.540	0.543	0.537
	y_{PROD}		0.1002	0.0667	0.0489	0.0393	0.0334	0.0293	0.0262	0.0240	0.0223	0.0209			0.0199	0.0187	0.0158	0.0140	0.0105	0.0082	0.0075
	α OR ε		0.7733	0.8412	0.8866	0.9155	0.9361	0.9521	0.9653	0.9758	0.9843	0.9917			0.0067	0.063	0.211	0.298	0.474	0.590	0.627
	δ		-5.24	-6.48	-7.14	-7.58	-7.95	-8.29	-8.61	-8.89	-9.14		-9.71		-9.92	-10.05	-10.45	-10.71	-11.31	-11.73	-11.87
	δ_{ADJ}		-6.78	-7.70	-8.05	-8.28	-8.49	-8.71	-8.92	-9.11	-9.29										
0.04	MODE				D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE				1552.36	1982.12	2367.93	2721.06	3046.90	3349.10	3630.41	3893.03	3971.36	4292.46	4291.06	4530.28	5323.91	5959.34	7866.82	10043.07	10959.18
	KGU/D				8.996	6.795	5.535	4.718	4.147	3.725	3.401	3.145			2.924	2.756	2.284	2.008	1.472	1.128	1.027
	R_{PROD}				0.615	0.594	0.585	0.579	0.576	0.573	0.571	0.568			0.548	0.570	0.563	0.558	0.544	0.542	0.543
	y_{PROD}				0.0984	0.0792	0.0675	0.0595	0.0538	0.0493	0.0459	0.0430			0.0399	0.0387	0.0325	0.0288	0.0213	0.0166	0.0152
	α OR ε				0.8826	0.9125	0.9334	0.9492	0.9617	0.9721	0.9808	0.9885			0.0025	0.032	0.186	0.280	0.466	0.585	0.620
	δ				-6.06	-6.81	-7.22	-7.49	-7.70	-7.87	-8.01		-7.43	-8.50		-8.75	-8.97	-9.15	-9.75	-10.34	-10.54
	δ_{ADJ}				-6.87	-7.46	-7.74	-7.89	-8.01	-8.10	-8.17										

TABLE I.4 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$8/LB, C_N = \$100/G, HIGH COSTS, L_F = 0.01 (R^* = 0.528)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	←0.45→		←0.50→		←0.55→		0.6	0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	229.39	528.61	913.96	1364.53	1780.90	2165.78	2522.22	2853.06	3160.86	3447.88	3446.87	3716.12	3841.84	4108.25	4115.71	4352.97	5170.24	5824.05	7785.47	10027.09	10972.78
	KGU/D	33.69	16.57	10.14	7.006	5.460	4.538	3.926	3.491	3.164	2.911		2.709			2.535	2.396	2.016	1.789	1.337	1.037	0.9475
	R_{PROD}	0.529	0.529	0.529	0.529	0.529	0.529	0.529	0.529	0.529	0.529		0.529			0.531	0.532	0.531	0.531	0.531	0.531	0.531
	y_{PROD}	0	0	0	0	0	0	0	0	0	0		0			0	0	0	0	0	0	0
	ϵ															0.023	0.076	0.223	0.311	0.485	0.600	0.635
0.01	MODE	D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	407.69	753.28	1163.38	1633.11	2061.96	2455.38	2817.69	3152.83	3463.83	3753.22	3744.23	4023.25	4150.15	4413.72	4434.08	4670.52	5484.04	6134.02	8081.39	10304.60	11242.06
	KGU/D	41.18	18.94	11.14	7.526	5.794	4.781	4.115	3.645	3.295	3.025		2.810			2.625	2.478	2.077	1.839	1.368	1.058	0.9660
	R_{PROD}	0.603	0.568	0.544	0.532	0.526	0.526	0.526	0.523	0.524	0.524		0.523			0.529	0.529	0.528	0.527	0.531	0.531	0.531
	y_{PROD}	0.0867	0.0498	0.0328	0.0238	0.0191	0.0162	0.0143	0.0129	0.0118	0.0110		0.0103			0.0097	0.0092	0.0078	0.0069	0.0052	0.0040	0.0037
	α OR ϵ	0.6671	0.7777	0.8453	0.8911	0.9199	0.9400	0.9553	0.9679	0.9779	0.9864		0.9939			0.025	0.078	0.224	0.312	0.482	0.598	0.633
	δ	-18.06	-23.00	-25.86	-28.22	-29.89	-31.12	-32.07	-32.83	-33.46	-33.98			-34.67		-35.95	-36.11	-36.55	-36.82	-37.38	-37.78	-37.90
	δ_{ADJ}	-27.07	-29.57	-30.59	-31.67	-32.49	-33.11	-33.57	-33.92	-34.22	-34.45											
0.02	MODE		D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE		921.32	1376.74	1864.04	2299.21	2696.97	3063.82	3402.99	3717.48	4009.87	4015.81	4282.46	4428.30	4699.93	4705.23	4941.98	5755.50	6404.53	8345.01	10555.34	11486.40
	KGU/D		20.89	12.09	8.066	6.153	5.040	4.316	3.809	3.434	3.145		2.916			2.722	2.565	2.141	1.891	1.401	1.080	0.9852
	R_{PROD}		0.618	0.579	0.568	0.559	0.544	0.538	0.535	0.532	0.529		0.529			0.534	0.532	0.531	0.530	0.531	0.531	0.531
	y_{PROD}		0.1000	0.0663	0.0486	0.0391	0.0329	0.0288	0.0260	0.0238	0.0220		0.0207			0.0196	0.0185	0.0156	0.0139	0.0104	0.0081	0.0074
	α OR ϵ		0.7735	0.8418	0.8872	0.9162	0.9378	0.9538	0.9664	0.9769	0.9858		0.9932			0.019	0.074	0.220	0.307	0.480	0.596	0.630
	δ		-20.16	-24.05	-26.34	-27.70	-28.73	-29.60	-30.35	-30.99		-31.84		-33.16		-33.59	-33.80	-34.43	-34.85	-35.76	-36.44	-36.65
	δ_{ADJ}		-26.06	-28.57	-29.69	-30.23	-30.64	-31.03	-31.41	-31.72												
0.04	MODE				D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE				2236.28	2721.37	3146.10	3526.71	3872.70	4190.41	4484.17	4417.54	4757.18	4874.33	5200.18	5198.93	5438.78	6240.47	6882.26	8806.79	10996.28	11917.01
	KGU/D				8.996	6.795	5.533	4.717	4.145	3.723	3.399		3.143			2.924	2.755	2.282	2.005	1.470	1.127	1.026
	R_{PROD}				0.615	0.594	0.582	0.576	0.571	0.568	0.565		0.562			0.548	0.567	0.556	0.543	0.535	0.530	0.530
	y_{PROD}				0.0984	0.0792	0.0673	0.0594	0.0535	0.0491	0.0456		0.0427			0.0399	0.0386	0.0323	0.0283	0.0211	0.0164	0.0150
	α OR ϵ				0.8826	0.9125	0.9337	0.9495	0.9622	0.9726	0.9815		0.9892			0.0025	0.035	0.193	0.292	0.472	0.591	0.626
	δ				-23.16	-25.29	-26.67	-27.63	-28.34	-28.90	-29.36			-29.65	-31.23		-31.50	-31.93	-32.28	-33.32	-34.26	-34.58
	δ_{ADJ}				-26.24	-27.72	-28.56	-29.10	-29.45	-29.71	-29.91											

TABLE I.5 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION :

$C_{U_3O_8}$ = \$6/LB, C_N = \$0/G, HIGH COSTS, L_F = 0.01 (R^* = 0.571)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	← 0.50 →		← 0.55 →		← 0.60 →		0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL
	VALUE	199.05	466.67	812.58	1217.72	1592.42	1938.99	2260.05	2558.14	2835.52	3094.22	3336.03	3372.97	3562.51	3691.11	3904.91	3915.72	4651.44	5240.02	7005.69	9023.72	9874.59
	KGU/D	34.07	16.67	10.18	7.024	5.471	4.546	3.933	3.496	3.169	2.915	2.712		2.546			2.401	2.020	1.792	1.340	1.039	0.9498
	R_{PROD}	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.571		0.570			0.574	0.574	0.574	0.576	0.574	0.578
	y_{PROD}	0	0	0	0	0	0	0	0	0	0	0		0			0	0	0	0	0	0
	ϵ																0.028	0.182	0.274	0.456	0.579	0.614
0.01	MODE	D	D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL
	VALUE	59.46	286.73	609.99	1000.29	1365.23	1704.32	2019.21	2312.03	2584.77	2839.30	3077.33	3102.31	3300.40	3413.45	3628.83	3641.71	4370.90	4954.08	6703.30	8701.84	9544.63
	KGU/D	41.52	19.09	11.22	7.568	5.820	4.798	4.129	3.655	3.304	3.033	2.816		2.640			2.486	2.083	1.844	1.372	1.061	0.9686
	R_{PROD}	0.603	0.615	0.597	0.588	0.582	0.579	0.579	0.576	0.576	0.576	0.573		0.573			0.577	0.577	0.578	0.576	0.574	0.578
	y_{PROD}	0.0858	0.0516	0.0343	0.0250	0.0201	0.0171	0.0151	0.0136	0.0124	0.0116	0.0108		0.0102			0.0098	0.0082	0.0073	0.0055	0.0042	0.0039
	α OR ϵ	0.6529	0.7642	0.8334	0.8804	0.9102	0.9313	0.9471	0.9602	0.9707	0.9795	0.9875		0.9942			0.024	0.178	0.270	0.454	0.577	0.612
	δ	13.86	17.53	19.45	20.52	21.13	21.53	21.82	22.05	22.24	22.40		23.69		24.08		23.48	23.40	23.35	23.23	23.16	23.12
	δ_{ADJ}	21.23	22.94	23.34	23.31	23.21	23.12	23.04	22.96	22.91	22.87											
0.02	MODE		D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL
	VALUE		145.04	427.89	790.78	1139.26	1467.45	1774.24	2060.56	2327.88	2577.78	2811.72	2829.04	3031.12	3134.31	3357.41	3360.36	4083.04	4661.14	6394.53	8374.50	9209.89
	KGU/D		21.06	12.16	8.112	6.183	5.066	4.337	3.827	3.450	3.158	2.928		2.740			2.578	2.151	1.899	1.406	1.083	0.9882
	R_{PROD}		0.679	0.618	0.615	0.603	0.597	0.591	0.588	0.588	0.585	0.585		0.582			0.586	0.583	0.581	0.581	0.574	0.578
	y_{PROD}		0.1040	0.0682	0.0505	0.0406	0.0346	0.0304	0.0274	0.0251	0.0233	0.0219		0.0206			0.0197	0.0166	0.0147	0.0110	0.0085	0.0078
	α OR ϵ		0.7593	0.8315	0.8777	0.9080	0.9293	0.9458	0.9588	0.9693	0.9785	0.9861		0.9931			0.015	0.171	0.265	0.449	0.575	0.609
	δ		15.61	18.42	20.13	21.07	21.64	22.03	22.32	22.55	22.73		23.82		24.15		23.85	23.77	23.70	23.55	23.44	23.36
	δ_{ADJ}		20.56	22.15	22.93	23.20	23.29	23.29	23.28	23.26	23.23											
0.04	MODE				D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL
	VALUE				449.37	749.79	1043.54	1323.89	1588.95	1838.76	2074.00	2295.55	2265.34	2504.29	2572.30	2805.78	2805.66	3508.17	4072.28	5769.23	7710.78	8529.98
	KGU/D				9.051	6.809	5.556	4.740	4.165	3.741	3.415	3.158		2.948			2.766	2.293	2.016	1.479	1.132	1.031
	R_{PROD}				0.679	0.606	0.615	0.621	0.618	0.615	0.612	0.609		0.606			0.598	0.596	0.595	0.590	0.586	0.584
	y_{PROD}				0.1029	0.0798	0.0692	0.0617	0.0558	0.0512	0.0476	0.0446		0.0422			0.0399	0.0337	0.0300	0.0225	0.0174	0.0159
	α OR ϵ				0.8721	0.9077	0.9275	0.9427	0.9556	0.9664	0.9755	0.9835		0.9904			0.0017	0.156	0.250	0.438	0.564	0.602
	δ				17.99	19.47	20.45	21.14	21.67	22.08	22.41	23.56			24.28	23.83		23.93	23.95	23.91	23.80	23.74
	δ_{ADJ}				20.63	21.45	22.05	22.42	22.68	22.85	22.97	23.96										

TABLE I.6 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8} = \$6/\text{LB}$, $C_N = \$60/\text{G}$, HIGH COSTS, $L_F = 0.01$ ($R^* = 0.552$)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	←0.50→		←0.55→		0.6	0.8	1.0	2	6	15
0	Mode	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	Value	199.07	466.73	812.67	12.17.85	1592.59	1939.19	2260.28	2558.40	2835.80	3094.53	3336.37	3413.74	3699.34	3698.98	3913.25	4648.47	5236.67	7001.32	9017.99	9868.37
	KGU/D	34.03	16.65	10.17	7.017	5.466	4.542	3.929	3.492	3.166	2.912	2.710			2.536	2.398	2.017	1.790	1.338	1.038	0.9483
	R_{PROD}	0.550	0.550	0.550	0.550	0.550	0.550	0.550	0.550	0.550	0.550	0.550			0.548	0.555	0.556	0.556	0.555	0.556	0.558
	y_{PROD}	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
	ε														0.0018	0.049	0.199	0.289	0.470	0.588	0.623
0.01	Mode	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	Value	255.11	536.88	889.57	1299.72	1677.80	2026.53	2348.91	2647.71	2925.37	3184.06	3425.66	3502.63	3782.84	3791.35	4003.78	4734.44	5318.55	7069.06	9067.83	9911.26
	KGU/D	41.57	19.05	11.19	7.550	5.808	4.788	4.120	3.648	3.298	3.027	2.811			2.628	2.481	2.079	1.840	1.369	1.059	0.9666
	R_{PROD}	0.612	0.591	0.576	0.562	0.556	0.550	0.550	0.547	0.547	0.547	0.547			0.549	0.553	0.550	0.552	0.550	0.549	0.551
	y_{PROD}	0.0864	0.0505	0.0337	0.0244	0.0196	0.0166	0.0147	0.0132	0.0121	0.0112	0.0105			0.0100	0.0095	0.0080	0.0071	0.0053	0.0041	0.0038
	α ORE	0.6522	0.7662	0.8354	0.8831	0.9130	0.9346	0.9505	0.9636	0.9741	0.9830	0.9907			0.0013	0.051	0.203	0.291	0.470	0.589	0.624
	δ	-5.80	-7.48	-8.50	-9.40	-10.11	-10.67	-11.12	-11.49	-11.79	-12.05		-12.30		-12.90	-12.97	-13.25	-13.42	-13.78	-14.00	-14.16
	δ_{ADJ}	-8.89	-9.76	-10.17	-10.64	-11.07	-11.42	-11.70	-11.92	-12.10	-12.26										
0.02	Mode		D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	Value		587.77	954.03	1366.57	1743.55	2090.81	2412.02	2710.02	2987.11	3245.38	3486.62	3571.85	3854.01	3853.87	4067.08	4794.58	5375.88	7116.29	9101.05	9937.91
	KGU/D		21.01	12.15	8.093	6.170	5.055	4.328	3.818	3.441	3.151	2.921			2.725	2.570	2.145	1.894	1.402	1.081	0.9860
	R_{PROD}		0.647	0.606	0.591	0.582	0.576	0.568	0.565	0.562	0.559	0.556			0.549	0.558	0.557	0.555	0.554	0.549	0.551
	y_{PROD}		0.1016	0.0676	0.0495	0.0399	0.0339	0.0297	0.0268	0.0245	0.0227	0.0213			0.0200	0.0191	0.0161	0.0143	0.0107	0.0083	0.0076
	α ORE		0.7616	0.8325	0.8801	0.9102	0.9316	0.9484	0.9614	0.9723	0.9815	0.9896			0.00068	0.045	0.195	0.286	0.465	0.587	0.621
	δ		-6.52	-7.88	-8.65	-9.14	-9.52	-9.85	-10.14	-10.40	-10.64		-11.32	-11.43		-11.60	-11.95	-12.20	-12.75	-13.17	-13.35
	δ_{ADJ}		-8.56	-9.47	-9.83	-10.04	-10.22	-10.39	-10.55	-10.70	-10.84										
0.04	Mode				D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	Value				1471.11	1862.45	2214.06	2535.05	2830.95	3105.05	3359.95	3597.74	3636.11	3951.30	3948.97	4179.75	4892.57	5463.01	7175.58	9131.22	9955.46
	KGU/D				9.026	6.812	5.551	4.729	4.155	3.732	3.407	3.150			2.924	2.763	2.288	2.012	1.474	1.129	1.028
	R_{PROD}				0.641	0.609	0.606	0.597	0.594	0.591	0.588	0.585			0.548	0.590	0.579	0.576	0.563	0.554	0.557
	y_{PROD}				0.1000	0.0800	0.0686	0.0604	0.0546	0.0501	0.0466	0.0437			0.0399	0.0396	0.0331	0.0294	0.0218	0.0168	0.0155
	α ORE				0.8753	0.9074	0.9284	0.9452	0.9582	0.9690	0.9782	0.9861			0.0025	0.011	0.171	0.265	0.454	0.579	0.614
	δ				-7.55	-8.34	-8.81	-9.13	-9.37	-9.57	-9.73		-8.97	-10.00		-10.58	-10.75	-10.90	-11.36	-11.85	-12.05
	δ_{ADJ}				-8.63	-9.19	-9.49	-9.66	-9.78	-9.88	-9.95										

TABLE I.7 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$10/LB, C_N = \$0/G, HIGH COSTS, L_F = 0.01 (R^* = 0.545)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	← 0.50 →		← 0.55 →		0.6	0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	258.37	587.47	1010.12	1503.68	1959.44	2380.58	2770.48	3132.30	3468.87	3782.67	4075.91	4190.09	4515.58	4515.61	4775.73	5671.79	6388.67	8539.17	10996.99	12033.52
	KGU/D	33.44	16.52	10.12	6.999	5.456	4.536	3.925	3.490	3.164	2.911	2.709			2.536	2.397	2.017	1.789	1.337	1.038	0.9480
	R_{PROD}	0.544	0.544	0.544	0.544	0.544	0.544	0.544	0.544	0.544	0.544	0.544			0.548	0.550	0.550	0.549	0.550	0.549	0.551
	y_{PROD}	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
	ε														0.0018	0.055	0.205	0.295	0.473	0.591	0.626
0.01	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	91.45	376.45	775.10	1252.92	1698.16	2111.04	2494.01	2849.80	3181.02	3490.01	3778.87	3878.64	4199.90	4203.54	4461.34	5349.21	6059.41	8189.41	10623.33	11649.79
	KGU/D	40.80	18.88	11.14	7.530	5.796	4.783	4.117	3.647	3.296	3.026	2.811			2.628	2.480	2.079	1.840	1.369	1.059	0.9666
	R_{PROD}	0.579	0.568	0.559	0.553	0.547	0.547	0.547	0.547	0.544	0.544	0.544			0.549	0.547	0.550	0.549	0.550	0.549	0.551
	y_{PROD}	0.0857	0.0501	0.0334	0.0244	0.0195	0.0166	0.0146	0.0132	0.0121	0.0112	0.0105			0.0100	0.0094	0.0080	0.0071	0.0053	0.0041	0.0038
	α OR ε	0.6804	0.7855	0.8492	0.8926	0.9203	0.9396	0.9543	0.9661	0.9762	0.9844	0.9915			0.0013	0.057	0.203	0.294	0.470	0.589	0.624
	δ	16.43	20.51	22.49	23.57	24.17	24.57	24.88	25.12	25.32	25.48		26.95		26.69	26.66	26.59	26.54	26.44	26.37	26.34
	δ_{ADJ}	24.15	26.11	26.48	26.41	26.26	26.15	26.07	26.00	25.94	25.88										
0.02	MODE		D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE		204.59	561.81	1008.02	1435.61	1836.86	2211.21	2560.10	2885.52	3189.45	3473.96	3566.31	3883.40	3883.41	4139.08	5019.23	5723.20	7833.96	10245.01	11261.73
	KGU/D		20.77	12.06	8.060	6.152	5.044	4.321	3.814	3.438	3.149	2.919			2.725	2.569	2.144	1.893	1.402	1.081	0.9860
	R_{PROD}		0.585	0.573	0.568	0.562	0.559	0.556	0.553	0.553	0.553	0.547			0.549	0.553	0.550	0.548	0.549	0.549	0.551
	y_{PROD}		0.0978	0.0662	0.0487	0.0393	0.0335	0.0294	0.0265	0.0243	0.0226	0.0211			0.0200	0.0190	0.0160	0.0142	0.0106	0.0083	0.0076
	α OR ε		0.7841	0.8478	0.8911	0.9187	0.9383	0.9533	0.9654	0.9752	0.9834	0.9912			0.00068	0.051	0.202	0.292	0.468	0.587	0.621
	δ		18.56	21.41	23.28	24.23	24.81	25.19	25.48	25.70	25.88		27.00		27.09	27.06	26.96	26.88	26.72	26.60	26.56
	δ_{ADJ}		23.67	25.25	26.13	26.37	26.44	26.42	26.39	26.35	26.32										
0.04	MODE				D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE				601.77	983.10	1342.76	1685.29	2009.66	2315.57	2603.50	2874.43	2928.39	3247.61	3246.85	3498.07	4355.64	5043.91	7112.57	9477.66	10475.16
	KGU/D				8.958	6.778	5.528	4.713	4.144	3.723	3.399	3.144			2.924	2.754	2.283	2.008	1.473	1.128	1.027
	R_{PROD}				0.582	0.576	0.576	0.571	0.571	0.568	0.565	0.565			0.548	0.564	0.560	0.558	0.553	0.548	0.550
	y_{PROD}				0.0959	0.0781	0.0671	0.0592	0.0536	0.0491	0.0456	0.0429			0.0399	0.0385	0.0324	0.0288	0.0216	0.0167	0.0153
	α OR ε				0.8897	0.9173	0.9365	0.9517	0.9635	0.9735	0.9820	0.9891			0.0025	0.038	0.189	0.280	0.460	0.582	0.617
	δ				21.04	22.45	23.56	24.36	24.93	25.36	25.70		27.35	27.18		27.17	27.23	27.23	27.13	26.99	26.93
	δ_{ADJ}				23.65	24.47	25.16	25.60	25.87	26.05	26.17										

TABLE I.8 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$10/LB, C_N = \$60/G, HIGH COSTS, L_F = 0.01 (R^* = 0.529)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	← 0.45	→	← 0.50	→	← 0.55	→	0.6	0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	258.39	587.50	1010.17	1503.75	1959.54	2380.69	2770.61	3132.44	3469.03	3782.84	3792.87	4076.10	4214.27	4506.13	4513.27	4773.29	5668.88	6385.35	8534.80	10991.29	12027.63
	KGU/D	33.44	16.52	10.12	6.999	5.456	4.536	3.925	3.490	3.164	2.911		2.709			2.535	2.396	2.016	1.789	1.337	1.037	0.9475
	R_{PROD}	0.529	0.529	0.529	0.529	0.529	0.529	0.529	0.529	0.529	0.529		0.529			0.531	0.532	0.531	0.531	0.531	0.531	0.531
	y_{PROD}	0	0	0	0	0	0	0	0	0	0		0			0	0	0	0	0	0	0
	ε															0.023	0.076	0.223	0.311	0.485	0.600	0.635
0.01	MODE	D	D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE	293.47	631.31	1058.59	1556.80	2015.20	2437.52	2827.72	3189.28	3525.22	3838.18	3829.04	4130.44	4262.96	4552.24	4567.98	4826.39	5715.82	6426.89	8558.45	10992.90	12019.64
	KGU/D	40.84	18.87	11.12	7.519	5.791	4.779	4.114	3.644	3.295	3.025		2.810			2.625	2.478	2.077	1.839	1.368	1.058	0.9660
	R_{PROD}	0.588	0.562	0.541	0.532	0.529	0.526	0.526	0.526	0.526	0.526		0.526			0.529	0.529	0.531	0.531	0.531	0.531	0.531
	y_{PROD}	0.0863	0.0498	0.0328	0.0238	0.0192	0.0163	0.0143	0.0129	0.0118	0.0110		0.0103			0.0097	0.0092	0.0078	0.0069	0.0052	0.0040	0.0037
	α_{ORE}	0.6798	0.7860	0.8510	0.8948	0.9223	0.9420	0.9568	0.9686	0.9783	0.9866		0.9937			0.025	0.078	0.221	0.309	0.482	0.598	0.633
	δ	-3.77	-4.97	-5.85	-6.81	-7.53	-8.06	-8.48	-8.82	-9.09	-8.32			-9.08		-9.98	-10.08	-10.36	-10.54	-10.90	-11.15	-11.23
	δ_{ADJ}	-5.55	-6.32	-6.87	-7.61	-8.16	-8.56	-8.86	-9.11	-9.29	-8.43											
0.02	MODE		D	D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE		656.14	1092.82	1587.76	2042.68	2463.33	2852.80	3213.95	3549.57	3862.11	3857.76	4153.94	4293.69	4586.64	4592.18	4849.76	5735.66	6443.21	8561.49	10977.54	11995.89
	KGU/D		20.81	12.06	8.056	6.148	5.037	4.315	3.808	3.434	3.145		2.916			2.721	2.565	2.141	1.891	1.401	1.080	0.9852
	R_{PROD}		0.600	0.571	0.562	0.553	0.541	0.535	0.532	0.532	0.529		0.529			0.532	0.532	0.531	0.530	0.531	0.531	0.531
	y_{PROD}		0.0991	0.0661	0.0485	0.0389	0.0328	0.0288	0.0259	0.0238	0.0220		0.0207			0.0196	0.0185	0.0156	0.0139	0.0104	0.0081	0.0074
	α_{ORE}		0.7828	0.8480	0.8917	0.9197	0.9403	0.9557	0.9679	0.9776	0.9862		0.9933			0.022	0.074	0.220	0.307	0.480	0.596	0.630
	δ		-4.02	-5.14	-5.70	-6.12	-6.51	-6.88	-7.21	-7.50	-7.25			-8.19		-8.46	-8.60	-9.01	-9.28	-9.87	-10.30	-10.44
	δ_{ADJ}		-5.14	-6.06	-6.39	-6.65	-6.92	-7.20	-7.45	-7.67	-7.35											
0.04	MODE				D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL	BL
	VALUE				1630.40	2095.53	2514.13	2897.79	3252.27	3581.37	3887.95	3830.95	4174.36	4284.81	4611.28	4610.75	4864.87	5735.69	6433.44	8524.53	10907.32	11910.61
	KGU/D				8.975	6.781	5.526	4.712	4.142	3.721	3.397		3.141			2.924	2.752	2.280	2.004	1.470	1.127	1.026
	R_{PROD}				0.600	0.579	0.571	0.568	0.565	0.562	0.559		0.556			0.548	0.556	0.546	0.540	0.535	0.530	0.530
	y_{PROD}				0.0974	0.0783	0.0668	0.0590	0.0533	0.0488	0.0453		0.0425			0.0399	0.0381	0.0319	0.0282	0.0211	0.0164	0.0150
	α_{ORE}				0.8880	0.9170	0.9370	0.9521	0.9641	0.9742	0.9827		0.9901			0.0025	0.047	0.202	0.294	0.472	0.591	0.626
	δ				-4.67	-5.36	-5.72	-5.95	-6.13	-6.28	-6.17			-5.98	-6.96		-7.06	-7.34	-7.59	-8.28	-8.89	-9.10
	δ_{ADJ}				-5.26	-5.85	-6.10	-6.25	-6.36	-6.45	-6.28											

TABLE I.9 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$8/LB, C_N = \$0/G, LOW COSTS, L_F = 0.01 (R^* = 0.497)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	← 0.45 →		← 0.50 →		0.55	0.6	0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	229.44	528.70	914.11	1364.76	1781.18	2166.13	2522.62	2853.51	3161.35	3448.41	3544.98	3858.54	3858.50	4111.38	4348.41	5164.79	5817.90	7777.18	10016.53	10961.06
	KGU/D	33.74	16.59	10.15	7.015	5.467	4.544	3.931	3.495	3.169	2.915			2.704	2.536	2.397	2.017	1.790	1.337	1.038	0.9481
	R_{PROD}	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497			0.499	0.502	0.501	0.502	0.500	0.499	0.502	0.499
	y_{PROD}	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0	0
	ϵ													0.0015	0.059	0.111	0.252	0.338	0.506	0.615	0.650
0.01	MODE	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	95.35	360.41	727.62	1164.96	1571.68	1948.76	2298.60	2623.69	2926.38	3208.81	3280.50	3605.13	3605.89	3856.46	4091.08	4899.15	5545.63	7485.06	9701.69	10636.42
	KGU/D	40.88	18.87	11.12	7.522	5.794	4.781	4.116	3.647	3.297	3.027			2.803	2.625	2.478	2.077	1.839	1.368	1.059	0.9662
	R_{PROD}	0.518	0.509	0.503	0.503	0.503	0.500	0.500	0.500	0.500	0.500			0.499	0.502	0.504	0.502	0.503	0.504	0.502	0.505
	y_{PROD}	0.0800	0.0468	0.0313	0.0230	0.0186	0.0158	0.0139	0.0125	0.0115	0.0107			0.0100	0.0094	0.0089	0.0075	0.0067	0.0050	0.0039	0.0036
	α OR ϵ	0.6738	0.7835	0.8498	0.8945	0.9227	0.9432	0.9586	0.9709	0.9810	0.9896			0.00081	0.058	0.108	0.250	0.333	0.500	0.613	0.645
	δ	13.18	16.30	17.73	18.62	19.17	19.57	19.88	20.13	20.34		22.90		21.41	21.38	21.38	21.40	21.41	21.43	21.47	21.50
	δ_{ADJ}	19.56	20.80	20.86	20.82	20.78	20.75	20.74	20.73	20.73											
0.02	MODE		D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		220.18	550.66	966.06	1361.17	1730.18	2073.59	2393.19	2691.03	2969.09	3030.44	3353.25	3353.22	3601.60	3833.97	4634.22	5274.28	7194.23	9388.17	10313.68
	KGU/D		20.70	12.04	8.038	6.135	5.031	4.311	3.806	3.432	3.144			2.907	2.719	2.563	2.140	1.890	1.400	1.080	0.9852
	R_{PROD}		0.515	0.515	0.506	0.506	0.503	0.503	0.503	0.503	0.503			0.500	0.505	0.504	0.505	0.503	0.503	0.502	0.505
	y_{PROD}		0.0909	0.0622	0.0455	0.0369	0.0314	0.0278	0.0251	0.0230	0.0214			0.0200	0.0189	0.0179	0.0151	0.0134	0.0100	0.0078	0.0072
	α OR ϵ		0.7829	0.8484	0.8941	0.9224	0.9428	0.9582	0.9705	0.9806	0.9892			0.00016	0.055	0.107	0.245	0.331	0.498	0.611	0.642
	δ		14.90	17.26	18.57	19.22	19.63	19.93	20.16	20.35		22.18	21.41		21.38	21.37	21.36	21.36	21.37	21.40	21.41
	δ_{ADJ}		19.03	20.34	20.77	20.84	20.82	20.80	20.77	20.75											
0.04	MODE				D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				630.49	981.09	1316.68	1636.55	1938.76	2222.98	2489.91	2536.72	2846.13	2845.80	3089.04	3316.32	4100.33	4728.00	6610.60	8761.01	9668.24
	KGU/D				8.912	6.756	5.510	4.699	4.130	3.710	3.388			3.123	2.914	2.741	2.273	2.000	1.469	1.126	1.025
	R_{PROD}				0.515	0.518	0.515	0.512	0.509	0.509	0.506			0.499	0.507	0.506	0.505	0.506	0.507	0.507	0.505
	y_{PROD}				0.0896	0.0736	0.0630	0.0556	0.0502	0.0462	0.0428			0.0399	0.0380	0.0359	0.0304	0.0270	0.0204	0.0159	0.0145
	α OR ϵ				0.8930	0.9209	0.9413	0.9570	0.9697	0.9798	0.9888			0.0018	0.051	0.102	0.241	0.324	0.490	0.603	0.638
	δ				16.99	18.22	19.07	19.63	20.02	20.30		21.66	21.45		21.45	21.45	21.45	21.43	21.39	21.37	21.36
	δ_{ADJ}				19.03	19.78	20.26	20.51	20.65	20.72											

TABLE I.10 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$8/LB, C_N = \$60/G, LOW COSTS, L_F = 0.01 (R^* = 0.480)

y \ R		0.03	0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	←0.45→		←0.50→		0.55	0.6	0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	229.47	528.76	914.21	1364.90	1781.37	2166.35	2522.88	2853.80	3161.67	3448.76	3564.03	3851.35	3856.26	4108.90	4345.79	5161.67	5814.42	7772.59	10010.44	10954.13
	KGU/D	33.78	16.62	10.17	7.024	5.474	4.550	3.936	3.500	3.173	2.919			2.706	2.538	2.399	2.018	1.791	1.338	1.038	0.9489
	R_{PROD}	0.479	0.479	0.479	0.479	0.479	0.479	0.479	0.479	0.479	0.479			0.484	0.485	0.484	0.485	0.484	0.484	0.485	0.481
	y_{PROD}	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0	0
	ϵ													0.022	0.081	0.132	0.270	0.353	0.516	0.624	0.659
0.01	MODE	D	D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	291.47	609.12	1006.42	1465.36	1886.36	2273.87	2631.70	2963.22	3271.21	3558.10	3661.79	3959.22	3969.27	4220.47	4455.89	5266.25	5914.01	7855.97	10073.78	11008.74
	KGU/D	40.89	18.87	11.12	7.524	5.796	4.784	4.119	3.649	3.299	3.029			2.803	2.626	2.479	2.078	1.840	1.369	1.059	0.9667
	R_{PROD}	0.529	0.509	0.497	0.491	0.488	0.485	0.485	0.482	0.482	0.482			0.486	0.485	0.487	0.485	0.484	0.484	0.485	0.487
	y_{PROD}	0.0809	0.0468	0.0311	0.0227	0.0182	0.0155	0.0136	0.0122	0.0112	0.0104			0.0098	0.0092	0.0087	0.0073	0.0065	0.0049	0.0038	0.0035
	α OR ϵ	0.6728	0.7835	0.8505	0.8960	0.9247	0.9452	0.9606	0.9734	0.9835	0.9921			0.019	0.081	0.128	0.268	0.351	0.514	0.622	0.653
	δ	-6.43	-8.56	-10.14	-11.41	-12.28	-12.92	-13.40	-13.80	-14.12		-13.34		-15.16	-15.27	-15.36	-15.62	-15.77	-16.11	-16.34	-16.42
	δ_{ADJ}	-9.56	-10.93	-11.92	-12.73	-13.28	-13.67	-13.95	-14.18	-14.36											
0.02	MODE		D	D	D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		658.99	1071.35	1534.88	1958.88	2348.70	2708.24	3040.93	3349.68	3637.07	3748.02	4051.46	4052.45	4303.17	4537.98	5345.43	5990.16	7920.17	10121.50	11049.15
	KGU/D		20.73	12.04	8.038	6.135	5.031	4.312	3.807	3.433	3.146			2.907	2.719	2.563	2.140	1.891	1.401	1.081	0.9856
	R_{PROD}		0.538	0.521	0.509	0.500	0.497	0.494	0.491	0.491	0.488			0.493	0.492	0.492	0.490	0.490	0.488	0.484	0.487
	y_{PROD}		0.0931	0.0626	0.0457	0.0367	0.0312	0.0275	0.0247	0.0227	0.0210			0.0198	0.0186	0.0176	0.0148	0.0131	0.0098	0.0076	0.0070
	α OR ϵ		0.7806	0.8477	0.8938	0.9231	0.9436	0.9594	0.9721	0.9823	0.9913			0.0092	0.071	0.121	0.260	0.343	0.508	0.620	0.651
	δ		-7.04	-8.77	-9.86	-10.66	-11.28	-11.79	-12.21	-12.56		-12.76		-13.67	-13.82	-13.96	-14.35	-14.60	-15.15	-15.56	-15.71
	δ_{ADJ}		-9.02	-10.35	-11.03	-11.55	-11.95	-12.29	-12.56	-12.79											
0.04	MODE				D	D	D	D	D	D	D	B	B	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				1635.77	2075.84	2469.63	2829.43	3161.25	3468.92	3755.17	3845.46	4175.42	4174.95	4425.59	4658.43	5459.10	6098.05	8007.35	10179.70	11093.63
	KGU/D				8.924	6.758	5.511	4.699	4.130	3.710	3.388			3.123	2.914	2.741	2.273	2.000	1.469	1.126	1.025
	R_{PROD}				0.535	0.526	0.524	0.518	0.512	0.509	0.506			0.499	0.507	0.506	0.499	0.499	0.492	0.490	0.486
	y_{PROD}				0.0915	0.0742	0.0636	0.0560	0.0504	0.0462	0.0428			0.0399	0.0380	0.0359	0.0301	0.0268	0.0200	0.0155	0.0141
	α OR ϵ				0.8907	0.9199	0.9402	0.9563	0.9693	0.9798	0.9888			0.0018	0.051	0.102	0.248	0.330	0.501	0.612	0.647
	δ				-8.14	-9.14	-9.75	-10.19	-10.54	-10.84		-10.60		-11.84	-12.03	-12.16	-12.60	-12.91	-13.64	-14.24	-14.44
	δ_{ADJ}				-9.14	-9.94	-10.37	-10.66	-10.87	-11.06											

TABLE I.11 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO FABRICATION:

$C_{U_3O_8}$ = \$8/LB, C_N = \$0/G, HIGH COSTS, L_F = 0.002 (R^* = 0.694)

y \ R		0.03	0.06	0.10	0.15	0.20	0.30	0.40	0.50	0.55	0.60	0.65		0.70		0.75		0.8	1.0	2	6	15
0	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	B	BL	BL	BL	BL	BL	BL
	VALUE	229.34	528.51	913.80	1364.30	1780.60	2521.81	3160.35	3715.52	3966.71	4202.43	4424.07	4548.78	4808.36	4808.41	4953.23	5007.09	5194.85	5851.72	7822.58	10074.32	11024.60
	KGU/D	33.68	16.56	10.13	7.003	5.457	3.924	3.163	2.708	2.542	2.405	2.288			2.182		2.095	2.019	1.791	1.339	1.039	0.9493
	R_{PROD}	0.697	0.697	0.697	0.697	0.697	0.697	0.697	0.697	0.697	0.697	0.697			0.698		0.700	0.698	0.697	0.698	0.695	0.701
	y_{PROD}	0	0	0	0	0	0	0	0	0	0	0			0		0	0	0	0	0	0
	ϵ														0.0021		0.040	0.076	0.181	0.388	0.526	0.565
0.01	MODE	D	D	D	D	D	D	D	D	D	D	D	B	B	BL	B	BL	BL	BL	BL	BL	BL
	VALUE	54.78	303.84	662.75	1094.71	1500.85	2232.89	2866.82	3418.53	3668.16	3902.38	4122.59	4200.88	4465.21	4494.15	4639.06	4693.55	4881.12	5536.95	7499.86	9738.96	10682.68
	KGU/D	41.72	19.11	11.25	7.592	5.833	4.130	3.302	2.813	2.637	2.491	2.367			2.255		2.163	2.083	1.843	1.371	1.060	0.9676
	R_{PROD}	0.857	0.762	0.759	0.744	0.729	0.712	0.706	0.703	0.703	0.703	0.700			0.698		0.704	0.702	0.701	0.703	0.702	0.701
	y_{PROD}	0.1025	0.0580	0.0391	0.0285	0.0228	0.0169	0.0139	0.0121	0.0114	0.0109	0.0104			0.0100		0.0096	0.0093	0.0082	0.0062	0.0048	0.0044
	α OR ϵ	0.6532	0.7637	0.8278	0.8724	0.9010	0.9370	0.9594	0.9753	0.9816	0.9872	0.9925			0.0016		0.036	0.073	0.177	0.382	0.521	0.562
	δ	17.23	21.94	24.19	25.59	26.19	26.37	26.19	25.98	25.89	25.80		30.24		26.62		26.35	26.18	25.63	24.45	23.46	23.17
	δ_{ADJ}	26.38	28.73	29.22	29.33	29.07	28.14	27.30	26.64	26.38	26.13											
0.02	MODE		D	D	D	D	D	D	D	D	D	D	B	B	BL	B	BL	BL	BL	BL	BL	BL
	VALUE		143.41	432.44	836.70	1223.82	1924.86	2536.98	3074.00	3318.19	3547.92	3764.34	3835.52	4114.02	4113.26	4307.39	4318.23	4504.55	5157.29	7114.58	9346.18	10285.80
	KGU/D		20.83	12.27	8.138	6.210	4.358	3.464	2.938	2.749	2.592	2.461			2.338		2.244	2.159	1.904	1.407	1.083	0.9878
	R_{PROD}		0.762	0.821	0.759	0.762	0.753	0.744	0.735	0.729	0.726	0.724			0.699		0.723	0.721	0.713	0.709	0.701	0.701
	y_{PROD}		0.1106	0.0788	0.0564	0.0460	0.0345	0.0285	0.0247	0.0233	0.0221	0.0212			0.0200		0.0196	0.0189	0.0167	0.0125	0.0096	0.0088
	α OR ϵ		0.7637	0.8241	0.8714	0.8987	0.9339	0.9564	0.9727	0.9795	0.9853	0.9905			0.0012		0.021	0.057	0.167	0.377	0.518	0.560
	δ		18.73	23.15	25.02	26.06	27.33	28.01	28.36	28.46	28.52		31.11	29.91			29.44	29.32	28.87	27.58	26.33	25.92
	δ_{ADJ}		24.53	28.09	28.71	29.00	29.26	29.29	29.16	29.06	28.95											
0.04	MODE				D	D	D	D	D	D	D	D	B	D	B	B	BL	BL	BL	BL	BL	BL
	VALUE				500.85	739.71	1363.27	1939.64	2447.75	2678.91	2896.43	3101.43	3077.73	3294.94	3379.93	3610.22	3609.41	3790.07	4417.10	6310.05	8492.87	9417.18
	KGU/D				9.060	6.885	4.784	3.757	3.172	2.963	2.790	2.644		2.520			2.404	2.312	2.032	1.487	1.137	1.033
	R_{PROD}				0.875	0.824	0.815	0.759	0.762	0.762	0.762	0.759		0.759			0.747	0.758	0.755	0.737	0.723	0.716
	y_{PROD}				0.1159	0.0928	0.0706	0.0570	0.0501	0.0475	0.0452	0.0433		0.0417			0.0399	0.0388	0.0345	0.0257	0.0198	0.0180
	α OR ϵ				0.8643	0.8946	0.9296	0.9553	0.9706	0.9769	0.9825	0.9877		0.9922			0.0023	0.029	0.137	0.358	0.504	0.549
	δ				20.22	24.24	26.44	27.36	27.98	28.23	28.45	31.63			30.90	29.91		29.92	30.01	29.99	29.46	29.16
	δ_{ADJ}				23.39	27.10	28.44	28.64	28.83	28.90	28.96	32.02										

TABLE I.12

Maximum Uranium Values and Optimum Conditions

Recycle to Fabrication - y = 0.0:

Pre-Enrichment by Gaseous Diffusion

L_F	Unit Costs	$C_{U_3O_8}$ (\$/lb)	C_N (\$/g Np)	R	$V_D(R,0)$ (\$/kgU)	F_D (kgU/day)	R_D
0.01	High	8	0	0.005	3.00	366.7	0.556
				0.01	39.22	121.6	0.556
			60	0.005	3.00	366.6	0.538
				0.01	39.23	121.6	0.538
		6	0	0.005	0.42	414.3	0.571
				0.01	30.99	126.4	0.571
			60	0.005	0.42	413.9	0.550
				0.01	30.99	126.3	0.550
		10	0	0.005	5.71	336.7	0.544
				0.01	47.30	118.2	0.544
			60	0.005	5.71	336.7	0.529
				0.01	47.30	118.2	0.529
		8	100	0.005	3.00	366.6	0.529
				0.01	39.23	121.6	0.529
	Low	8	0	0.005	3.00	367.1	0.497
				0.01	39.24	121.7	0.497
			60	0.005	3.00	367.6	0.479
				0.01	39.25	121.9	0.479
0.002	High	8	0	0.005	2.99	366.4	0.697
				0.01	39.21	121.5	0.697

TABLE I.13 Maximum Uranium Values and Optimum Conditions
Recycle to Fabrication - y=0.15:
Blending with Natural Uranium

L_F	Unit Costs	$C_{U_3O_8}$ ($/lb)	C_N ($/g Np)	R	$V_B(R,0)$ ($/kgU)	$V_B(R,0.15)$ ($/kgU)	F_B (kgU/day)	R_B	y_B	ϵ	$\delta(R,0.15)$ ($/g U-236)
0.01	High	8	0	2	7792.76	3154.32	1.912	0.594	0.0891	0.406	23.13
				6	10036.45	4902.52	1.437	0.588	0.0701	0.532	24.19
				15	10982.76	5656.10	1.299	0.588	0.0644	0.571	24.53
			60	2	7788.29	7755.44	1.916	0.610	0.0905	0.397	-7.57
				6	10030.90	9740.45	1.438	0.595	0.0706	0.529	-8.09
				15	10976.78	10562.93	1.299	0.588	0.0644	0.571	-8.22
		6	0	2	7005.69	2723.42	1.915	0.605	0.0900	0.400	21.54
				6	9023.72	4293.69	1.442	0.614	0.0719	0.520	22.51
				15	9874.59	4973.01	1.304	0.616	0.0662	0.559	22.80
			60	2	7001.32	7349.23	1.923	0.631	0.0923	0.385	-9.32
				6	9017.99	9151.52	1.442	0.614	0.0719	0.520	-9.91
				15	9868.37	9895.62	1.304	0.616	0.0662	0.559	-10.05
		10	0	2	8539.17	3562.80	1.906	0.574	0.0873	0.418	24.64
				6	10996.99	5483.49	1.434	0.576	0.0692	0.538	25.76
				15	12033.52	6311.61	1.297	0.574	0.0635	0.577	26.11
			60	2	8534.80	8142.78	1.913	0.600	0.0896	0.403	-5.92
				6	10991.29	10303.60	1.434	0.576	0.0692	0.538	-6.41
				15	12027.63	11201.55	1.297	0.574	0.0635	0.577	-6.52
		8	100	2	7785.47	10821.10	1.920	0.621	0.0914	0.391	-28.02
				6	10027.09	12953.54	1.438	0.595	0.0706	0.529	-29.54
				15	10972.78	13820.39	1.299	0.588	0.0644	0.571	-29.96
	Low	8	0	2	7777.18	3622.82	1.894	0.517	0.0819	0.454	19.92
				6	10016.53	5396.45	1.426	0.516	0.0647	0.569	20.78
				15	10961.06	6166.25	1.290	0.515	0.0594	0.604	21.00
			60	2	7772.59	8110.44	1.898	0.540	0.0842	0.439	-10.02
				6	10010.44	10129.60	1.428	0.533	0.0660	0.560	-10.80
				15	10954.13	10963.82	1.291	0.527	0.0603	0.598	-11.02
0.002	High	8	0	2	7822.58	2786.34	1.948	0.871	0.1092	0.272	25.75
				6	10074.32	4300.59	1.464	0.821	0.0843	0.438	28.42
				15	11024.60	5047.51	1.323	0.815	0.0773	0.484	28.82

TABLE I.14 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$8/LB, C_N = \$0/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0309)

y \ R		0.005	0.01	0.015	0.02	←0.025→		←0.03→		←0.035→			0.04	0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	B	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	3.14	39.66	84.30	131.98	181.10	181.19	230.95	244.45	276.41	292.13	293.45	340.41	432.99	523.82	700.44	870.63	1636.52	3321.41	5006.37	6690.93	8616.77	9427.84
	KGU/D	323.7	107.4	64.61	46.33	36.20		29.75		25.37		24.89	21.20	16.40	13.43	9.925	7.939	4.166	2.036	1.349	1.010	0.7828	0.7164
	R_{PROD}	0.0309	0.0309	0.0309	0.0309	0.0309		0.0308		0.0352		0.0326	0.0326	0.0325	0.0325	0.0325	0.0327	0.0325	0.0324	0.0326	0.0328	0.0327	0.0330
	y_{PROD}	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0	0
	ϵ											0.086	0.221	0.398	0.508	0.636	0.707	0.847	0.926	0.950	0.963	0.971	0.973
0.005	MODE	D	D	D	D	D	B	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	-12.93	9.56	46.61	89.17	134.51	122.41	181.43	191.67	227.74	241.48	241.72	288.16	379.92	470.09	645.60	814.82	1576.64	3252.98	4929.46	6605.59	8521.78	9328.84
	KGU/D	413.6	126.3	73.26	51.42	39.59		32.20		27.22		26.92	22.67	17.28	14.02	10.26	8.154	4.235	2.058	1.361	1.017	0.7884	0.7214
	R_{PROD}	0.0400	0.0365	0.0350	0.0341	0.0332		0.0329		0.0352		0.0339	0.0335	0.0330	0.0328	0.0327	0.0327	0.0325	0.0324	0.0326	0.0328	0.0327	0.0330
	y_{PROD}	0.0243	0.0137	0.0097	0.0076	0.0063		0.0054		0.0050		0.0048	0.0040	0.0031	0.0025	0.0018	0.0015	0.00077	0.00037	0.00025	0.00019	0.00014	0.00013
	α_{ORE}	0.3356	0.6213	0.7643	0.8561	0.9241		0.9739		0.9957		0.040	0.193	0.385	0.501	0.632	0.706	0.846	0.925	0.950	0.962	0.971	0.973
	δ	3.21	5.98	7.45	8.43	9.16			10.31			10.06	10.11	10.18	10.23	10.27	10.29	10.34	10.36	10.38	10.38	10.38	10.37
	δ_{ADJ}	9.56	9.62	9.75	9.85	9.91																	
0.01	MODE		D	D	D	D	B	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		-18.57	12.46	50.68	92.51	57.29	136.41	137.96	181.60	193.43	193.43	239.17	329.42	418.40	592.15	760.05	1517.28	3184.80	4852.74	6520.39	8426.91	9229.95
	KGU/D		143.0	81.17	56.07	42.72		34.48		28.91		28.81	24.22	18.27	14.69	10.62	8.381	4.310	2.080	1.373	1.025	0.7941	0.7265
	R_{PROD}		0.0421	0.0391	0.0373	0.0365		0.0356		0.0352		0.0350	0.0353	0.0346	0.0341	0.0334	0.0329	0.0327	0.0324	0.0326	0.0328	0.0327	0.0329
	y_{PROD}		0.0304	0.0212	0.0164	0.0135		0.0115		0.0100		0.0100	0.0086	0.0065	0.0052	0.0038	0.0030	0.0016	0.00075	0.00050	0.00038	0.00029	0.00027
	α_{ORE}		0.6018	0.7450	0.8382	0.9034		0.9556		0.9957		0.00017	0.138	0.347	0.475	0.622	0.702	0.845	0.925	0.950	0.962	0.971	0.973
	δ		5.78	7.10	8.00	8.69			10.40		9.71		9.78	9.93	10.02	10.13	10.19	10.28	10.34	10.36	10.36	10.37	10.36
	δ_{ADJ}		9.60	9.53	9.54	9.62																	
0.02	MODE				D	D	B	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				-26.37	9.86	-110.70	49.72	20.41	91.16	94.57	94.46	144.12	233.29	320.41	490.13	654.50	1400.31	3049.23	4699.81	6350.44	8237.48	9032.49
	KGU/D				65.00	48.64		38.84		32.28		32.02	27.17	20.11	15.98	11.40	8.890	4.466	2.129	1.397	1.042	0.8057	0.7368
	R_{PROD}				0.0477	0.0421		0.0403		0.0394		0.0350	0.0380	0.0369	0.0361	0.0353	0.0344	0.0332	0.0327	0.0326	0.0328	0.0327	0.0329
	y_{PROD}				0.0394	0.0301		0.0252		0.0220		0.0200	0.0188	0.0141	0.0113	0.0081	0.0063	0.0032	0.0015	0.0010	0.00076	0.00059	0.00054
	α_{ORE}				0.7950	0.8750		0.9289		0.9702		0.0017	0.059	0.293	0.435	0.593	0.684	0.841	0.923	0.949	0.962	0.971	0.973
	δ				7.79	8.39		9.49			9.65		9.47	9.55	9.65	9.82	9.94	10.17	10.29	10.32	10.33	10.35	10.34
	δ_{ADJ}				9.80	9.59		10.22															

TABLE I.15 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$8/LB, C_N = \$60/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0315)

y \ R		0.005	0.01	0.015	0.02	0.025	←0.03→		←0.035→			←0.04→		0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	Mode	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value	3.14	39.65	84.29	131.97	181.09	230.93	244.07	277.86	293.56	294.14	332.62	341.22	434.04	525.11	702.18	872.81	1640.65	3329.92	5019.07	6708.45	8638.94	9451.80
	KGU/D	323.8	107.4	64.62	46.34	36.20	29.76		25.37		25.02		21.32	16.49	13.50	9.981	7.974	4.186	2.048	1.354	1.013	0.7854	0.7160
	R_{PROD}	0.0315	0.0315	0.0315	0.0315	0.0315	0.0314		0.0352		0.0333		0.0334	0.0333	0.0333	0.0334	0.0334	0.0333	0.0334	0.0332	0.0333	0.0332	0.0329
	y_{PROD}	0	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0
	ϵ										0.059		0.197	0.379	0.493	0.624	0.700	0.843	0.923	0.949	0.962	0.971	0.973
0.005	Mode	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value	6.20	45.78	91.46	139.32	188.32	237.93	248.42	287.31	303.17	303.16	346.38	349.63	441.12	531.17	706.67	876.07	1639.33	3319.71	5000.21	6681.14	8601.91	9410.66
	KGU/D	417.1	126.6	73.35	51.47	39.63	32.23		27.22		27.13		23.00	17.51	14.19	10.35	8.223	4.266	2.071	1.366	1.021	7.912	0.7211
	R_{PROD}	0.0450	0.0379	0.0362	0.0353	0.0344	0.0341		0.0352		0.0350		0.0356	0.0349	0.0345	0.0340	0.0339	0.0336	0.0334	0.0332	0.0333	0.0332	0.0329
	y_{PROD}	0.0266	0.0141	0.0100	0.0078	0.0064	0.0055		0.0050		0.0050		0.0044	0.0033	0.0027	0.0019	0.0015	0.00080	0.00039	0.00026	0.00019	0.00015	0.00013
	α or ϵ	0.3273	0.6159	0.7583	0.8491	0.9162	0.9654		0.9957		0.00090		0.130	0.342	0.468	0.614	0.693	0.840	0.922	0.949	0.962	0.970	0.973
	δ	-0.61	-1.27	-1.52	-1.60	-1.63		-1.11		-2.10			-2.02	-1.85	-1.74	-1.60	-1.52	-1.38	-1.29	-1.25	-1.25	-1.23	-1.22
	δ_{ADJ}	-1.86	-2.06	-2.00	-1.88	-1.78																	
0.01	Mode		D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value		50.03	97.70	147.61	197.96	248.29	249.63	298.49	314.20	314.19	362.67	363.22	453.36	541.94	714.94	882.41	1639.67	3310.27	4981.92	6654.23	8565.19	9369.78
	KGU/D		144.8	81.61	56.24	42.81	34.52		28.94		28.81		24.71	18.58	14.93	10.78	8.500	4.348	2.094	1.383	1.029	7.971	0.7263
	R_{PROD}		0.0485	0.0421	0.0391	0.0379	0.0368		0.0364		0.0350		0.0383	0.0372	0.0364	0.0355	0.0349	0.0340	0.0334	0.0337	0.0334	0.0332	0.0329
	y_{PROD}		0.0339	0.0224	0.0170	0.0139	0.0118		0.0103		0.0100		0.0095	0.0071	0.0057	0.0041	0.0032	0.0016	0.00078	0.00052	0.00038	0.00030	0.00027
	α or ϵ		0.5844	0.7330	0.8293	0.8956	0.9482		0.9878		0.00017		0.051	0.289	0.431	0.592	0.680	0.837	0.922	0.948	0.961	0.970	0.973
	δ		-1.08	-1.42	-1.70	-1.87		-0.80		-2.30			-2.54	-2.36	-2.21	-1.98	-1.83	-1.54	-1.36	-1.30	-1.29	-1.26	-1.25
	δ_{ADJ}		-1.85	-1.94	-2.05	-2.09																	
0.02	Mode				D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value				154.32	209.50	261.47	223.90	312.95	318.41	318.19	383.22	383.15	478.08	567.30	738.28	902.32	1645.22	3294.00	4947.33	6601.58	8492.66	9289.51
	KGU/D				65.24	49.22	39.19		32.48		32.02		27.56	20.71	16.37	11.61	9.053	4.521	2.150	1.408	1.046	0.8090	0.7417
	R_{PROD}				0.0494	0.0485	0.0456		0.0429		0.0350		0.0399	0.0410	0.0396	0.0381	0.0371	0.0350	0.0341	0.0337	0.0334	0.0333	0.0339
	y_{PROD}				0.0404	0.0336	0.0278		0.0235		0.0200		0.0200	0.0160	0.0126	0.0089	0.0069	0.0034	0.0016	0.0011	0.00078	0.00060	0.00056
	α or ϵ				0.7895	0.8498	0.9048		0.9523		0.0017		0.0016	0.199	0.370	0.554	0.654	0.830	0.919	0.947	0.961	0.970	0.972
	δ				-1.25	-1.60	-1.11			-1.51		-2.44		-2.63	-2.63	-2.51	-2.35	-1.87	-1.53	-1.43	-1.36	-1.33	-1.34
	δ_{ADJ}				-1.58	-1.88	-1.23																

TABLE I.16 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$8/LB, C_N = \$100/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0319)

y \ R		0.005	0.01	0.015	0.02	0.025	←0.03→		←0.035→			←0.04→		0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	3.14	39.65	84.28	131.96	181.07	230.91	243.69	278.67	294.36	294.61	334.69	341.78	434.75	525.98	703.36	874.29	1643.46	3335.59	5027.71	6719.94	8653.60	9469.88
	KGU/D	323.8	107.4	64.62	46.35	36.21	29.76		25.37		25.10		21.38	16.55	13.55	10.01	8.002	4.204	2.053	1.359	1.018	0.7900	0.7206
	R_{PROD}	0.0318	0.0318	0.0318	0.0318	0.0318	0.0320		0.0352		0.0338		0.0339	0.0339	0.0339	0.0338	0.0339	0.0339	0.0337	0.0337	0.0340	0.0341	0.0339
	y_{PROD}	0	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0
	ϵ										0.041		0.182	0.367	0.481	0.618	0.694	0.839	0.922	0.948	0.961	0.970	0.972
0.005	MODE	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	19.24	70.01	121.43	172.85	224.30	275.74	286.14	326.90	344.16	344.14	389.81	391.39	482.67	572.60	748.07	917.54	1681.72	3364.79	5048.08	6731.89	8655.87	9467.89
	KGU/D	420.5	126.7	73.42	51.51	39.66	32.25		27.22		27.13		23.20	17.65	14.29	10.43	8.267	4.286	2.080	1.376	1.026	0.7959	0.7258
	R_{PROD}	0.0494	0.0388	0.0371	0.0359	0.0353	0.0347		0.0352		0.0350		0.0369	0.0361	0.0356	0.0351	0.0347	0.0343	0.0341	0.0342	0.0340	0.0341	0.0339
	y_{PROD}	0.0287	0.0144	0.0102	0.0080	0.0066	0.0056		0.0050		0.0050		0.0045	0.0034	0.0028	0.0020	0.0016	0.00082	0.00040	0.00026	0.00020	0.00015	0.00014
	α_{ORE}	0.3212	0.6127	0.7539	0.8457	0.9105	0.9614		0.9957		0.00090		0.091	0.314	0.447	0.599	0.684	0.836	0.920	0.947	0.961	0.969	0.972
	δ	-3.22	-6.11	-7.51	-8.31	-8.83		-8.73		-10.20			-10.26	-10.02	-9.85	-9.64	-9.52	-9.30	-9.18	-9.10	-9.11	-9.11	-9.07
	δ_{ADJ}	-10.02	-9.97	-9.96	-9.83	-9.70																	
0.01	MODE		D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		96.62	155.33	212.52	268.49	323.08	323.96	376.63	394.59	394.58	447.69	447.68	537.67	625.92	798.36	965.47	1722.56	3395.13	5069.55	6744.45	8658.63	9466.33
	KGU/D		145.7	82.07	56.36	42.87	34.56		28.96		28.81		24.98	18.79	15.08	10.87	8.560	4.372	2.103	1.388	1.034	0.8018	0.7310
	R_{PROD}		0.0515	0.0453	0.0403	0.0388	0.0376		0.0370		0.0350		0.0399	0.0389	0.0380	0.0368	0.0360	0.0348	0.0341	0.0342	0.0341	0.0341	0.0339
	y_{PROD}		0.0356	0.0238	0.0174	0.0142	0.0120		0.0105		0.0100		0.0100	0.0075	0.0060	0.0043	0.0033	0.0017	0.00080	0.00053	0.00040	0.00031	0.00028
	α_{ORE}		0.5776	0.7218	0.8237	0.8909	0.9435		0.9841		0.00017		0.0029	0.249	0.402	0.574	0.668	0.832	0.920	0.947	0.960	0.969	0.972
	δ		-5.74	-7.19	-8.19	-8.92		-8.27		-10.29		-10.93		-10.73	-10.52	-10.20	-9.99	-9.55	-9.29	-9.21	-9.17	-9.16	-9.12
	δ_{ADJ}		-9.94	-9.96	-9.94	-10.01																	
0.02	MODE				D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				274.83	345.21	405.93	359.46	463.25	467.52	467.22	543.07	542.93	647.17	736.07	907.24	1070.85	1811.51	3459.88	5114.73	6771.30	8665.56	9464.48
	KGU/D				65.28	49.52	39.53		32.69		32.02		27.56	21.42	16.68	11.76	9.148	4.557	2.159	1.413	1.051	0.8138	0.7417
	R_{PROD}				0.0497	0.0515	0.0503		0.0465		0.0350		0.0399	0.0465	0.0424	0.0399	0.0387	0.0361	0.0348	0.0343	0.0341	0.0342	0.0339
	y_{PROD}				0.0406	0.0352	0.0300		0.0250		0.0200		0.0200	0.0184	0.0137	0.0094	0.0073	0.0035	0.0017	0.0011	0.00080	0.00062	0.00056
	α_{ORE}				0.7886	0.8398	0.8872		0.9365		0.0017		0.0016	0.077	0.317	0.528	0.636	0.823	0.917	0.946	0.960	0.969	0.972
	δ				-7.28	-8.39	-8.36			-8.94		-10.41		-11.06	-11.03	-10.90	-10.70	-10.05	-9.55	-9.38	-9.29	-9.25	-9.20
	δ_{ADJ}				-9.23	-9.99	-9.42																

TABLE I.17 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$6/LB, C_N = \$0/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0318)

y \ R		0.005	0.01	0.015	0.02	0.025	← 0.03 →		← 0.035 →			0.04	0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	Mode	D	D	D	D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value	0.54	31.39	70.42	112.54	156.15	200.55	212.39	242.68	257.05	257.37	298.97	380.99	461.46	617.94	768.72	1447.25	2940.02	4432.78	5925.06	7630.51	8351.14
	KGU/D	364.4	111.2	65.88	46.93	36.53	29.96		25.49		25.22	21.47	16.62	13.61	10.06	8.032	4.222	2.064	1.366	1.023	0.7942	0.7245
	R_{PROD}	0.0318	0.0318	0.0318	0.0318	0.0318	0.0317		0.0352		0.0338	0.0337	0.0337	0.0338	0.0338	0.0336	0.0338	0.0337	0.0337	0.0340	0.0341	0.0339
	y_{PROD}	0	0	0	0	0	0		0		0	0	0	0	0	0	0	0	0	0	0	0
	ϵ										0.044	0.188	0.370	0.484	0.618	0.697	0.840	0.922	0.948	0.961	0.970	0.972
0.005	Mode	D	D	D	D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value	-12.20	5.35	37.22	74.52	114.57	156.18	164.36	198.20	210.76	210.76	251.88	333.13	412.99	568.43	718.32	1393.21	2878.37	4363.62	5848.43	7545.32	8262.34
	KGU/D	462.8	130.4	74.55	52.01	39.91	32.39		27.32		27.23	22.98	17.53	14.22	10.40	8.261	4.292	2.086	1.378	1.031	0.8000	0.7296
	R_{PROD}	0.0406	0.0374	0.0359	0.0350	0.0344	0.0338		0.0352		0.0350	0.0349	0.0345	0.0342	0.0340	0.0339	0.0338	0.0337	0.0337	0.0340	0.0341	0.0339
	y_{PROD}	0.0242	0.0138	0.0099	0.0078	0.0064	0.0055		0.0050		0.0050	0.0042	0.0032	0.0026	0.0019	0.0015	0.00080	0.00039	0.00026	0.00020	0.00015	0.00014
	α or ϵ	0.2943	0.5943	0.7449	0.8416	0.9111	0.9656		0.9956		0.00090	0.151	0.351	0.474	0.614	0.693	0.839	0.921	0.948	0.961	0.969	0.972
	δ	2.55	5.18	6.57	7.49	8.16		9.39		9.06		9.12	9.19	9.23	9.28	9.31	9.36	9.39	9.40	9.40	9.41	9.41
	δ_{ADJ}	8.66	8.72	8.82	8.90	8.96																
0.01	Mode		D	D	D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value		-19.09	7.15	40.36	77.10	115.91	115.32	156.01	166.67	166.67	207.76	287.72	366.53	520.38	669.06	1339.73	2816.98	4294.64	5771.94	7460.26	8173.63
	KGU/D		147.6	82.40	56.63	43.00	34.65		29.02		28.90	24.49	18.48	14.87	10.76	8.504	4.368	2.109	1.390	1.039	0.8059	0.7348
	R_{PROD}		0.0429	0.0397	0.0382	0.0371	0.0365		0.0361		0.0350	0.0365	0.0358	0.0353	0.0346	0.0344	0.0340	0.0337	0.0337	0.0341	0.0341	0.0339
	y_{PROD}		0.0306	0.0213	0.0166	0.0136	0.0117		0.0102		0.0100	0.0090	0.0068	0.0055	0.0040	0.0031	0.0016	0.00079	0.00052	0.00040	0.00031	0.00028
	α or ϵ		0.5755	0.7269	0.8236	0.8940	0.9470		0.9893		0.00017	0.102	0.319	0.452	0.604	0.686	0.837	0.921	0.948	0.960	0.969	0.972
	δ		5.02	6.26	7.11	7.75	9.44			8.81		8.82	8.95	9.03	9.14	9.20	9.30	9.36	9.38	9.39	9.39	9.40
	δ_{ADJ}		8.72	8.61	8.63	8.67	9.97															
0.02	Mode				D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	Value				-28.14	2.95	38.10	8.57	74.84	76.73	76.61	122.07	201.05	278.20	428.58	574.22	1234.65	2695.05	4157.20	5619.42	7290.49	7996.54
	KGU/D				65.54	48.95	38.97		32.34		32.02	27.34	20.27	16.13	11.51	9.003	4.524	2.159	1.415	1.056	0.8178	0.7455
	R_{PROD}				0.0479	0.0429	0.0409		0.0400		0.0350	0.0388	0.0378	0.0372	0.0363	0.0357	0.0345	0.0341	0.0337	0.0341	0.0342	0.0339
	y_{PROD}				0.0393	0.0305	0.0255		0.0222		0.0200	0.0193	0.0146	0.0117	0.0084	0.0066	0.0033	0.0016	0.0011	0.00080	0.00062	0.00056
	α or ϵ				0.7825	0.8640	0.9216		0.9651		0.0017	0.035	0.272	0.415	0.578	0.669	0.833	0.919	0.947	0.960	0.969	0.972
	δ				6.92	7.50	8.50			8.77		8.55	8.62	8.70	8.85	8.96	9.18	9.31	9.35	9.36	9.37	9.38
	δ_{ADJ}				8.84	8.68	9.22															

TABLE I.18 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = $6/LB, C_N = $60/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0325)

y \ R		0.005	0.01	0.015	0.02	0.025	← 0.03 →		← 0.035 →		← 0.04 →			0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	0.54	31.38	70.41	112.52	156.13	200.52	211.67	243.81	258.14	258.16	295.09	299.90	382.19	462.93	619.93	771.21	1451.99	2949.68	4447.39	5945.10	7656.01	8378.66
	KGU/D	364.5	111.2	65.90	46.95	36.55	29.97		25.49		25.37		21.61	16.72	13.69	10.11	8.084	4.244	2.077	1.375	1.027	0.7986	0.7288
	R_{PROD}	0.0326	0.0326	0.0326	0.0326	0.0326	0.0326		0.0352		0.0347		0.0347	0.0346	0.0347	0.0347	0.0347	0.0346	0.0348	0.0347	0.0348	0.0350	0.0349
	y_{PROD}	0	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0
	ϵ										0.011		0.157	0.349	0.466	0.606	0.685	0.835	0.919	0.946	0.960	0.969	0.971
0.005	MODE	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	4.18	39.05	79.60	122.28	166.08	210.49	218.42	255.16	269.74	269.72	310.59	311.82	392.91	472.73	628.30	778.45	1455.12	2944.93	4435.02	5925.17	7627.64	8346.57
	KGU/D	467.3	130.7	74.66	52.07	39.96	32.43		27.32		27.23		23.31	17.76	14.39	10.50	8.346	4.325	2.100	1.387	1.036	0.8044	0.7340
	R_{PROD}	0.0456	0.0388	0.0371	0.0362	0.0356	0.0350		0.0352		0.0350		0.0371	0.0365	0.0361	0.0355	0.0355	0.0350	0.0348	0.0347	0.0347	0.0350	0.0349
	y_{PROD}	0.0265	0.0143	0.0102	0.0080	0.0066	0.0057		0.0050		0.0050		0.0046	0.0035	0.0028	0.0020	0.0016	0.00084	0.00041	0.00027	0.00020	0.00016	0.00014
	α OR ϵ	0.2867	0.5891	0.7389	0.8345	0.9032	0.9570		0.9956		0.00090		0.085	0.305	0.438	0.593	0.675	0.832	0.918	0.946	0.960	0.968	0.971
	δ	-0.73	-1.57	-1.91	-2.06	-2.15		-1.56		-2.57			-2.68	-2.53	-2.42	-2.29	-2.22	-2.08	-2.00	-1.97	-1.96	-1.98	-1.96
	δ_{ADJ}	-2.55	-2.67	-2.58	-2.47	-2.38																	
0.01	MODE		D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		45.12	88.26	133.13	178.34	223.54	222.19	268.65	282.53	282.52	328.40	328.40	408.28	486.80	640.16	788.59	1459.84	2940.92	4423.13	5905.62	7599.58	8314.76
	KGU/D		149.6	82.99	56.82	43.12	34.72		29.06		28.90		25.01	18.81	15.12	10.93	8.606	4.410	2.127	1.399	1.044	0.8103	0.7393
	R_{PROD}		0.0497	0.0432	0.0400	0.0388	0.0379		0.0373		0.0350		0.0398	0.0386	0.0380	0.0370	0.0363	0.0355	0.0351	0.0348	0.0348	0.0350	0.0349
	y_{PROD}		0.0343	0.0228	0.0172	0.0141	0.0120		0.0105		0.0100		0.0099	0.0074	0.0060	0.0043	0.0034	0.0017	0.00083	0.00054	0.00040	0.00032	0.00029
	α OR ϵ		0.5574	0.7129	0.8146	0.8843	0.9384		0.9813		0.00017		0.0059	0.255	0.402	0.571	0.665	0.828	0.917	0.946	0.959	0.968	0.971
	δ		-1.41	-1.86	-2.17	-2.38	-1.40			-2.70		-3.15		-2.99	-2.85	-2.64	-2.51	-2.24	-2.07	-2.02	-2.00	-2.01	-1.99
	δ_{ADJ}		-2.53	-2.61	-2.66	-2.69	-1.49																
0.02	MODE				D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				145.45	195.81	243.15	205.24	290.01	293.14	292.91	353.94	353.85	439.98	518.63	669.91	815.27	1473.82	2935.38	4400.93	5867.55	7544.32	8251.92
	KGU/D				65.78	49.61	39.42		32.60		32.02		27.56	21.00	16.56	11.75	9.173	4.583	2.178	1.429	1.061	0.8224	0.7500
	R_{PROD}				0.0494	0.0497	0.0468		0.0441		0.0350		0.0399	0.0431	0.0411	0.0395	0.0387	0.0365	0.0355	0.0353	0.0348	0.0351	0.0349
	y_{PROD}				0.0402	0.0341	0.0283		0.0240		0.0200		0.0200	0.0169	0.0132	0.0093	0.0073	0.0036	0.0017	0.0011	0.00082	0.00064	0.00058
	α OR ϵ				0.7774	0.8369	0.8943		0.9438		0.0017		0.0016	0.153	0.341	0.534	0.636	0.821	0.915	0.944	0.959	0.968	0.971
	δ				-1.76	-2.14	-1.79			-2.01		-3.00		-3.27	-3.25	-3.12	-2.97	-2.54	-2.23	-2.12	-2.07	-2.07	-2.04
	δ_{ADJ}				-2.26	-2.56	-2.00																

TABLE I.19 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$10/LB, C_N = \$0/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0300)

y \ R		0.005	0.01	0.015	0.02	0.025	← 0.03 →		← 0.035 →			0.04	0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	5.88	47.78	97.75	150.71	205.05	260.06	274.80	308.26	325.26	328.08	380.14	482.78	583.48	779.29	967.98	1817.07	3685.05	5553.12	7420.81	9555.68	10455.34
	KGU/D	298.1	104.6	63.68	45.90	35.96	29.61		25.27		24.62	20.98	16.23	13.28	9.827	7.847	4.124	2.018	1.334	0.9955	0.7747	0.7086
	R_{PROD}	0.0300	0.0300	0.0300	0.0300	0.0300	0.0302		0.0352		0.0316	0.0316	0.0316	0.0315	0.0317	0.0316	0.0317	0.0317	0.0316	0.0314	0.0318	0.0320
	y_{PROD}	0	0	0	0	0	0		0		0	0	0	0	0	0	0	0	0	0	0	0
	ϵ										0.119	0.249	0.419	0.526	0.647	0.719	0.852	0.928	0.952	0.965	0.972	0.974
0.005	MODE	D	D	D	D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	-13.39	13.78	55.78	103.33	153.71	205.66	217.56	255.66	270.52	271.50	323.03	424.85	524.88	719.53	907.18	1751.86	3610.32	5469.06	7327.47	9451.51	10346.63
	KGU/D	382.8	123.4	72.35	51.01	39.38	32.07		27.15		26.62	22.41	17.09	13.85	10.13	8.060	4.188	2.034	1.346	1.003	0.7803	0.7136
	R_{PROD}	0.0397	0.0359	0.0344	0.0332	0.0326	0.0320		0.0352		0.0327	0.0323	0.0320	0.0317	0.0315	0.0316	0.0315	0.0314	0.0316	0.0314	0.0318	0.0320
	y_{PROD}	0.0244	0.0136	0.0097	0.0075	0.0062	0.0053		0.0050		0.0046	0.0039	0.0030	0.0024	0.0018	0.0014	0.00074	0.00036	0.00024	0.00018	0.00014	0.00013
	α OR ϵ	0.3683	0.6423	0.7790	0.8686	0.9318	0.9815		0.9957		0.079	0.227	0.409	0.522	0.649	0.718	0.852	0.928	0.952	0.964	0.972	0.974
	δ	3.85	6.75	8.30	9.33	10.06		11.17			10.99	11.04	11.10	11.14	11.17	11.19	11.22	11.26	11.26	11.25	11.28	11.29
	δ_{ADJ}	10.45	10.51	10.65	10.74	10.80																
0.01	MODE		D	D	D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		-17.82	17.69	60.66	107.34	156.10	159.49	205.98	218.78	218.78	269.33	369.40	468.10	660.90	847.21	1687.05	3535.90	5385.16	7234.23	9347.44	10238.03
	KGU/D		139.8	80.30	55.71	42.53	34.37		28.85		28.76	24.03	18.09	14.53	10.49	8.286	4.257	2.056	1.357	1.011	0.7859	0.7186
	R_{PROD}		0.0415	0.0385	0.0368	0.0359	0.0350		0.0352		0.0350	0.0345	0.0336	0.0330	0.0321	0.0319	0.0315	0.0314	0.0316	0.0314	0.0318	0.0320
	y_{PROD}		0.0303	0.0210	0.0162	0.0133	0.0113		0.0100		0.0100	0.0084	0.0063	0.0050	0.0036	0.0029	0.0015	0.00072	0.00048	0.00036	0.00028	0.00026
	α OR ϵ		0.6226	0.7598	0.8485	0.9114	0.9613		0.9957		0.00017	0.162	0.371	0.496	0.639	0.714	0.852	0.928	0.952	0.964	0.972	0.974
	δ		6.51	7.91	8.85	9.57		11.26		10.60		10.70	10.86	10.95	11.06	11.11	11.18	11.23	11.24	11.24	11.27	11.28
	δ_{ADJ}		10.46	10.41	10.43	10.50																
0.02	MODE				D	D	D	B	D	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				-24.60	16.68	60.89	31.71	106.75	111.44	111.34	165.16	264.12	360.79	548.98	731.26	1558.78	3387.57	5217.77	7048.02	9139.63	10021.16
	KGU/D				64.80	48.43	38.78		32.26		32.04	27.06	19.98	15.86	11.28	8.817	4.412	2.106	1.382	1.027	0.7974	0.7289
	R_{PROD}				0.0488	0.0415	0.0400		0.0388		0.0350	0.0374	0.0361	0.0353	0.0342	0.0336	0.0320	0.0317	0.0315	0.0314	0.0318	0.0319
	y_{PROD}				0.0402	0.0298	0.0251		0.0217		0.0200	0.0185	0.0138	0.0110	0.0078	0.0061	0.0030	0.0015	0.00097	0.00072	0.00057	0.00052
	α OR ϵ				0.8010	0.8835	0.9337		0.9746		0.0017	0.077	0.311	0.450	0.608	0.693	0.848	0.926	0.951	0.964	0.972	0.974
	δ				8.61	9.21	10.42			10.50		10.37	10.45	10.55	10.74	10.87	11.10	11.19	11.21	11.22	11.25	11.25
	δ_{ADJ}				10.75	10.42	11.16															

TABLE I.20 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$10/LB, C_N = \$60/G, HIGH COSTS, L_F = 0.01 (R^* = 0.0307)

y \ R		0.005	0.01	0.015	0.02	0.025	←0.03→		←	0.035	→	←0.04→		0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	5.88	47.77	97.73	150.67	205.01	260.02	274.65	309.92	326.91	328.65	367.90	380.81	483.65	584.54	780.72	969.76	1820.48	3691.99	5563.49	7435.03	9572.57	10475.70
	KGU/D	298.1	104.6	63.68	45.90	35.96	29.61		25.27		24.74		21.07	16.31	13.35	9.871	7.891	4.139	2.027	1.339	1.001	0.7796	0.7086
	R_{PROD}	0.0306	0.0306	0.0306	0.0306	0.0306	0.0305		0.0352		0.0323		0.0322	0.0322	0.0323	0.0324	0.0324	0.0322	0.0324	0.0321	0.0321	0.0327	0.0320
	y_{PROD}	0	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0
	ϵ										0.095		0.231	0.404	0.511	0.638	0.710	0.849	0.926	0.951	0.964	0.971	0.974
0.005	MODE	D	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	8.04	52.12	102.70	155.49	209.42	263.98	276.57	317.43	334.48	334.48	379.85	385.73	487.14	586.95	781.48	969.20	1814.94	3676.72	5538.59	7400.71	9527.80	10426.06
	KGU/D	385.8	123.6	72.41	51.04	39.40	32.10		27.15		27.04		22.75	17.32	14.02	10.24	8.125	4.214	2.049	1.351	1.008	0.7852	0.7136
	R_{PROD}	0.0450	0.0371	0.0356	0.0344	0.0338	0.0332		0.0352		0.0349		0.0344	0.0337	0.0333	0.0329	0.0327	0.0324	0.0324	0.0321	0.0321	0.0327	0.0320
	y_{PROD}	0.0269	0.0140	0.0099	0.0077	0.0064	0.0054		0.0050		0.0050		0.0042	0.0032	0.0025	0.0019	0.0015	0.00076	0.00037	0.00024	0.00018	0.00014	0.00013
	α OR ϵ	0.3590	0.6376	0.7730	0.8615	0.9240	0.9730		0.9957		0.0039		0.166	0.369	0.492	0.629	0.706	0.847	0.925	0.951	0.963	0.971	0.974
	δ	−0.44	−0.92	−1.09	−1.11	−1.09		−0.66		−1.49			−1.36	−1.18	−1.07	−0.93	−0.86	−0.71	−0.64	−0.58	−0.57	−0.62	−0.55
	δ_{ADJ}	−1.23	−1.44	−1.41	−1.29	−1.18																	
0.01	MODE		D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		54.39	106.37	161.06	216.33	271.55	275.20	326.59	343.68	343.67	394.53	396.30	496.20	594.34	786.09	971.72	1811.01	3662.23	5514.27	7366.76	9483.37	10376.68
	KGU/D		141.3	80.65	55.82	42.59	34.40		28.86		28.76		24.47	18.40	14.77	10.66	8.397	4.295	2.072	1.368	1.016	0.7909	0.7186
	R_{PROD}		0.0476	0.0412	0.0382	0.0371	0.0362		0.0355		0.0350		0.0370	0.0360	0.0351	0.0342	0.0336	0.0327	0.0324	0.0326	0.0321	0.0327	0.0320
	y_{PROD}		0.0337	0.0222	0.0167	0.0137	0.0116		0.0101		0.0100		0.0091	0.0068	0.0054	0.0039	0.0031	0.0016	0.00075	0.00050	0.00037	0.00029	0.00026
	α OR ϵ		0.6058	0.7490	0.8417	0.9048	0.9541		0.9938		0.00017		0.087	0.316	0.455	0.610	0.695	0.845	0.925	0.950	0.963	0.971	0.974
	δ		−0.71	−0.96	−1.19	−1.34		−0.33		−1.83			−1.93	−1.74	−1.56	−1.32	−1.17	−0.87	−0.72	−0.64	−0.61	−0.65	−0.57
	δ_{ADJ}		−1.17	−1.28	−1.41	−1.48																	
0.02	MODE				D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				161.98	221.88	278.22	240.77	334.06	341.42	341.21	409.99	409.94	514.09	613.31	802.98	984.75	1808.11	3635.61	5467.58	7300.00	9395.47	10278.66
	KGU/D				64.89	48.95	39.06		32.41		32.04		27.58	20.49	16.21	11.49	8.969	4.472	2.122	1.392	1.038	0.8025	0.7289
	R_{PROD}				0.0497	0.0476	0.0450		0.0418		0.0350		0.0399	0.0396	0.0383	0.0368	0.0360	0.0338	0.0327	0.0326	0.0328	0.0327	0.0319
	y_{PROD}				0.0408	0.0332	0.0276		0.0230		0.0200		0.0200	0.0153	0.0121	0.0086	0.0067	0.0033	0.0015	0.0010	0.00076	0.00059	0.00052
	α OR ϵ				0.7983	0.8597	0.9115		0.9595		0.0017		0.0016	0.233	0.394	0.572	0.666	0.837	0.923	0.949	0.962	0.971	0.974
	δ				−0.72	−1.05	−0.45			−0.97		−1.84		−2.01	−2.02	−1.89	−1.72	−1.20	−0.87	−0.77	−0.68	−0.72	−0.62
	δ_{ADJ}				−0.90	−1.22	−0.49																

TABLE I.21 MAXIMUM URANIUM VALUES AND OPTIMUM CONDITIONS.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$8/LB, C_N = \$0/G, LOW COSTS, L_F = 0.01 (R* = 0.0270)

y \ R		0.005	0.01	0.015	0.02	← 0.025 →		← 0.03 →			← 0.035 →		0.04	0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	3.20	39.83	84.59	132.38	181.61	191.51	228.03	241.94	242.73	278.93	289.43	335.69	426.89	516.37	690.35	858.00	1612.47	3272.31	4931.91	6590.97	8488.90	9288.64
	KGU/D	323.7	107.4	64.61	46.34	36.20		29.75		29.25		24.11	20.54	15.89	13.01	9.622	7.678	4.038	1.975	1.309	0.9736	0.7573	0.6909
	R_{PROD}	0.0267	0.0267	0.0267	0.0267	0.0267		0.0302		0.0283		0.0282	0.0282	0.0282	0.0283	0.0283	0.0281	0.0283	0.0283	0.0284	0.0279	0.0282	0.0280
	y_{PROD}	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0	0
	ε									0.075		0.239	0.352	0.499	0.588	0.695	0.758	0.872	0.938	0.958	0.970	0.976	0.978
0.005	MODE	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	-10.84	13.23	51.37	95.15	141.79	145.66	187.73	200.04	200.69	238.43	247.54	293.90	385.11	474.44	647.90	814.91	1565.92	3217.56	4868.94	6520.27	8408.21	9204.27
	KGU/D	411.5	126.1	73.15	51.29	39.43		32.15		31.42		25.48	21.50	16.45	13.39	9.834	7.819	4.086	1.988	1.314	0.9808	0.7626	0.6956
	R_{PROD}	0.0356	0.0318	0.0297	0.0285	0.0273		0.0302		0.0280		0.0276	0.0275	0.0274	0.0275	0.0277	0.0276	0.0280	0.0279	0.0279	0.0279	0.0282	0.0280
	y_{PROD}	0.0221	0.0123	0.0085	0.0066	0.0054		0.0050		0.0046		0.0037	0.0031	0.0024	0.0020	0.0015	0.0012	0.00063	0.00031	0.00020	0.00015	0.00012	0.00010
	α OR ε	0.3447	0.6424	0.7964	0.8962	0.9724		0.9953		0.084		0.259	0.372	0.515	0.602	0.703	0.763	0.873	0.938	0.959	0.969	0.976	0.978
	δ	2.80	5.28	6.56	7.31		8.98			8.17		8.09	8.02	7.93	7.87	7.80	7.76	7.70	7.68	7.66	7.55	7.65	7.59
	δ_{ADJ}	8.12	8.22	8.24	8.16																		
0.01	MODE		D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		-10.70	21.57	60.66	103.20	96.06	147.85	158.27	158.28	200.66	204.37	249.96	340.67	429.98	603.46	770.24	1518.66	3162.62	4806.04	6449.23	8327.30	9119.68
	KGU/D		142.2	80.78	55.91	42.64		34.43		34.33		27.83	23.13	17.32	13.91	10.09	7.978	4.133	2.008	1.324	0.9881	0.7679	0.7003
	R_{PROD}		0.0373	0.0344	0.0329	0.0318		0.0308		0.0300		0.0305	0.0295	0.0283	0.0278	0.0275	0.0274	0.0277	0.0279	0.0279	0.0279	0.0282	0.0280
	y_{PROD}		0.0276	0.0191	0.0148	0.0121		0.0102		0.0100		0.0084	0.0069	0.0051	0.0041	0.0030	0.0023	0.0013	0.00062	0.00041	0.00031	0.00024	0.00020
	α OR ε		0.6182	0.7675	0.8637	0.9341		0.9902		0.00004		0.156	0.311	0.493	0.595	0.705	0.765	0.875	0.938	0.959	0.969	0.976	0.978
	δ		5.01	6.22	7.04	8.64				8.20		8.22	8.24	8.20	8.12	8.00	7.92	7.77	7.70	7.66	7.58	7.67	7.61
	δ_{ADJ}		8.10	8.10	8.15	9.25																	
0.02	MODE				D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				-5.22	32.68	-28.56	72.97	68.86	68.87	124.35	124.40	168.90	256.16	342.21	511.84	677.10	1421.44	3051.51	4679.02	6306.21	8164.81	8949.80
	KGU/D				64.10	48.33		38.64		38.69		31.91	26.29	19.41	15.37	10.85	8.430	4.249	2.041	1.347	1.003	0.7787	0.7100
	R_{PROD}				0.0391	0.0374		0.0359		0.0300		0.0345	0.0336	0.0321	0.0309	0.0292	0.0282	0.0275	0.0276	0.0280	0.0279	0.0282	0.0281
	y_{PROD}				0.0337	0.0274		0.0230		0.0200		0.0197	0.0162	0.0119	0.0094	0.0064	0.0049	0.0025	0.0012	0.00083	0.00062	0.00049	0.00044
	α OR ε				0.8293	0.8983		0.9537		0.00004		0.017	0.188	0.403	0.532	0.679	0.754	0.875	0.938	0.958	0.969	0.976	0.978
	δ				6.75	7.75		8.25				7.96	8.00	8.11	8.19	8.24	8.19	7.94	7.77	7.71	7.65	7.72	7.65
	δ_{ADJ}				8.14	8.63		8.65															

TABLE I.22 MAXIMUM URANIUM VALUES AND OPTIMUM ~~CONDITIONS~~.

RECYCLE TO DIFFUSION PLANT:

$C_{U_3O_8}$ = \$8/LB, C_N = \$60/G, LOW COSTS, L_F = 0.01 (R^* = 0.0275)

y \ R		0.005	0.01	0.015	0.02	← 0.025 →		← 0.03 →			← 0.035 →		0.04	0.05	0.06	0.08	0.1	0.2	0.5	1.0	2	6	15
0	MODE	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	3.19	39.80	84.54	132.32	181.53	190.90	228.96	242.84	243.16	281.86	289.95	336.30	427.68	517.33	691.65	859.64	1615.59	3278.62	4941.68	6604.37	8504.89	9307.04
	KGU/D	323.7	107.4	64.61	46.34	36.20		29.75		29.40		24.23	20.64	15.98	13.08	9.672	7.729	4.055	1.986	1.314	0.9793	0.7629	0.6966
	R_{PROD}	0.0270	0.0270	0.0270	0.0270	0.0270		0.0302		0.0289		0.0288	0.0288	0.0288	0.0289	0.0289	0.0289	0.0288	0.0290	0.0290	0.0286	0.0291	0.0290
	y_{PROD}	0	0	0	0	0		0		0		0	0	0	0	0	0	0	0	0	0	0	0
	ϵ									0.048		0.218	0.334	0.484	0.576	0.686	0.749	0.869	0.936	0.957	0.969	0.975	0.977
0.005	MODE	D	D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE	7.86	48.98	95.39	143.99	193.77	198.23	243.74	257.98	257.99	301.52	304.59	350.52	441.31	530.49	703.96	871.14	1623.38	3278.10	4932.85	6587.37	8478.20	9276.36
	KGU/D	412.5	126.1	73.16	51.33	39.50		32.15		32.05		26.26	22.07	16.79	13.62	9.955	7.917	4.117	2.006	1.325	0.9867	0.7682	0.7013
	R_{PROD}	0.0382	0.0335	0.0315	0.0303	0.0294		0.0302		0.0300		0.0307	0.0301	0.0295	0.0292	0.0289	0.0289	0.0288	0.0290	0.0290	0.0286	0.0291	0.0290
	y_{PROD}	0.0234	0.0128	0.0090	0.0069	0.0057		0.0050		0.0050		0.0042	0.0035	0.0027	0.0022	0.0016	0.0013	0.00066	0.00032	0.00021	0.00016	0.00012	0.00011
	α OR ϵ	0.3391	0.6341	0.7844	0.8818	0.9532		0.9953		0.00004		0.151	0.294	0.467	0.569	0.685	0.748	0.868	0.935	0.957	0.968	0.975	0.977
	δ	-0.94	-1.88	-2.25	-2.47		-1.66			-3.21		-3.22	-3.18	-3.15	-3.15	-3.15	-3.16	-3.17	-3.17	-3.18	-3.20	-3.17	-3.17
	δ_{ADJ}	-2.77	-2.96	-2.87	-2.80																		
0.01	MODE		D	D	D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE		55.74	105.42	156.35	207.26	197.41	258.04	271.05	271.06	322.75	322.81	367.78	456.74	544.60	716.46	882.58	1631.01	3277.53	4923.99	6570.30	8451.50	9245.67
	KGU/D		143.2	80.89	55.93	42.63		34.42		34.33		28.71	23.90	17.91	14.36	10.34	8.149	4.186	2.026	1.336	0.9941	0.7736	0.7061
	R_{PROD}		0.0426	0.0365	0.0347	0.0335		0.0326		0.0300		0.0345	0.0335	0.0320	0.0311	0.0300	0.0295	0.0290	0.0290	0.0290	0.0286	0.0291	0.0290
	y_{PROD}		0.0307	0.0201	0.0154	0.0126		0.0107		0.0100		0.0098	0.0081	0.0059	0.0047	0.0033	0.0026	0.0013	0.00065	0.00043	0.00032	0.00025	0.00023
	α OR ϵ		0.6002	0.7568	0.8525	0.9221		0.9761		0.00004		0.018	0.192	0.408	0.532	0.669	0.741	0.867	0.935	0.957	0.968	0.975	0.977
	δ		-1.63	-2.17	-2.54	-1.83				-3.03		-3.58	-3.48	-3.33	-3.24	-3.17	-3.15	-3.16	-3.17	-3.17	-3.20	-3.17	-3.17
	δ_{ADJ}		-2.72	-2.87	-2.98	-1.98																	
0.02	MODE				D	D	B	D	B	BL	B	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL	BL
	VALUE				171.84	226.08	148.42	279.51	273.33	273.34	349.38	349.28	401.44	492.31	579.29	746.83	908.88	1646.40	3276.25	4906.18	6535.96	8398.09	9184.26
	KGU/D				64.66	48.64		38.75		38.69		32.02	27.25	20.01	15.85	11.22	8.724	4.341	2.067	1.359	1.009	0.7846	0.7159
	R_{PROD}				0.0450	0.0421		0.0388		0.0300		0.0350	0.0384	0.0362	0.0350	0.0331	0.0319	0.0297	0.0290	0.0290	0.0286	0.0291	0.0290
	y_{PROD}				0.0376	0.0301		0.0245		0.0200		0.0200	0.0191	0.0138	0.0109	0.0075	0.0058	0.0028	0.0013	0.00087	0.00064	0.00051	0.00046
	α OR ϵ				0.8046	0.8750		0.9368		0.00004		0.0017	0.047	0.308	0.456	0.623	0.712	0.862	0.934	0.956	0.968	0.975	0.977
	δ				-2.11	-1.95		-2.06			-3.26		-3.59	-3.66	-3.62	-3.45	-3.32	-3.16	-3.16	-3.17	-3.18	-3.16	-3.17
	δ_{ADJ}				-2.62	-2.23		-2.20															

TABLE I.23 Maximum Uranium Values and Optimum Conditions
Recycle to Diffusion Plant - y=0.15:
Blending with Natural Uranium

L_F	Unit Costs	$C_{U_3O_8}$ ($/lb)	C_N ($/g Np)	R	$V_B(R,0)$ ($/kgU)	$V_B(R,0.15)$ ($/kgU)	F_B (kgU/day)	R_B	y_B	$\in$	$\delta(R,0.15)$ ($/g U-236)
0.01	High	8	0	2	6690.93	4204.51	1.317	0.0350	0.0071	0.953	9.88
				6	8616.77	5821.98	1.000	0.0345	0.0054	0.964	10.02
				15	9427.84	6506.71	0.9073	0.0342	0.0049	0.967	10.05
			60	2	6708.45	6065.02	1.339	0.0374	0.0077	0.949	-2.42
				6	8638.94	7676.02	1.016	0.0368	0.0059	0.961	-2.22
				15	9451.80	8357.81	0.9179	0.0359	0.0052	0.965	-2.16
		6	0	2	5925.06	3699.65	1.332	0.0362	0.0074	0.951	8.91
				6	7630.51	5132.97	1.009	0.0352	0.0056	0.963	9.02
				15	8351.14	5739.50	0.9160	0.0351	0.0051	0.966	9.06
			60	2	5945.10	5508.90	1.358	0.0392	0.0081	0.946	-3.04
				6	7656.01	6936.98	1.029	0.0384	0.0062	0.959	-2.86
				15	8378.66	7541.74	0.9311	0.0377	0.0055	0.963	-2.80
		10	0	2	7420.81	4685.69	1.302	0.0337	0.0068	0.955	10.81
				6	9555.68	6480.52	0.9877	0.0331	0.0052	0.966	10.95
				15	10455.34	7240.24	0.8936	0.0325	0.0046	0.969	10.98
			60	2	7435.03	6589.44	1.325	0.0362	0.0074	0.951	-1.80
				6	9572.57	8375.02	1.003	0.0352	0.0056	0.963	-1.59
				15	10475.70	9130.19	0.9104	0.0351	0.0051	0.966	-1.51
		8	100	2	6719.94	7330.78	1.355	0.0392	0.0081	0.946	-10.79
				6	8653.60	8936.06	1.026	0.0384	0.0062	0.959	-10.54
				15	9469.88	9615.73	0.9282	0.0377	0.0055	0.963	-10.44
	Low	8	0	2	6590.97	4370.84	1.252	0.0288	0.0056	0.963	8.21
				6	8488.90	5996.19	0.9433	0.0277	0.0041	0.973	8.13
				15	9288.64	6681.81	0.8552	0.0275	0.0037	0.975	8.09
			60	2	6604.37	6119.96	1.293	0.0324	0.0065	0.957	-3.37
				6	8504.89	7716.65	0.9723	0.0308	0.0047	0.969	-3.25
				15	9307.04	8394.17	0.8840	0.0308	0.0043	0.971	-3.22

APPENDIX J

EFFECT OF NP-237 PRICE ON U-236 PENALTY

The tables of this appendix give the magnitude of the change of the U-236 penalty δ when the price of Np-237 per gram, C_N, is increased by specified amounts. Table J.1 and Table J.2 give results for recycle to fabrication and recycle to a diffusion plant, respectively. Units for the quantity tabulated are given as negative in the tables to indicate that δ decreases as C_N increases.

Various sets of economic conditions are considered. The unit cost condition and the price of natural U_3O_8 ($C_{U_3O_8}$) are varied, and C_N is increased either from $0/g to $60/g or from $0/g to $100/g (column marked "$C_N$ Limits"). Results are given for various values for the weight ratio of U-235 to U-238 in feed uranium R and for the weight fraction of U-236 in feed uranium y.

TABLE J.1 CHANGE OF U-236 PENALTY WITH NEPTUNIUM PRICE – RECYCLE TO FABRICATION

$$\left(-\frac{\$/G\ U\text{-}236}{\$/G\ NP\text{-}237}\right)$$

UNIT COSTS	$C_{U_3O_8}$ ($/LB)	C_N LIMITS ($/G NP)	y \ R		0.03	0.06	0.15	0.3	0.4	0.5	0.6	0.8	1.0	2	6	15
HIGH	8	0, 60	0.01		0.333	0.422	0.503	0.553	0.571	0.600	0.611	0.614	0.616	0.621	0.623	0.624
			0.04				0.428	0.505	0.528	0.555	0.572	0.577	0.580	0.589	0.596	0.599
			0.15											0.512	0.538	0.546
		0, 100	0.01		0.332	0.421	0.503	0.555	0.573	0.600	0.612	0.616	0.618	0.622	0.626	0.627
			0.04				0.428	0.505	0.527	0.555	0.571	0.576	0.580	0.589	0.597	0.600
			0.15											0.512	0.537	0.545
	6	0, 60	0.01		0.328	0.417	0.499	0.549	0.567	0.600	0.608	0.611	0.613	0.617	0.619	0.621
			0.04				0.426	0.504	0.528	0.542	0.574	0.578	0.581	0.588	0.594	0.597
			0.15											0.514	0.540	0.548
	10	0, 60	0.01		0.337	0.425	0.506	0.556	0.574	0.600	0.612	0.616	0.618	0.622	0.625	0.626
			0.04				0.428	0.505	0.527	0.556	0.570	0.576	0.580	0.590	0.598	0.600
			0.15											0.509	0.536	0.544
LOW	8	0, 60	0.01		0.327	0.414	0.500	0.555	0.574	0.610	0.612	0.617	0.620	0.626	0.630	0.632
			0.04				0.419	0.497	0.519	0.555	0.560	0.568	0.572	0.584	0.594	0.597
			0.15											0.499	0.526	0.534

TABLE J.2 CHANGE OF U-236 PENALTY WITH NEPTUNIUM PRICE – RECYCLE TO DIFFUSION PLANT

$$\left(-\frac{\$/G\ U\text{-}236}{\$/G\ NP\text{-}237}\right)$$

UNIT COSTS	$C_{U_3O_8}$ ($/LB)	C_N LIMITS ($/G NP)	y \ R		0.005	0.01	0.02	0.03	0.04	0.06	0.10	0.5	1.0	2	6	15
HIGH	8	0,60	0.005		0.064	0.121	0.167	0.190	0.202	0.200	0.197	0.194	0.194	0.194	0.194	0.193
			0.02				0.151	0.177	0.198	0.205	0.205	0.197	0.196	0.195	0.195	0.195
			0.15											0.205	0.204	0.204
		0,100	0.005		0.064	0.121	0.167	0.190	0.204	0.201	0.198	0.195	0.195	0.195	0.195	0.194
			0.02				0.151	0.178	0.199	0.207	0.206	0.198	0.197	0.196	0.196	0.195
			0.15											0.207	0.206	0.205
	6	0,60	0.005		0.055	0.112	0.159	0.182	0.197	0.194	0.192	0.190	0.190	0.189	0.190	0.190
			0.02				0.145	0.172	0.192	0.199	0.199	0.192	0.191	0.190	0.191	0.190
			0.15											0.199	0.198	0.198
	10	0,60	0.005		0.072	0.128	0.174	0.197	0.207	0.204	0.201	0.198	0.197	0.197	0.198	0.197
			0.02				0.156	0.181	0.204	0.210	0.210	0.201	0.200	0.198	0.200	0.198
			0.15											0.210	0.209	0.208
LOW	8	0,60	0.005		0.062	0.119	0.163	0.190	0.187	0.184	0.182	0.181	0.181	0.179	0.180	0.179
			0.02				0.148	0.172	0.193	0.197	0.192	0.182	0.181	0.181	0.181	0.180
			0.15											0.193	0.190	0.189

APPENDIX K

COMPARISON OF MATCHED-R AND OPTIMUM CONSTANT-KEY-WEIGHT CASCADE CHARACTERISTICS

Studies by de la Garza(30) have shown that the discrepancy between separative work in a "matched-R" cascade(12) and in more efficient modes of operation becomes greater as the U-236 content of diffusion plant feed increases. Consequently, to see if significant error might have been made by using the matched-R method in this study, one of the cases with the highest U-236 content in diffusion plant feed was examined using the "optimum constant-key-weight" method of diffusion plant operation.(30) It has been shown by de la Garza(30) that the optimum constant-key-weight method yields a separative work requirement much closer to the absolute minimum than does the matched-R method. As a result, if the separative work calculated by the matched-R method and the optimum constant-key-weight method are not significantly different for the case examined, it may be concluded that the separative work calculated by the matched-R method is sufficiently close to the minimum for all other cases as well.

The case examined is shown in Figure K.1. The nomenclature used is summarized at the end of the appendix. As usual, R_i and y_i refer to the weight ratio of U-235 to U-238 and the weight fraction of U-236, respectively, in the uranium stream denoted by

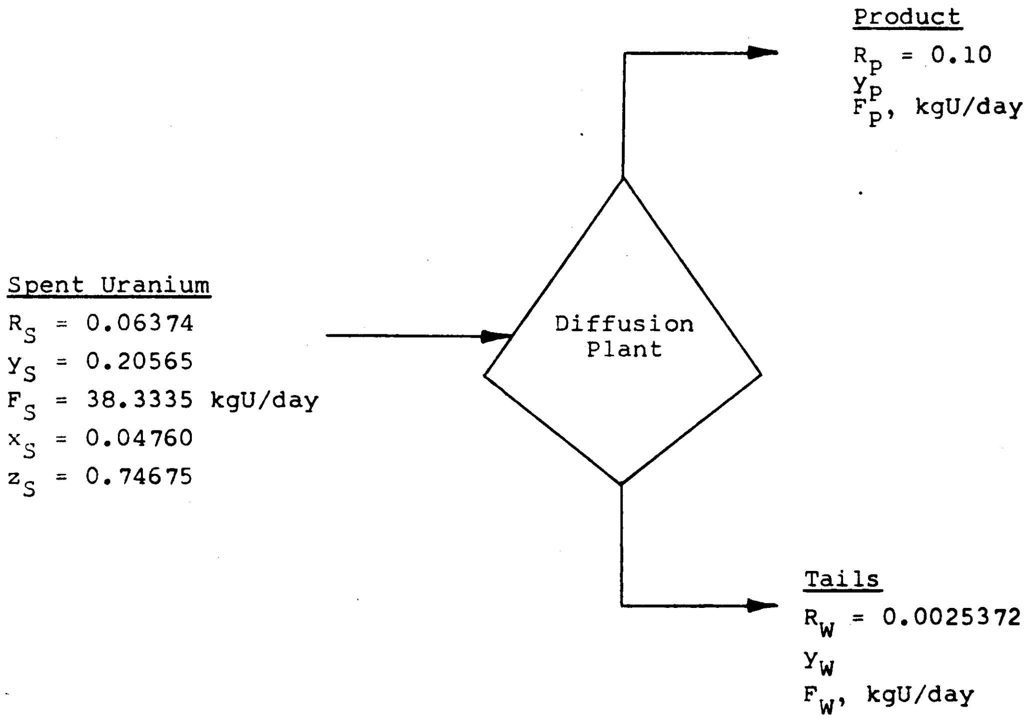


FIGURE K.1 Test Case for Comparison of Matched-R and Optimum Constant-Key-Weight Cascade Performance i, while F_i is the time-averaged uranium flow rate. The value indicated for R_W is optimum for a U_3O_8 price of \$8/lb and a unit separative work charge of \$30/kgU. The values indicated for R_S, y_S, and F_S apply to uranium discharged from the PWR when $R_R = 0.10$ and $y_R = 0.20$ for the reactor feed uranium. R_P is specified as 0.10. From the known values of R_S and y_S, the weight fractions of U-235, x_S, and U-238, z_S, in the spent uranium were calculated and are indicated in the figure. The remaining unknowns are y_P, F_P, y_W, and F_W.

Of particular interest is a comparison of results for separative work, for y_P, and for F_P when the matched-R and optimum constant-key-weight methods are applied to the test case. For the matched-R case, the procedure used in calculating y_P, F_P, y_W, and F_W is described in detail in Part A.2 of Section IV, while the separative work Δ, in kgU/day, is calculated using Equation V.2.

Following Mitchell's work(31), the principal equations for the optimum constant-key-weight cascade can be written in terms of the fraction A_i of component i in the feed which is recovered in the product as:

$$\text{U-235:} \quad A_5 = \frac{F_P(1-y_P)R_P}{F_S x_S(1+R_P)} = \frac{1-e^{-(M-235)N_S}}{1-e^{-(M-235)N_T}} \qquad (K.1)$$

$$\text{U-236:} \quad A_6 = \frac{F_P y_P}{F_S y_S} = \frac{1-e^{-(M-236)N_S}}{1-e^{-(M-236)N_T}} \qquad (K.2)$$

$$\text{U-238:}\quad A_8 = \frac{F_P(1-y_P)}{F_S z_S(1+R_P)} = \frac{1-e^{-(M-238)N_S}}{1-e^{-(M-238)N_T}} \qquad (K.3)$$

$$\Delta = 2.25F_S\left[\frac{x_S(A_5N_T-N_S)}{M-235} + \frac{y_S(A_6N_T-N_S)}{M-236} + \frac{z_S(A_8N_T-N_S)}{M-238}\right] \qquad (K.4)$$

In these equations, N_S is the product of the number of stripping stages and the enrichment factor for isotopes differing by one mass number, while N_T is the product of the total number of stages and the enrichment factor for isotopes differing by one mass number. M is the cascade "key weight" and is defined as the arithmetic mean of the mass numbers of the two "key" components, i.e., the two components whose weight ratio is matched at each point in the cascade where two streams are mixed. The key components need not be physically real isotopes, as "dummy" components can be assumed present. The matched-R cascade is actually a constant-key-weight cascade having M=236.5, with the key components being U-235 and U-238.

For each of a series of assumed values for M, Equations K.1, K.2, and K.3 can be used together with cascade mass balance relations for U-235, U-236, and total uranium to determine N_S, N_T, F_P, y_P, F_W, and y_W, and Δ can be calculated from Equation K.4. The value of M which gives minimum Δ is denoted by M^*, and the cascade operating with a key weight of M^* is the optimum constant-key-weight cascade.

Calculated results are given in Table K.1. The close agreement between the separative work requirements and the values of F_P and y_P for the matched-R method and the optimum constant-key-weight method for this high-y_S case indicates that no significant error has been introduced by using the matched-R method throughout this work.

Nomenclature

A_5	fraction of the U-235 contained in the feed which is recovered in the product
A_6	fraction of the U-236 contained in the feed which is recovered in the product
A_8	fraction of the U-238 contained in the feed which is recovered in the product
F_P	time-averaged flow rate of uranium for the product stream from the diffusion plant, kgU/day
F_S	time-averaged flow rate of uranium for the feed stream to the diffusion plant, kgU/day
F_W	time-averaged flow rate of uranium for the tails stream from the diffusion plant, kgU/day
M	constant "key weight" of the cascade
M^*	optimum constant "key weight" of the cascade
N_S	product of the number of stripping stages and the enrichment factor for isotopes differing by one mass number
N_T	product of the total number of stages and the enrichment factor for isotopes differing by one mass number

TABLE K.1

Comparison of Cascade Characteristics Given by Matched-R and Optimum Constant-Key-Weight Methods

Note: Conditions for test case are specified in Figure K.1

Cascade Operating Method	Matched-R	Optimum Constant-Key-Weight
Key Weight	236.5	236.555
Separative Work, kgU/day	31.755	31.726
U-236 Fractions:		
Product, y_P	0.27105	0.27123
Tails, y_W	0.04741	0.04682
Uranium Flowrates:		
Product, F_P	27.1242	27.1337
Tails, F_W	11.2093	11.1998

R_P	weight ratio of U-235 to U-238 in the product stream from the diffusion plant
R_R	weight ratio of U-235 to U-238 in the reactor feed uranium
R_S	weight ratio of U-235 to U-238 in the feed stream to the diffusion plant
R_W	weight ratio of U-235 to U-238 in the tails stream from the diffusion plant
x_S	weight fraction of U-235 in the uranium feed stream to the diffusion plant
y_P	weight fraction of U-236 in the uranium product stream from the diffusion plant
y_R	weight fraction of U-236 in the reactor feed uranium
y_S	weight fraction of U-236 in the uranium feed stream to the diffusion plant
y_W	weight fraction of U-236 in the uranium tails stream from the diffusion plant
z_S	weight fraction of U-238 in the uranium feed stream to the diffusion plant
Δ	average daily separative work requirement of the cascade, kgU/day

APPENDIX L

FLOWSHEET CHARACTERISTICS AS FUNCTIONS OF REACTOR FEED COMPOSITION R_R AND y_R

The tables of this appendix contain detailed reactor and basic recycle flowsheet characteristics under steady-state operating conditions for all reactor feed isotopic compositions considered. Results are presented as printed out by the scatter-refueling version of the MOVE code. Definitions for all variables appearing in the tables are given on subsequent pages. Under "Calculated Results", the first block of data given is common to all recycle flowsheets for a fixed reactor feed isotopic composition. Recycle flowsheet characteristics are then given for each of a series of RW values, where RW is the weight ratio of U-235 to U-238 in the tails stream from the diffusion plant used to re-enrich recycled spent uranium. Note that when "None" is entered under RW, results given are for the recycle-to-fabrication case (Figure IV.1); otherwise, recycle to a diffusion plant is implied (Figure IV.2). In addition to the values of RW established in Appendix F corresponding to U_3O_8 prices of $10, $8, and $6/lb, results are given for RW = 0.0032052, which is the optimum value corresponding to a U_3O_8 price of $4/lb and a charge for separative work of $30/kgU.

Definitions for all output variables are given below. Where applicable, the symbol used in the recycle flowsheets shown in Figures IV.1 and IV.2 is given in parentheses following the definition of the output variable to which it corresponds.

B	Average discharge burnup, MWD/T
F	Time-averaged flowrate of makeup uranium fed to fabrication plant, kgU/day (F)
FP	Time-averaged flowrate of uranium in product stream from diffusion plant used to re-enrich recycled uranium, kgU/day (F_P)
FR	Time-averaged flowrate of uranium fed to reactor, kgU/day (F_R)
FRLC	Fractional loss of uranium during conversion of UO_3 to UF_6, based on product from conversion (L_C)
FRLFB	Fractional loss of uranium during fabrication, based on fabricated product (L_F)
FRLRP	Fractional loss of Pu and Np during reprocessing, based on material fed to reprocessing plant (L_{RP})
FRLRU	Fractional loss of uranium during reprocessing, based on uranium fed to reprocessing plant (L_{RU})
FS	Time-averaged flowrate of uranium leaving reprocessing plant, kgU/day (F_S)
FSP	Time-averaged flowrate of uranium discharged from reactor, kgU/day

FW	Time-averaged flowrate of uranium in tails stream from diffusion plant used to re-enrich recycled uranium, kgU/day (F_W)
KEFF	Multiplication factor at start of steady-state cycle, with equilibrium xenon and samarium but with no control poison
NTAR	Number of RW values (see RW below) to be considered for the recycle-to-diffusion plant scheme
PF	Average load factor for power plant
PTH	Full-power thermal output from reactor, MW
R	Weight ratio of U-235 to U-238 in makeup uranium fed to fabrication plant (R)
RP	Weight ratio of U-235 to U-238 in product stream from diffusion plant used to re-enrich recycled uranium (R_P)
RR	Weight ratio of U-235 to U-238 in uranium fed to reactor (R_R)
RS	Weight ratio of U-235 to U-238 in uranium leaving reprocessing plant (R_S)
RW	Weight ratio of U-235 to U-238 in tails stream from diffusion plant used to re-enrich recycled uranium (R_W)
TCYC	Time interval between reactor refuelings, days
TOTINV	Total mass of uranium in reactor at start of steady-state cycle, kgU

TRES	Residence time in reactor for fuel charged, days
WCH5	Mass of U-235 in batch charged to reactor during refueling, kg
WCH6	Mass of U-236 in batch charged to reactor during refueling, kg
WCH8	Mass of U-238 in batch charged to reactor during refueling, kg
WK	Time-averaged flowrate of fissile plutonium leaving reprocessing plant, kg/day (K)
WKP	Time-averaged flowrate of fissile plutonium leaving reactor, kg/day
WN	Time-averaged flowrate of Np-237 leaving reprocessing plant, kg/day (N)
WNP	Time-averaged flowrate of Np-237 leaving reactor, kg/day
X	Weight fraction of U-235 in makeup uranium fed to fabrication plant
Y	Weight fraction of U-236 in makeup uranium fed to fabrication plant (y)
YP	Weight fraction of U-236 in product stream from diffusion plant used to re-enrich recycled uranium (y_P)
YR	Weight fraction of U-236 in uranium fed to reactor (y_R)
YS	Weight fraction of U-236 in uranium leaving reprocessing plant (y_S)

YW Weight fraction of U-236 in tails stream from diffusion plant used to re-enrich recycled uranium (y_W)

A key to the numbering of the 52 cases considered is given on the following page, with each case characterized by specified values for R_R and y_R, the weight ratio of U-235 to U-238 in reactor feed uranium and the weight fraction of U-236 in reactor feed uranium, respectively. The 52 tables are then given in numerical order.

TABLE L.1 Table Numbers for Steady-State Flowsheet Characteristics

R_R y_R	0.02	0.025	0.03	0.04	0.05	0.06	0.08	0.10	0.12
0.0	2	7	12	18	25	32			
0.01	3	8	13	19	26	33			
0.025	4	9	14	20	27	34	39		
0.04	5	10							
0.05	6	11	15	21	28	35	40	45	
0.08			16	22	29	36	41	46	50
0.12			17	23	30	37	42	47	51
0.20				24	31	38	43	48	52
0.28							44	49	53

TABLE L.2 Steady-State Flowsheet Characteristics

$R_R = 0.02,\ y_R = 0.0$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .19999998E-01       WK=  .34469509E 00     WCH5   =  .25993997E 03  KG     B    = 15119.47
   YR =  .00000000E 00       WN=  .10255220E-01     WCH6   =  .00000000E 00  KG     KEFF = 1.05474
   FR =  .71219432E 02       FS=  .68915245E 02     WCH8   =  .12997000E 05  KG
   FSP=  .69611359E 02       RS=  .89012035E-02     TOTINV=  .53027760E 05  KG
   WKP=  .34817687E 00       YS=  .18872372E-02     TRES   =  .74456869E 03  DAYS
   WNP=  .10358809E-01                              TCYC   =  .18614217E 03  DAYS

   RW          R            Y            F             X            YW           FW            RP           YP           FP

   NONE      3.42977E-01 -4.31177E-02  3.01638E 00  2.66397E-01
2.31730E-03  2.00000E-02 -1.98721E-03  4.60247E 01  1.96468E-02  8.92706E-04  4.28022E 01  2.00000E-02  3.53035E-03  2.59070E 01
2.53720E-03  2.00000E-02 -1.91314E-03  4.65750E 01  1.96454E-02  9.35723E-04  4.33525E 01  2.00000E-02  3.51405E-03  2.53566E 01
2.81950E-03  2.00000E-02 -1.81972E-03  4.73021E 01  1.96435E-02  9.88975E-04  4.40796E 01  2.00000E-02  3.49486E-03  2.46295E 01
3.20520E-03  2.00000E-02 -1.69463E-03  4.83349E 01  1.96411E-02  1.05870E-03  4.51124E 01  2.00000E-02  3.47125E-03  2.35967E 01
```

TABLE L.3 Steady-State Flowsheet Characteristics

$R_R = 0.02,\ y_R = 0.01$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .20000000E-01       WK=  .41175480E 00     WCH5   =  .25731939E 03  KG     B    = 10738.62
   YR =  .10000018E-01       WN=  .58291323E-01     WCH6   =  .13255871E 03  KG     KEFF = 1.04469
   FR =  .10027358E 03       FS=  .97557303E 02     WCH8   =  .12865969E 05  KG
   FSP=  .98542731E 02       RS=  .11190691E-01     TOTINV=  .53023390E 05  KG
   WKP=  .41591394E 00       YS=  .11069570E-01     TRES   =  .52878724E 03  DAYS
   WNP=  .58880125E-01                              TCYC   =  .13219681E 03  DAYS

   RW          R            Y            F             X            YW           FW            RP           YP           FP

   NONE      3.11039E-01 -1.80565E-02  3.71901E 00  2.41530E-01
2.31730E-03  2.00000E-02  2.99246E-03  5.17291E 01  1.95492E-02  4.58356E-03  4.77183E 01  2.00000E-02  1.73162E-02  4.95472E 01
2.53720E-03  2.00000E-02  3.21454E-03  5.23513E 01  1.95448E-02  4.80358E-03  4.83405E 01  2.00000E-02  1.72607E-02  4.89250E 01
2.81950E-03  2.00000E-02  3.49081E-03  5.31729E 01  1.95394E-02  5.07584E-03  4.91621E 01  2.00000E-02  1.71952E-02  4.81034E 01
3.20520E-03  2.00000E-02  3.85482E-03  5.43393E 01  1.95323E-02  5.43212E-03  5.03285E 01  2.00000E-02  1.71144E-02  4.69370E 01
```

TABLE L.4 Steady-State Flowsheet Characteristics

$R_R = 0.02,\ y_R = 0.025$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .19999954E-01       WK=  .50011600E 00     WCH5   =  .25338901E 03  KG     B    = 6535.73
   YR =  .24999965E-01       WN=  .12048297E 00     WCH6   =  .33135513E 03  KG     KEFF = 1.03093
   FR =  .16475599E 03       FS=  .16124366E 03     WCH8   =  .12669480E 05  KG
   FSP=  .16287239E 03       RS=  .13921040E-01     TOTINV=  .53016895E 05  KG
   WKP=  .50516768E 00       YS=  .25527751E-01     TRES   =  .32179039E 03  DAYS
   WNP=  .12169997E 00                              TCYC   =  .80447598E 02  DAYS

   RW          R            Y            F             X            YW           FW            RP           YP           FP

   NONE      2.50212E-01  8.50691E-03  5.15989E 00  1.98433E-01
2.31730E-03  2.00000E-02  9.38584E-03  5.93824E 01  1.94238E-02  9.32536E-03  5.37403E 01  2.00000E-02  3.36637E-02  1.07021E 02
2.53720E-03  2.00000E-02  9.78870E-03  6.00956E 01  1.94159E-02  9.77076E-03  5.44534E 01  2.00000E-02  3.35988E-02  1.06308E 02
2.81950E-03  2.00000E-02  1.02884E-02  6.10367E 01  1.94061E-02  1.03216E-02  5.53946E 01  2.00000E-02  3.35221E-02  1.05367E 02
3.20520E-03  2.00000E-02  1.09443E-02  6.23720E 01  1.93932E-02  1.10420E-02  5.67298E 01  2.00000E-02  3.34270E-02  1.04032E 02
```

TABLE L.5 Steady-State Flowsheet Characteristics

$R_R = 0.02,\ y_R = 0.04$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .19999941E-01      WK=  .58959675E 00      WCH5   =  .24945995E 03  KG      B    = 3613.39
   YR =  .39999929E-01      WN=  .17427508E 00      WCH6   =  .53010293E 03  KG      KEFF = 1.01889
   FR =  .29800237E 03      FS=  .29300788E 03      WCH8   =  .12473034E 05  KG
   FSP=  .29596755E 03      RS=  .16259996E-01      TOTINV=  .53010387E 05  KG
   WKP=  .59555228E 00      YS=  .40278074E-01      TRES   =  .17788579E 03  DAYS
   WNP=  .17603544E 00                              TCYC   =  .44471446E 02  DAYS

    RW           R             Y            F             X            YW           FW            RP           YP           FP

   NONE      1.77496E-01  2.97800E-02  7.97452E 00  1.46251E-01
2.31730E-03  1.99999E-02  1.57401E-02  6.81353E 01  1.92992E-02  1.34888E-02  5.92844E 01  1.99999E-02  4.70988E-02  2.32847E 02
2.53720E-03  1.99999E-02  1.62730E-02  6.89341E 01  1.92887E-02  1.41302E-02  6.00831E 01  1.99999E-02  4.70484E-02  2.32048E 02
2.81950E-03  1.99999E-02  1.69334E-02  6.99877E 01  1.92758E-02  1.49231E-02  6.11368E 01  1.99999E-02  4.69887E-02  2.30995E 02
3.20520E-03  1.99999E-02  1.77995E-02  7.14817E 01  1.92588E-02  1.59595E-02  6.26308E 01  1.99999E-02  4.69146E-02  2.29501E 02
```

TABLE L.6 Steady-State Flowsheet Characteristics

$R_R = 0.02,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .19999999E-01      WK=  .65783772E 00      WCH5   =  .24684126E 03  KG      B    = 2062.73
   YR =  .50000006E-01      WN=  .20729051E 00      WCH6   =  .66257402E 03  KG      KEFF = 1.01020
   FR =  .52202587E 03      FS=  .51466700E 03      WCH8   =  .12342064E 05  KG
   FSP=  .51986565E 03      RS=  .17711503E-01      TOTINV=  .53005915E 05  KG
   WKP=  .66448255E 00      YS=  .50166764E-01      TRES   =  .10153887E 03  DAYS
   WNP=  .20938436E 00                              TCYC   =  .25384716E 02  DAYS

    RW           R             Y            F             X            YW           FW            RP           YP           FP

   NONE      1.22521E-01  4.31772E-02  1.25791E 01  1.04435E-01
2.31730E-03  2.00000E-02  2.11329E-02  7.72541E 01  1.91935E-02  1.60329E-02  6.31356E 01  2.00000E-02  5.49559E-02  4.49992E 02
2.53720E-03  2.00000E-02  2.16997E-02  7.81126E 01  1.91824E-02  1.67932E-02  6.39941E 01  2.00000E-02  5.49219E-02  4.49134E 02
2.81950E-03  2.00000E-02  2.24019E-02  7.92447E 01  1.91686E-02  1.77329E-02  6.51262E 01  2.00000E-02  5.48817E-02  4.48001E 02
3.20520E-03  2.00000E-02  2.33226E-02  8.08494E 01  1.91505E-02  1.89607E-02  6.67309E 01  2.00000E-02  5.48317E-02  4.46397E 02
```

TABLE L.7 Steady-State Flowsheet Characteristics

$R_R = 0.025,\ y_R = 0.0$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .25000029E-01      WK=  .28018341E 00      WCH5   =  .32332033E 03  KG      B    = 22369.32
   YR =  .00000000E 00      WN=  .12085436E-01      WCH6   =  .00000000E 00  KG      KEFF = 1.06985
   FR =  .48137368E 02      FS=  .46135290E 02      WCH8   =  .12932798E 05  KG
   FSP=  .46601304E 02      RS=  .90801848E-02      TOTINV=  .53024476E 05  KG
   WKP=  .28301355E 00      YS=  .27151875E-02      TRES   =  .11015242E 04  DAYS
   WNP=  .12207611E-01                              TCYC   =  .27538106E 03  DAYS

    RW           R             Y            F             X            YW           FW            RP           YP           FP

   NONE      4.20164E-01 -5.04403E-02  2.48345E 00  3.10779E-01
2.31730E-03  2.50000E-02 -2.40831E-03  3.46426E 01  2.44490E-02  1.29481E-03  3.20212E 01  2.50000E-02  5.94947E-03  1.39761E 01
2.53720E-03  2.50000E-02 -2.31790E-03  3.49652E 01  2.44468E-02  1.35561E-03  3.23437E 01  2.50000E-02  5.93587E-03  1.36536E 01
2.81950E-03  2.50000E-02 -2.20438E-03  3.53885E 01  2.44440E-02  1.44076E-03  3.27671E 01  2.50000E-02  5.89631E-03  1.32302E 01
3.20520E-03  2.50000E-02 -2.05312E-03  3.59845E 01  2.44403E-02  1.52896E-03  3.33630E 01  2.50000E-02  5.84762E-03  1.26343E 01
```

TABLE L.8 Steady-State Flowsheet Characteristics

$R_R = 0.025,\ y_R = 0.01$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=    .800      NTAR=   4
   FRLFB=  .010              FRLC=  .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .25000027E-01      WK=  .32738081E 00     WCH5   =  .32006069E 03  KG         B    = 17516.07
   YR =  .10000014E-01      WN=  .54067383E-01     WCH6   =  .13255044E 03  KG         KEFF = 1.06177
   FR =  .61474975E 02      FS=  .59240628E 02     WCH8   =  .12802414E 05  KG
   FSP=  .59839018E 02      RS=  .11329877E-01     TOTINV=  .53020100E 05  KG
   WKP=  .33068769E 00      YS=  .11671867E-01     TRES   =  .86246637E 03  DAYS
   WNP=  .54613519E-01                             TCYC   =  .21561659E 03  DAYS

    RW            R           Y            F            X            YW           FW           RP           YP           FP

   NONE      4.06158E-01 -2.47625E-02  2.84910E 00  2.95955E-01
2.31730E-03  2.50000E-02  2.72070E-03  3.80650E 01  2.43239E-02  4.91017E-03  3.50387E 01  2.50000E-02  2.15334E-02  2.40247E 01
2.53720E-03  2.50000E-02  2.95276E-03  3.84239E 01  2.43183E-02  5.13987E-03  3.53976E 01  2.50000E-02  2.14420E-02  2.36658E 01
2.81950E-03  2.50000E-02  3.24094E-03  3.88948E 01  2.43112E-02  5.42365E-03  3.58685E 01  2.50000E-02  2.13341E-02  2.31949E 01
3.20520E-03  2.50000E-02  3.61982E-03  3.95572E 01  2.43020E-02  5.79434E-03  3.65309E 01  2.50000E-02  2.12008E-02  2.25325E 01
```

TABLE L.9 Steady-State Flowsheet Characteristics

$R_R = 0.025,\ y_R = 0.025$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=    .800      NTAR=   4
   FRLFB=  .010              FRLC=  .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .25000023E-01      WK=  .38856157E 00     WCH5   =  .31517268E 03  KG         B    = 12502.97
   YR =  .25000038E-01      WN=  .10969142E 00     WCH6   =  .33133559E 03  KG         KEFF = 1.05135
   FR =  .86123522E 02      FS=  .83522800E 02     WCH8   =  .12606895E 05  KG
   FSP=  .84366465E 02      RS=  .14137007E-01     TOTINV=  .53013613E 05  KG
   WKP=  .39248644E 00      YS=  .25930295E-01     TRES   =  .61555324E 03  DAYS
   WNP=  .11079942E 00                             TCYC   =  .15388831E 03  DAYS

    RW            R           Y            F            X            YW           FW           RP           YP           FP

   NONE      3.71001E-01  2.55677E-03  3.46196E 00  2.69914E-01
2.31730E-03  2.50000E-02  9.15552E-03  4.24789E 01  2.41670E-02  9.69669E-03  3.87871E 01  2.50000E-02  4.01229E-02  4.45059E 01
2.53720E-03  2.50000E-02  9.56980E-03  4.28847E 01  2.41569E-02  1.00853E-02  3.91820E 01  2.50000E-02  4.00050E-02  4.41000E 01
2.81950E-03  2.50000E-02  1.00827E-02  4.34167E 01  2.41443E-02  1.06392E-02  3.97049E 01  2.50000E-02  3.98656E-02  4.35681E 01
3.20520E-03  2.50000E-02  1.07544E-02  4.41644E 01  2.41280E-02  1.13622E-02  4.04627E 01  2.50000E-02  3.94928E-02  4.28203E 01
```

TABLE L.10 Steady-State Flowsheet Characteristics

$R_R = 0.025,\ y_R = 0.04$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=    .800      NTAR=   4
   FRLFB=  .010              FRLC=  .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .24999995E-01      WK=  .44026044E 00     WCH5   =  .31028580E 03  KG         B    = 9132.69
   YR =  .40000016E-01      WN=  .15799206E 00     WCH6   =  .53007191E 03  KG         KEFF = 1.04179
   FR =  .11790616E 03      FS=  .11488912E 03     WCH8   =  .12411434E 05  KG
   FSP=  .11604961E 03      RS=  .16373511E-01     TOTINV=  .53007168E 05  KG
   WKP=  .44470752E 00      YS=  .40599246E-01     TRES   =  .44957081E 03  DAYS
   WNP=  .15958794E 00                             TCYC   =  .11239270E 03  DAYS

    RW            R           Y            F            X            YW           FW           RP           YP           FP

   NONE      3.28305E-01  2.35931E-02  4.19611E 00  2.41330E-01
2.31730E-03  2.50000E-02  1.50074E-02  4.63385E 01  2.40242E-02  1.39351E-02  4.17988E 01  2.50000E-02  5.59199E-02  7.27467E 01
2.53720E-03  2.50000E-02  1.55802E-02  4.67846E 01  2.40102E-02  1.45808E-02  4.22449E 01  2.50000E-02  5.58017E-02  7.23006E 01
2.81950E-03  2.50000E-02  1.62885E-02  4.73690E 01  2.39930E-02  1.53777E-02  4.28292E 01  2.50000E-02  5.56616E-02  7.17162E 01
3.20520E-03  2.50000E-02  1.72148E-02  4.81898E 01  2.39704E-02  1.64175E-02  4.36500E 01  2.50000E-02  5.54878E-02  7.08954E 01
```

TABLE L.11 Steady-State Flowsheet Characteristics

$R_R = 0.025,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .24999944E-01      WK=  .47433287E 00      WCH5   =  .30702846E 03  KG        B     = 7292.46
   YR =  .50000013E-01      WN=  .18754809E 00      WCH6   =  .66253673E 03  KG        KEFF  = 1.03672
   FR =  .14765931E 03      FS=  .14428295E 03      WCH8   =  .12281166E 05  KG
   FSP=  .14574036E 03      RS=  .17751847E-01      TOTINV=  .53002924E 05  KG
   WKP=  .47912412E 00      YS=  .50472096E-01      TRES   =  .35895416E 03  DAYS
   WNP=  .18944252E 00                              TCYC   =  .89738540E 02  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE       2.95088E-01  3.59645E-02  4.85295E 00  2.19657E-01
 2.31730E-03  2.49999E-02  1.88174E-02  4.89950E 01  2.39312E-02  1.66012E-02  4.37105E 01  2.49999E-02  6.52564E-02  1.00141E 02
 2.53720E-03  2.49999E-02  1.94814E-02  4.94671E 01  2.39150E-02  1.73682E-02  4.41826E 01  2.49999E-02  6.51468E-02  9.96688E 01
 2.81950E-03  2.49999E-02  2.03020E-02  5.00851E 01  2.38950E-02  1.83147E-02  4.48006E 01  2.49999E-02  6.50169E-02  9.90508E 01
 3.20520E-03  2.49999E-02  2.13745E-02  5.09529E 01  2.38689E-02  1.95492E-02  4.56684E 01  2.49999E-02  6.48555E-02  9.81830E 01
```

TABLE L.12 Steady-State Flowsheet Characteristics

$R_R = 0.03,\ y_R = 0.0$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .30000000E-01      WK=  .24336487E 00      WCH5   =  .38607747E 03  KG        B     = 28929.73
   YR =  .00000000E 00      WN=  .13589726E-01      WCH6   =  .00000000E 00  KG        KEFF  = 1.08181
   FR =  .37221223E 02      FS=  .35369498E 02      WCH8   =  .12869249E 05  KG
   FSP=  .35726766E 02      RS=  .95345950E-02      TOTINV=  .53021305E 05  KG
   WKP=  .24582311E 00      YS=  .35024080E-02      TRES   =  .14244912E 04  DAYS
   WNP=  .13726996E-01                              TCYC   =  .35612280E 03  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE       4.80580E-01 -5.57023E-02  2.22394E 00  3.42670E-01
 2.31730E-03  3.00000E-02 -2.87142E-03  2.81653E 01  2.92098E-02  1.65020E-03  2.58355E 01  3.00000E-02  8.57792E-03  9.42818E 00
 2.53720E-03  3.00000E-02 -2.76756E-03  2.83798E 01  2.92068E-02  1.72610E-03  2.60501E 01  3.00000E-02  8.52465E-03  9.21361E 00
 2.81950E-03  3.00000E-02 -2.63751E-03  2.86603E 01  2.92030E-02  1.81980E-03  2.63305E 01  3.00000E-02  8.46191E-03  8.93317E 00
 3.20520E-03  3.00000E-02 -2.46482E-03  2.90528E 01  2.91980E-02  1.94206E-03  2.67231E 01  3.00000E-02  8.38467E-03  8.54061E 00
```

TABLE L.13 Steady-State Flowsheet Characteristics

$R_R = 0.03,\ y_R = 0.01$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .29999935E-01      WK=  .28270992E 00      WCH5   =  .38218537E 03  KG        B     = 23538.28
   YR =  .99999791E-02      WN=  .51179537E-01      WCH6   =  .13254240E 03  KG        KEFF  = 1.07260
   FR =  .45746763E 02      FS=  .43721215E 02      WCH8   =  .12739540E 05  KG
   FSP=  .44162843E 02      RS=  .11900495E-01      TOTINV=  .53017069E 05  KG
   WKP=  .28556557E 00      YS=  .12260912E-01      TRES   =  .11589250E 04  DAYS
   WNP=  .51696502E-01                              TCYC   =  .28973126E 03  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE       4.75818E-01 -2.98108E-02  2.48302E 00  3.32021E-01
 2.31730E-03  2.99999E-02  2.30725E-03  3.06411E 01  2.90590E-02  5.10623E-03  2.80273E 01  2.99999E-02  2.51457E-02  1.55631E 01
 2.53720E-03  2.99999E-02  2.54297E-03  3.08784E 01  2.90521E-02  5.34025E-03  2.82646E 01  2.99999E-02  2.50243E-02  1.53258E 01
 2.81950E-03  2.99999E-02  2.83533E-03  3.11833E 01  2.90436E-02  5.62902E-03  2.85745E 01  2.99999E-02  2.48810E-02  1.50159E 01
 3.20520E-03  2.99999E-02  3.21913E-03  3.16218E 01  2.90324E-02  6.00565E-03  2.90080E 01  2.99999E-02  2.47041E-02  1.45825E 01
```

TABLE L.14 Steady-State Flowsheet Characteristics

$R_R = 0.03,\ y_R = 0.025$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800       NTAR=   4
   FRLFB=  .010             FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .30000001E-01      WK=  .33177850E 00      WCH5   =  .37634916E 03  KG      B    = 17929.12
   YR =  .25000006E-01      WN=  .10192544E 00      WCH6   =  .33131600E 03  KG      KEFF = 1.06454
   FR =  .60058708E 02      FS=  .57784338E 02      WCH8   =  .12544971E 05  KG
   FSP=  .58368019E 02      RS=  .14823040E-01      TOTINV=  .53010545E 05  KG
   WKP=  .33512980E 00      YS=  .26339454E-01      TRES   =  .88264544E 03  DAYS
   WNP=  .10295499E 00                              TCYC   =  .22066136E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      4.55029E-01 -1.92183E-03  2.87496E 00  3.13330E-01
 2.31730E-03  3.00000E-02  8.81444E-03  3.37204E 01  2.88695E-02  9.72200E-03  3.06726E 01  3.00000E-02  4.52601E-02  2.69389E 01
 2.53720E-03  3.00000E-02  9.22519E-03  3.39867E 01  2.88575E-02  1.01654E-02  3.09389E 01  3.00000E-02  4.51005E-02  2.66726E 01
 2.81950E-03  3.00000E-02  9.73304E-03  3.43341E 01  2.88427E-02  1.07123E-02  3.12863E 01  3.00000E-02  4.49116E-02  2.63252E 01
 3.20520E-03  3.00000E-02  1.03971E-02  3.48195E 01  2.88234E-02  1.14251E-02  3.17717E 01  3.00000E-02  4.46776E-02  2.58398E 01
```

TABLE L.15 Steady-State Flowsheet Characteristics

$R_R = 0.03,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800       NTAR=   4
   FRLFB=  .010             FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .29999998E-01      WK=  .39623059E 00      WCH5   =  .36662474E 03  KG      B    = 12022.21
   YR =  .50000000E-01      WN=  .17377631E 00      WCH6   =  .66249736E 03  KG      KEFF = 1.05195
   FR =  .89567546E 02      FS=  .86862998E 02      WCH8   =  .12220825E 05  KG
   FSP=  .87740403E 02      RS=  .18538022E-01      TOTINV=  .52995789E 05  KG
   WKP=  .40023292E 00      YS=  .50753318E-01      TRES   =  .59172983E 03  DAYS
   WNP=  .17553163E 00                              TCYC   =  .14793246E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      4.03658E-01  3.18246E-02  3.60022E 00  2.78424E-01
 2.31730E-03  3.00000E-02  1.83328E-02  3.79234E 01  2.85922E-02  1.86596E-02  3.40634E 01  3.00000E-02  7.28575E-02  5.25398E 01
 2.53720E-03  3.00000E-02  1.89975E-02  3.82301E 01  2.85729E-02  1.74138E-02  3.43701E 01  3.00000E-02  7.26911E-02  5.22331E 01
 2.81950E-03  3.00000E-02  1.98178E-02  3.86297E 01  2.85490E-02  1.83434E-02  3.47697E 01  3.00000E-02  7.24937E-02  5.18335E 01
 3.20520E-03  3.00000E-02  2.08882E-02  3.91874E 01  2.85178E-02  1.95540E-02  3.53273E 01  3.00000E-02  7.22486E-02  5.12759E 01
```

TABLE L.16 Steady-State Flowsheet Characteristics

$R_R = 0.03,\ y_R = 0.08$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800       NTAR=   4
   FRLFB=  .010             FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .30000001E-01      WK=  .46510711E 00      WCH5   =  .35496072E 03  KG      B    = 7271.34
   YR =  .79999993E-01      WN=  .24826327E 00      WCH6   =  .10597377E 04  KG      KEFF = 1.03836
   FR =  .14808818E 03      FS=  .14466159E 03      WCH8   =  .11832024E 05  KG
   FSP=  .14612282E 03      RS=  .22206136E-01      TOTINV=  .52986888E 05  KG
   WKP=  .46980517E 00      YS=  .80505408E-01      TRES   =  .35780631E 03  DAYS
   WNP=  .25077098E 00                              TCYC   =  .89451579E 02  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      3.22296E-01  6.51015E-02  4.90747E 00  2.27872E-01
 2.31730E-03  3.00000E-02  2.94635E-02  4.28597E 01  2.82681E-02  2.42135E-02  3.75196E 01  3.00000E-02  1.00298E-01  1.06709E 02
 2.53720E-03  3.00000E-02  3.03740E-02  4.32107E 01  2.82415E-02  2.53010E-02  3.78705E 01  3.00000E-02  1.00162E-01  1.06358E 02
 2.81950E-03  3.00000E-02  3.14963E-02  4.36674E 01  2.82088E-02  2.66402E-02  3.83273E 01  3.00000E-02 10.00000E-02  1.05902E 02
 3.20520E-03  3.00000E-02  3.29589E-02  4.43038E 01  2.81662E-02  2.83826E-02  3.89637E 01  3.00000E-02  9.97985E-02  1.05265E 02
```

TABLE L.17 Steady-State Flowsheet Characteristics

$R_R = 0.03$, $y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=  .003        FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .30000090E-01      WK=  .55788135E 00      WCH5   =  .33941765E 03  KG  B    = 3002.60
   YR =  .12000039E 00      WN=  .33839821E 00      WCH6   =  .15890929E 04  KG  KEFF = 1.01818
   FR =  .35862307E 03      FS=  .35289945E 03      WCH8   =  .11313888E 05  KG
   FSP=  .35646410E 03      RS=  .26303204E-01      TOTINV=  .52969592E 05  KG
   WKP=  .56351652E 00      YS=  .12029548E 00      TRES   =  .14770269E 03  DAYS
   WNP=  .34181638E 00                              TCYC   =  .36925672E 02  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP


   NONE      1.90454E-01  1.08815E-01  9.30984E 00  1.42576E-01
2.31730E-03  3.00001E-02  4.88476E-02  5.21408E 01  2.77035E-02  3.36784E-02  4.17754E 01  3.00001E-02  1.31965E-01  3.10068E 02
2.53720E-03  3.00001E-02  4.99314E-02  5.25499E 01  2.76720E-02  3.51756E-02  4.21845E 01  3.00001E-02  1.31891E-01  3.09659E 02
2.81950E-03  3.00001E-02  5.12660E-02  5.30816E 01  2.76331E-02  3.70177E-02  4.27162E 01  3.00001E-02  1.31803E-01  3.09128E 02
3.20520E-03  3.00001E-02  5.30028E-02  5.38212E 01  2.75825E-02  3.94113E-02  4.34558E 01  3.00001E-02  1.31693E-01  3.08388E 02
```

TABLE L.18 Steady-State Flowsheet Characteristics

$R_R = 0.04$, $y_R = 0.0$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=  .003        FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .39999996E-01      WK=  .20283240E 00      WCH5   =  .50975935E 03  KG  B      40578.93
   YR =  .00000000E 00      WN=  .16042856E-01      WCH6   =  .00000000E 00  KG  KEFF = 1.10406
   FR =  .26536939E 02      FS=  .24827006E 02      WCH8   =  .12743985E 05  KG
   FSP=  .25087885E 02      RS=  .10862483E-01      TOTINV=  .53014977E 05  KG
   WKP=  .20467919E 00      YS=  .50289557E-02      TRES   =  .19978556E 04  DAYS
   WNP=  .16204906E-01                              TCYC   =  .49946351E 03  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP


   NONE      5.78029E-01 -6.35879E-02  1.96429E 00  3.89550E-01
2.31730E-03  4.00000E-02 -3.89847E-03  2.09714E 01  3.86115E-02  2.25932E-03  1.89928E 01  4.00000E-02  1.50236E-02  5.82992E 00
2.53720E-03  4.00000E-02 -3.77328E-03  2.10866E 01  3.86067E-02  2.36081E-03  1.90500E 01  4.00000E-02  1.49292E-02  5.71269E 00
2.81950E-03  4.00000E-02 -3.61713E-03  2.12410E 01  3.86007E-02  2.48405E-03  1.92025E 01  4.00000E-02  1.48180E-02  5.56026E 00
3.20520E-03  4.00000E-02 -3.41074E-03  2.14529E 01  3.85927E-02  2.64563E-03  1.94255E 01  4.00000E-02  1.46809E-02  5.34836E 00
```

TABLE L.19 Steady-State Flowsheet Characteristics

$R_R = 0.04$, $y_R = 0.01$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=  .003        FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .39999998E-01      WK=  .23358574E 00      WCH5   =  .50462142E 03  KG  B    = 34404.74
   YR =  .99999986E-02      WN=  .47420875E-01      WCH6   =  .13252682E 03  KG  KEFF = 1.09300
   FR =  .31298919E 02      FS=  .29476627E 02      WCH8   =  .12615536E 05  KG
   FSP=  .29774371E 02      RS=  .13476533E-01      TOTINV=  .53010736E 05  KG
   WKP=  .23594519E 00      YS=  .13479013E-01      TRES   =  .16936922E 04  DAYS
   WNP=  .47899874E-01                              TCYC   =  .42342306E 03  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP


   NONE      5.83797E-01 -3.80263E-02  2.13528E 00  3.82623E-01
2.31730E-03  4.00000E-02  1.30049E-03  2.25147E 01  3.84115E-02  5.38600E-03  2.02912E 01  4.00000E-02  3.15304E-02  9.09723E 00
2.53720E-03  4.00000E-02  1.53942E-03  2.26432E 01  3.84023E-02  5.62524E-03  2.04197E 01  4.00000E-02  3.13602E-02  8.96873E 00
2.81950E-03  4.00000E-02  1.83525E-03  2.28101E 01  3.83909E-02  5.91989E-03  2.05867E 01  4.00000E-02  3.11592E-02  8.80180E 00
3.20520E-03  4.00000E-02  2.22275E-03  2.30419E 01  3.83760E-02  6.30329E-03  2.08185E 01  4.00000E-02  3.09106E-02  8.56997E 00
```

TABLE L.20 Steady-State Flowsheet Characteristics

R_R = 0.04, y_R = 0.025

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800     NTAR=   4
   FRLFB=  .010             FRLC=   .003     FRLRU=  .C10      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =   .39999986E-01     WK=   .27124814E 00      WCH5   =  .49691617E 03  KG   B    = 27814.49
   YR =   .25000000E-01     WN=   .91082887E-01      WCH6   =  .33127756E 03  KG   KEFF = 1.08253
   FR =   .38713633E 02     FS=   .36726886E 02      WCH8   =  .12422908E 05  KG
   FSP=   .37097865E 02     RS=   .16710561E-01      TOTINV=  .53004408E 05  KG
   WKP=   .27398802E 00     YS=   .27247168E-01      TRES   =  .13691406E 04  DAYS
   WNP=   .92002917E-01                              TCYC   =  .34228516E 03  DAYS

     RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE        5.79115E-01 -9.76645E-03  2.37388E 00  3.70316E-01
2.31730E-03   4.C0000E-02  7.88793E-03  2.43989E 01  3.81581E-02  9.70324E-03  2.19152E 01  4.00000E-02  5.33989E-02  1.47019E 01
2.53720E-03   4.C0000E-02  8.28415E-03  2.45419E 01  3.81429E-02  1.01323E-02  2.20582E 01  4.00000E-02  5.31781E-02  1.45588E 01
2.81950E-03   4.C0C00E-02  8.77316E-03  2.47276E 01  3.81241E-02  1.06605E-02  2.22438E 01  4.00000E-02  5.29165E-02  1.43732E 01
3.20520E-03   4.C0000E-02  9.41124E-03  2.49850E 01  3.80996E-02  1.13474E-02  2.25013E 01  4.00000E-02  5.25922E-02  1.41158E 01
```

TABLE L.21 Steady-State Flowsheet Characteristics

R_R = 0.04, y_R = 0.05

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800     NTAR=   4
   FRLFB=  .010             FRLC=   .003     FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =   .40000054E-01     WK=   .31897362E 00      WCH5   =  .48407789E 03  KG   B    = 20621.87
   YR =   .50000020E-01     WN=   .15447073E 00      WCH6   =  .66242181E 03  KG   KEFF = 1.07111
   FR =   .52216408E 02     FS=   .49980520E 02      WCH8   =  .12101931E 05  KG
   FSP=   .50485375E 02     RS=   .20850818E-01      TOTINV=  .52993722E 05  KG
   WKP=   .32219558E 00     YS=   .51405369E-01      TRES   =  .10148864E 04  DAYS
   WNP=   .15603104E 00                              TCYC   =  .25372159E 03  DAYS

     RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE        5.53547E-01  2.45327E-02  2.75805E 00  3.47570E-01
2.31730E-03   4.00001E-02  1.73886E-02  2.68845E 01  3.77928E-02  1.63548E-02  2.39769E 01  4.00001E-02  8.39111E-02  2.58541E 01
2.53720E-03   4.00001E-02  1.80233E-02  2.70481E 01  3.77684E-02  1.70729E-02  2.41406E 01  4.00001E-02  8.36667E-02  2.56904E 01
2.81950E-03   4.00001E-02  1.88051E-02  2.72602E 01  3.77383E-02  1.79563E-02  2.43526E 01  4.00001E-02  8.33765E-02  2.54784E 01
3.20520E-03   4.00001E-02  1.98229E-02  2.75537E 01  3.76992E-02  1.91043E-02  2.46462E 01  4.00001E-02  8.30156E-02  2.51849E 01
```

TABLE L.22 Steady-State Flowsheet Characteristics

R_R = 0.04, y_R = 0.08

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800     NTAR=   4
   FRLFB=  .010             FRLC=   .003     FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =   .39999955E-01     WK=   .36511227E 00      WCH5   =  .46867881E 03  KG   B    = 14812.17
   YR =   .80000060E-01     WN=   .22086492E 00      WCH6   =  .10692232E 04  KG   KEFF = 1.05945
   FR =   .72696999E 02     FS=   .70147554E 02      WCH8   =  .11716988E 05  KG
   FSP=   .70856116E 02     RS=   .24795367E-01      TOTINV=  .52981120E 05  KG
   WKP=   .36880028E 00     YS=   .81086208E-01      TRES   =  .72879384E 03  DAYS
   WNP=   .22309588E 00                              TCYC   =  .18219854E 03  DAYS

     RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE        5.06378E-01  5.71740E-02  3.27641E 00  3.16936E-01
2.31730E-03   4.00000E-02  2.79202E-02  2.94674E 01  3.73878E-02  2.38010E-02  2.59812E 02  4.00000E-02  1.12491[illegible]E-01  [illegible]E 01
2.53720E-03   4.00000E-02  2.88093E-02  2.96635E 01  3.73539E-02  2.48987E-02  2.82672E 02  4.00000E-02  1.1268[illegible]E-01  4.37706E 01
2.81950E-03   4.00000E-02  2.99033E-02  2.98941E 01  3.73114E-02  2.62133E-02  2.85070E 02  4.00000E-02  1.125[illegible]E-01  [illegible]E 01
3.20520E-03   4.00000E-02  3.13254E-02  3.02264E 01  3.72567E-02  2.72880E-02  2.87405E 02  4.00000E-02  1.14059[illegible]E-01  [illegible]E 01
```

TABLE L.23 Steady-State Flowsheet Characteristics

$R_R = 0.04$, $y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=    .800      NTAR=   4
   FRLFB=  .010             FRLC=  .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .39999955E-01     WK=  .42004849E 00     WCH5   =  .44815787E 03  KG     B    = 9273.32
   YR =  .12000008E 00     WN=  .30138891E 00     WCH6   =  .15889263E 04  KG     KEFF = 1.04640
   FR =  .11611804E 03     FS=  .11300822E 03     WCH8   =  .11203569E 05  KG
   FSP=  .11414972E 03     RS=  .29298740E-01     TOTINV=  .52964173E 05  KG
   WKP=  .42429141E 00     YS=  .12087801E 00     TRES   =  .45612385E 03  DAYS
   WNP=  .30443325E 00                            TCYC   =  .11403089E 03  DAYS

    RW           R           Y            F            X            YW           FW           RP           YP           FP

   NONE      4.20273E-01  9.67707E-02  4.27100E 00  2.67274E-01
2.31730E-03  4.00000E-02  4.23239E-02  3.29404E 01  3.68237E-02  3.31788E-02  2.83314E 01  4.00000E+02  1.50938E-01  8.43388E 01
2.53720E-03  4.00000E-02  4.34966E-02  3.31552E 01  3.67886E-02  3.46096E-02  2.85462E 01  4.00000E+02  1.50152E-01  8.41251E 01
2.81950E-03  4.00000E-02  4.49379E-02  3.34325E 01  3.67331E-02  3.63669E-02  2.88235E 01  4.00000E+02  1.49930E-01  8.38467E 01
3.20520E-03  4.00000E-02  4.68090E-02  3.38149E 01  3.66612E-02  3.86455E-02  2.92059E 01  4.00000E+02  1.49659E-01  8.34643E 01
```

TABLE L.24 Steady-State Flowsheet Characteristics

$R_R = 0.04$, $y_R = 0.20$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=    .800      NTAR=   4
   FRLFB=  .010             FRLC=  .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .39999962E-01     WK=  .53919878E 00     WCH5   =  .40715586E 03  KG     B    = 1957.47
   YR =  .19999999E 00     WN=  .45367981E 00     WCH6   =  .26465154E 04  KG     KEFF = 1.01364
   FR =  .55009805E 03     FS=  .54225472E 03     WCH8   =  .10178906E 05  KG
   FSP=  .54773206E 03     RS=  .37194644E-01     TOTINV=  .52930309E 05  KG
   WKP=  .54464523E 00     YS=  .20036085E 00     TRES   =  .96219772E 02  DAYS
   WNP=  .45826244E 00                            TCYC   =  .24054943E 02  DAYS

    RW           R           Y            F            X            YW           FW           RP           YP           FP

   NONE      1.65764E-01  1.85336E-01  1.33443E 01  1.15840E-01
2.31730E-03  4.00000E-02  9.37372E-02  4.77451E 01  3.48562E-02  5.11713E-02  3.27789E 01  4.00000E+02  2.09590E-01  5.07854E 02
2.53720E-03  4.00000E-02  9.49829E-02  4.80201E 01  3.48083E-02  5.33352E-02  3.30539E 01  4.00000E+02  2.09935E-01  5.07579E 02
2.81950E-03  4.00000E-02  9.65103E-02  4.83741E 01  3.47496E-02  5.59882E-02  3.34079E 01  4.00000E+02  2.09870E-01  5.07225E 02
3.20520E-03  4.00000E-02  9.84878E-02  4.88605E 01  3.46735E-02  5.94204E-02  3.38943E 01  4.00000E+02  2.09788E-01  5.06739E 02
```

TABLE L.25 Steady-State Flowsheet Characteristics

$R_R = 0.05$, $y_R = 0.0$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=    .800      NTAR=   4
   FRLFB=  .010             FRLC=  .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .50000001E-01     WK=  .18131489E 00     WCH5   =  .63105679E 03  KG     B    = 50711.56
   YR =  .00000000E 00     WN=  .18046910E-01     WCH6   =  .00000000E 00  KG     KEFF = 1.12766
   FR =  .21233818E 02     FS=  .19611970E 02     WCH8   =  .12621135E 05  KG
   FSP=  .19810071E 02     RS=  .12548083E-01     TOTINV=  .53008769E 05  KG
   WKP=  .18314636E 00     YS=  .65322419E-02     TRES   =  .24964313E 04  DAYS
   WNP=  .18229202E-01                            TCYC   =  .62410782E 03  DAYS

    RW           R           Y            F            X            YW           FW           RP           YP           FP

   NONE      6.59439E-01 -6.98458E-02  1.83419E 00  4.25142E-01
2.31730E-03  5.00000E-02 -5.03666E-03  1.70382E 01  4.78589E-02  2.78725E-03  1.51454E 01  5.00000E-02  1.94685E-02  4.40792E 00
2.53720E-03  5.00000E-02 -4.89518E-03  1.71136E 01  4.78522E-02  2.88770E-03  1.52207E 01  5.00000E-02  1.93358E-02  4.33258E 00
2.81950E-03  5.00000E-02 -4.71915E-03  1.72112E 01  4.78438E-02  3.03586E-03  1.53184E 01  5.00000E-02  1.91792E-02  4.23492E 00
3.20520E-03  5.00000E-02 -4.48720E-03  1.73464E 01  4.78327E-02  3.22838E-03  1.54536E 01  5.00000E-02  1.89858E-02  4.09973E 00
```

TABLE L.26 Steady-State Flowsheet Characteristics

$R_R = 0.05,\ y_R = 0.01$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .49999940E-01       WK=  .20526301E 00      WCH5   =  .62469692E 03  KG      B    = 44462.15
   YR =  .99999814E-02       WN=  .45064483E-01      WCH6   =  .13251137E 03  KG      KEFF = 1.11115
   FR =  .24218351E 02       FS=  .22501267E 02      WCH8   =  .12493953E 05  KG
   FSP=  .22728553E 02       RS=  .15190855E-01      TOTINV=  .53004646E 05  KG
   WKP=  .20733638E 00       YS=  .14772625E-01      TRES   =  .21886150E 04  DAYS
   WNP=  .45519681E-01                               TCYC   =  .54715375E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      6.70185E-01 -4.48116E-02  1.95927E 00  4.19245E-01
2.31730E-03  4.99999E-02  2.08529E-04  1.80477E 01  4.76091E-02  5.65297E-03  1.60212E 01  4.99999E-02  3.75564E-02  6.41279E 00
2.53720E-03  4.99999E-02  4.50957E-04  1.81295E 01  4.75975E-02  5.89827E-03  1.61029E 01  4.99999E-02  3.73443E-02  6.33106E 00
2.81950E-03  4.99999E-02  7.50715E-04  1.82353E 01  4.75832E-02  6.19994E-03  1.62087E 01  4.99999E-02  3.70935E-02  6.22523E 00
3.20520E-03  4.99999E-02  1.14274E-03  1.83816E 01  4.75646E-02  6.59179E-03  1.63551E 01  4.99999E-02  3.67829E-02  6.07890E 00
```

TABLE L.27 Steady-State Flowsheet Characteristics

$R_R = 0.05,\ y_R = 0.025$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .49999996E-01       WK=  .23752822E 00      WCH5   =  .61515914E 03  KG      B    = 36985.99
   YR =  .24999993E-01       WN=  .83626971E-01      WCH6   =  .33123946E 03  KG      KEFF = 1.09745
   FR =  .29113728E 02       FS=  .27266082E 02      WCH8   =  .12303184E 05  KG
   FSP=  .27541497E 02       RS=  .18796100E-01      TOTINV=  .52998329E 05  KG
   WKP=  .23992750E 00       YS=  .28280425E-01      TRES   =  .18203896E 04  DAYS
   WNP=  .84471689E-01                               TCYC   =  .45509741E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      6.75021E-01 -1.68203E-02  2.13878E 00  4.09771E-01
2.31730E-03  5.00000E-02  6.83212E-03  1.93935E 01  4.72937E-02  9.67599E-03  1.71732E 01  5.00000E-02  6.01941E-02  1.00113E 01
2.53720E-03  5.00000E-02  7.21581E-03  1.94842E 01  4.72754E-02  1.00941E-02  1.72638E 01  5.00000E-02  5.99281E-02  9.92068E 00
2.81950E-03  5.00000E-02  7.68878E-03  1.96014E 01  4.72529E-02  1.06081E-02  1.73811E 01  5.00000E-02  5.96126E-02  9.80347E 00
3.20520E-03  5.00000E-02  8.30501E-03  1.97632E 01  4.72236E-02  1.12754E-02  1.75429E 01  5.00000E-02  5.92210E-02  9.64164E 00
```

TABLE L.28 Steady-State Flowsheet Characteristics

$R_R = 0.05,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .50000245E-01       WK=  .27963549E 00      WCH5   =  .59926985E 03  KG      B    = 28384.34
   YR =  .49999950E-01       WN=  .14122988E 00      WCH6   =  .66234710E 03  KG      KEFF = 1.08455
   FR =  .37936410E 02       FS=  .35895839E 02      WCH8   =  .11985338E 05  KG
   FSP=  .36258424E 02       RS=  .23608373E-01      TOTINV=  .52987821E 05  KG
   WKP=  .28246010E 00       YS=  .52198329E-01      TRES   =  .13967537E 04  DAYS
   WNP=  .14265645E 00                               TCYC   =  .34918842E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      6.63773E-01  1.73905E-02  2.41993E 00  3.92018E-01
2.31730E-03  5.00002E-02  1.62809E-02  2.12089E 01  4.68440E-02  1.59308E-02  1.86816E 01  5.00002E-02  9.18043E-02  1.71069E 01
2.53720E-03  5.00002E-02  1.68820E-02  2.13126E 01  4.68154E-02  1.66146E-02  1.87853E 01  5.00002E-02  9.15116E-02  1.70032E 01
2.81950E-03  5.00002E-02  1.76214E-02  2.14465E 01  4.67801E-02  1.74548E-02  1.89192E 01  5.00002E-02  9.11638E-02  1.68693E 01
3.20520E-03  5.00002E-02  1.85826E-02  2.16310E 01  4.67344E-02  1.85447E-02  1.91037E 01  5.00002E-02  9.07308E-02  1.66848E 01
```

TABLE L.29 Steady-State Flowsheet Characteristics

$R_R = 0.05,\ y_R = 0.08$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800       NTAR=    4
   FRLFB=  .010             FRLC=   .003       FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .49999798E-01      WK=  .31786213E 00      WCH5   =  .58020527E 03  KG    B     = 21504.22
   YR =  .79999926E-01      WN=  .20223241E 00      WCH6   =  .10595083E 04  KG    KEFF = 1.07457
   FR =  .50073902E 02      FS=  .47814076E 02      WCH8   =  .11604152E 05  KG
   FSP=  .48297048E 02      RS=  .28066103E-01      TOTINV=  .52975463E 05  KG
   WKP=  .32107286E 00      YS=  .81743722E-01      TRES   =  .10579456E 04  DAYS
   WNP=  .20427516E 00                              TCYC   =  .26448639E 03  DAYS

    RW          R            Y            F            X            YW           FW           RP           YP           FP

   NONE      6.33237E-01  4.97967E-02  2.76056E 00  3.68412E-01
2.31730E-03  4.99998E-02  2.66452E-02  2.29988E 01  4.63500E-02  2.30727E-02  2.00953E 01  4.99998E-02  1.24499E-01  2.75758E 01
2.53720E-03  4.99998E-02  2.74865E-02  2.31167E 01  4.63100E-02  2.40556E-02  2.02131E 01  4.99998E-02  1.24211E-01  2.74579E 01
2.81950E-03  4.99998E-02  2.85202E-02  2.32686E 01  4.62608E-02  2.52623E-02  2.03650E 01  4.99998E-02  1.23868E-01  2.73061E 01
3.20520E-03  4.99998E-02  2.98619E-02  2.34773E 01  4.61969E-02  2.68265E-02  2.05737E 01  4.99998E-02  1.23440E-01  2.70973E 01
```

TABLE L.30 Steady-State Flowsheet Characteristics

$R_R = 0.05,\ y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800       NTAR=    4
   FRLFB=  .010             FRLC=   .003       FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .49999932E-01      WK=  .35855024E 00      WCH5   =  .55480509E 03  KG    B     = 15136.36
   YR =  .11999984E 00      WN=  .27611307E 00      WCH6   =  .15887597E 04  KG    KEFF = 1.06200
   FR =  .71139937E 02      FS=  .68561760E 02      WCH8   =  .11096117E 05  KG
   FSP=  .69254304E 02      RS=  .32846909E-01      TOTINV=  .52958725E 05  KG
   WKP=  .36217196E 00      YS=  .12153445E 00      TRES   =  .74443031E 03  DAYS
   WNP=  .27890209E 00                              TCYC   =  .18610758E 03  DAYS

    RW          R            Y            F            X            YW           FW           RP           YP           FP

   NONE      5.75191E-01  8.80152E-02  3.28957E 00  3.33017E-01
2.31730E-03  4.99999E-02  4.03277E-02  2.51578E 01  4.56986E-02  3.23176E-02  2.16632E 01  4.99999E-02  1.62926E-01  4.66935E 01
2.53720E-03  4.99999E-02  4.14595E-02  2.52937E 01  4.56447E-02  3.36808E-02  2.17991E 01  4.99999E-02  1.62669E-01  4.65576E 01
2.81950E-03  4.99999E-02  4.28488E-02  2.54683E 01  4.55786E-02  3.53528E-02  2.19737E 01  4.99999E-02  1.62362E-01  4.63830E 01
3.20520E-03  4.99999E-02  4.46495E-02  2.57078E 01  4.54928E-02  3.75177E-02  2.22132E 01  4.99999E-02  1.61980E-01  4.61435E 01
```

TABLE L.31 Steady-State Flowsheet Characteristics

$R_R = 0.05,\ y_R = 0.20$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800       NTAR=    4
   FRLFB=  .010             FRLC=   .003       FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .49999953E-01      WK=  .43460406E 00      WCH5   =  .50405107E 03  KG    B     = 6434.27
   YR =  .19999987E 00      WN=  .41577882E 00      WCH6   =  .26462683E 04  KG    KEFF = 1.03597
   FR =  .16735381E 03      FS=  .16361391E 03      WCH8   =  .10081031E 05  KG
   FSP=  .16526658E 03      RS=  .41146188E-01      TOTINV=  .52925400E 05  KG
   WKP=  .43899401E 00      YS=  .20111835E 00      TRES   =  .31624855E 03  DAYS
   WNP=  .41997861E 00                              TCYC   =  .79062137E 02  DAYS

    RW          R            Y            F            X            YW           FW           RP           YP           FP

   NONE      3.93040E-01  1.66196E-01  5.41344E 00  2.35254E-01
2.31730E-03  5.00000E-02  7.33587E-02  3.04322E 01  4.41257E-02  5.03215E-02  2.45294E 01  5.00000E-02  2.27807E-01  1.38595E 02
2.53720E-03  5.00000E-02  7.49084E-02  3.06054E 01  4.40519E-02  5.24030E-02  2.47026E 01  5.00000E-02  2.27658E-01  1.38422E 02
2.81950E-03  5.00000E-02  7.68071E-02  3.08272E 01  4.39615E-02  5.49517E-02  2.49244E 01  5.00000E-02  2.27480E-01  1.38200E 02
3.20520E-03  5.00000E-02  7.92626E-02  3.11302E 01  4.38446E-02  5.82442E-02  2.52274E 01  5.00000E-02  2.27256E-01  1.37897E 02
```

TABLE L.32 Steady-State Flowsheet Characteristics

$R_R = 0.06$, $y_R = 0.0$

```
INPUT DATA

    PTH=  1346.0 MW(T)        PF=     .800       NTAR=    4
    FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
    RW(I), I=1,NTAR =
        .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

    RR =  .59999891E-01      WK=  .16884113E 00      WCH5   =  .75003569E 03  KG    B    = 59612.99
    YR =  .00000000E 00      WN=  .19756529E-01      WCH6   =  .00000000E 00  KG    KEFF = 1.14651
    FR =  .18063176E 02      FS=  .16487146E 02      WCH8   =  .12500617E 05  KG
    FSP=  .16653683E 02      RS=  .14556241E-01      TOTINV=  .53002612E 05  KG
    WKP=  .17054660E 00      YS=  .80193971E-02      TRES   =  .29342908E 04  DAYS
    WNP=  .19956090E-01                              TCYC   =  .73357271E 03  DAYS

      RW            R             Y            F            X            YW           FW           RP           YP           FP

    NONE      7.31546E-01 -7.52660E-02  1.75666E 00  4.54280E-01
  2.31730E-03 5.99999E-02 -6.27383E-03  1.45379E 01  5.69588E-02  3.18990E-03  1.27319E 01  5.99999E-02  2.46113E-02  3.70594E 00
  2.53720E-03 5.99999E-02 -6.11986E-03  1.45911E 01  5.69501E-02  3.32618E-03  1.27852E 01  5.99999E-02  2.44467E-02  3.65267E 00
  2.81950E-03 5.99999E-02 -5.92866E-03  1.46600E 01  5.69393E-02  3.49362E-03  1.28541E 01  5.99999E-02  2.42522E-02  3.58377E 00
  3.20520E-03 5.99999E-02 -5.67727E-03  1.47551E 01  5.69250E-02  3.71087E-03  1.29492E 01  5.99999E-02  2.40116E-02  3.48868E 00
```

TABLE L.33 Steady-State Flowsheet Characteristics

$R_R = 0.06$, $y_R = 0.01$

```
INPUT DATA

    PTH=  1346.0 MW(T)        PF=     .800       NTAR=    4
    FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
    RW(I), I=1,NTAR =
        .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

    RR =  .59999930E-01      WK=  .18895080E 00      WCH5   =  .74247736E 03  KG    B    = 53281.93
    YR =  .10000024E-01      WN=  .43677157E-01      WCH6   =  .13249643E 03  KG    KEFF = 1.12973
    FR =  .20209479E 02      FS=  .18553241E 02      WCH8   =  .12374637E 05  KG
    FSP=  .18740648E 02      RS=  .17275132E-01      TOTINV=  .52998444E 05  KG
    WKP=  .19085939E 00      YS=  .16108556E-01      TRES   =  .26224647E 04  DAYS
    WNP=  .44118340E-01                              TCYC   =  .65561367E 03  DAYS

      RW            R             Y            F            X            YW           FW           RP           YP           FP

    NONE      7.44981E-01 -5.09864E-02  1.85833E 00  4.48696E-01
  2.31730E-03 5.99999E-02 -1.02054E-03  1.52742E 01  5.66615E-02  5.85820E-03  1.33604E 01  5.99999E-02  4.27681E-02  5.13735E 00
  2.53720E-03 5.99999E-02 -7.76347E-04  1.53317E 01  5.66477E-02  6.10777E-03  1.34178E 01  5.99999E-02  4.25242E-02  5.07991E 00
  2.81950E-03 5.99999E-02 -4.74710E-04  1.54059E 01  5.66306E-02  6.41433E-03  1.34920E 01  5.99999E-02  4.22377E-02  5.00571E 00
  3.20520E-03 5.99999E-02 -8.06963E-05  1.55082E 01  5.66083E-02  6.81198E-03  1.35943E 01  5.99999E-02  4.18826E-02  4.90341E 00
```

TABLE L.34 Steady-State Flowsheet Characteristics

$R_R = 0.06$, $y_R = 0.025$

```
INPUT DATA

    PTH=  1346.0 MW(T)        PF=     .800       NTAR=    4
    FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
    RW(I), I=1,NTAR =
        .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

    RR =  .59999940E-01      WK=  .21659808E 00      WCH5   =  .73114275E 03  KG    B    = 45370.52
    YR =  .25000041E-01      WN=  .78297874E-01      WCH6   =  .33120228E 03  KG    KEFF = 1.11308
    FR =  .23733471E 02      FS=  .21967856E 02      WCH8   =  .12185725E 05  KG
    FSP=  .22189754E 02      RS=  .21106455E-01      TOTINV=  .52992278E 05  KG
    WKP=  .21878594E 00      YS=  .29413353E-01      TRES   =  .22328078E 04  DAYS
    WNP=  .79088762E-01                              TCYC   =  .55820194E 03  DAYS

      RW            R             Y            F            X            YW           FW           RP           YP           FP

    NONE      7.55538E-01 -2.34041E-02  2.00295E 00  4.40447E-01
  2.31730E-03 5.99999E-02  5.65847E-03  1.62755E 01  5.62834E-02  9.64599E-03  1.42068E 01  5.99999E-02  6.59070E-02  7.69534E 00
  2.53720E-03 5.99999E-02  6.03142E-03  1.63389E 01  5.62623E-02  1.00553E-02  1.42702E 01  5.99999E-02  6.56090E-02  7.63195E 00
  2.81950E-03 5.99999E-02  6.49074E-03  1.64206E 01  5.62363E-02  1.05579E-02  1.43520E 01  5.99999E-02  6.52553E-02  7.55017E 00
  3.20520E-03 5.99999E-02  7.08852E-03  1.65332E 01  5.62025E-02  1.12095E-02  1.44645E 01  5.99999E-02  6.48158E-02  7.43762E 00
```

TABLE L.35 Steady-State Flowsheet Characteristics

$R_R = 0.06,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730     .00253720     .00281950     .00320520

CALCULATED RESULTS

   RR =  .60000077E-01     WK=  .25358837E 00     WCH5   =  .71226128E 03  KG    B    = 35849.63
   YR =  .50000068E-01     WN=  .13105800E 00     WCH6   =  .66227816E 03  KG    KEFF = 1.09744
   FR =  .30036571E 02     FS=  .28111088E 02     WCH8   =  .11871008E 06  KG
   FSP=  .28395038E 02     RS=  .28375043E-01     TOTINV=  .52982180E 05  KG
   WKP=  .25614987E 00     YS=  .53119645E-01     TRES   =  .17639224E 04  DAYS
   WNP=  .13238182E 00                            TCYC   =  .44098060E 03  DAYS

     RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE       7.54881E-01  1.06017E-02  2.22585E 00  4.25600E-01
 2.31730E-03  6.00001E-02  1.51594E-02  1.76569E 01  5.57458E-02  1.58125E-02  1.53469E 01  6.00001E+02  9.85152E-02  1.26801E 01
 2.53720E-03  6.00001E-02  1.57338E-02  1.77293E 01  5.57132E-02  1.62708E-02  1.54193E 01  6.00001E+02  9.81863E-02  1.26077E 01
 2.81950E-03  6.00001E-02  1.64399E-02  1.78225E 01  5.56733E-02  1.70787E-02  1.55126E 01  6.00001E+02  9.77951E-02  1.25144E 01
 3.20520E-03  6.00001E-02  1.73564E-02  1.79505E 01  5.56214E-02  1.81264E-02  1.56406E 01  6.00001E+02  9.73076E-02  1.23864E 01
```

TABLE L.36 Steady-State Flowsheet Characteristics

$R_R = 0.06,\ y_R = 0.08$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730     .00253720     .00281950     .00320520

CALCULATED RESULTS

   RR =  .60000084E-01     WK=  .28669414E 00     WCH5   =  .68960919E 03  KG    B    = 28093.29
   YR =  .79999663E-01     WN=  .18766904E 00     WCH6   =  .10593934E 04  KG    KEFF = 1.08560
   FR =  .38329441E 02     FS=  .36230904E 02     WCH8   =  .11493470E 05  KG
   FSP=  .36596873E 02     RS=  .31265796E-01     TOTINV=  .52969892E 05  KG
   WKP=  .28959004E 00     YS=  .82550070E-01     TRES   =  .13819636E 04  DAYS
   WNP=  .18956469E 00                            TCYC   =  .34549089E 03  DAYS

     RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE       7.37289E-01  4.27677E-02  2.48183E 00  4.06240E-01
 2.31730E-03  6.00001E-02  2.54988E-02  1.90051E 01  5.51605E-02  2.25112E-02  1.64149E 01  6.00001E-02  1.32558E-01  1.97077E 01
 2.53720E-03  6.00001E-02  2.63003E-02  1.90874E 01  5.51151E-02  2.34535E-02  1.64972E 01  6.00001E-02  1.32227E-01  1.96253E 01
 2.81950E-03  6.00001E-02  2.72843E-02  1.91932E 01  5.50594E-02  2.46091E-02  1.66030E 01  6.00001E-02  1.31834E-01  1.95196E 01
 3.20520E-03  6.00001E-02  2.85599E-02  1.93380E 01  5.49872E-02  2.61051E-02  1.67478E 01  6.00001E-02  1.31342E-01  1.93747E 01
```

TABLE L.37 Steady-State Flowsheet Characteristics

$R_R = 0.06,\ y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800      NTAR=   4
   FRLFB=  .010              FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730     .00253720     .00281950     .00320520

CALCULATED RESULTS

   RR =  .60000322E-01     WK=  .32200857E 00     WCH5   =  .65942170E 03  KG    B    = 20670.63
   YR =  .12000000E 00     WN=  .25699352E 00     WCH6   =  .15885988E 04  KG    KEFF = 1.07448
   FR =  .52093243E 02     FS=  .49757589E 02     WCH8   =  .10990303E 05  KG
   FSP=  .50260191E 02     RS=  .36627385E-01     TOTINV=  .52953292E 05  KG
   WKP=  .32526118E 00     YS=  .12228975E 00     TRES   =  .10165098E 04  DAYS
   WNP=  .25958942E 00                            TCYC   =  .25412745E 03  DAYS

     RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE       6.95273E-01  8.01159E-02  2.85659E 00  3.77267E-01
 2.31730E-03  6.00003E-02  3.88492E-02  2.06185E 01  5.44050E-02  3.14513E-02  1.76131E 01  6.00003E-02  1.72295E-01  3.19957E 01
 2.53720E-03  6.00003E-02  3.99300E-02  2.07136E 01  5.43439E-02  3.27552E-02  1.77082E 01  6.00003E-02  1.71991E-01  3.19005E 01
 2.81950E-03  6.00003E-02  4.12554E-02  2.08355E 01  5.42688E-02  3.43531E-02  1.78301E 01  6.00003E-02  1.71629E-01  3.17786E 01
 3.20520E-03  6.00003E-02  4.29711E-02  2.10020E 01  5.41717E-02  3.64193E-02  1.79966E 01  6.00003E-02  1.71175E-01  3.16121E 01
```

TABLE L.38 Steady-State Flowsheet Characteristics

$R_R = 0.06,\ y_R = 0.20$

```
INPUT DATA

   PTH=  1346.0 MW(T)      PF=     .800      NTAR=   4
   FRLFB=  .010            FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .59999759E-01     WK=  .38095427E 00     WCH5   =  .59909821E 03  KG    B    = 10651.06
   YR =  .20000000E 00     WN=  .38784709E 00     WCH6   =  .26460270E 04  KG    KEFF = 1.05124
   FR =  .10109789E 03     FS=  .98098924E 02     WCH8   =  .99850100E 04  KG
   FSP=  .99089824E 02     RS=  .45556325E-01     TOTINV=  .52920540E 05  KG
   WKP=  .38480229E 00     YS=  .20190790E 00     TRES   =  .52345839E 03  DAYS
   WNP=  .39176475E 00                            TCYC   =  .13086460E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      5.55519E-01  1.53325E-01  4.00994E 00  3.02371E-01
2.31730E-03  5.99998E-02  6.84524E-02  2.40099E 01  5.27289E-02  4.91951E-02  1.97065E 01  5.99998E-02  2.40441E-01  7.80990E 01
2.53720E-03  5.99998E-02  6.99994E-02  2.41313E 01  5.26413E-02  5.11959E-02  1.98280E 01  5.99998E-02  2.40231E-01  7.79775E 01
2.81950E-03  5.99998E-02  7.18932E-02  2.42864E 01  5.25341E-02  5.36434E-02  1.99830E 01  5.99998E-02  2.39979E-01  7.78225E 01
3.20520E-03  5.99998E-02  7.43395E-02  2.44972E 01  5.23957E-02  5.68015E-02  2.01939E 01  5.99998E-02  2.39663E-01  7.75116E 01
```

TABLE L.39 Steady-State Flowsheet Characteristics

$R_R = 0.08,\ y_R = 0.025$

```
INPUT DATA

   PTH=  1346.0 MW(T)      PF=     .800      NTAR=   4
   FRLFB=  .010            FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .80000164E-01     WK=  .19355697E 00     WCH5   =  .95659917E 03  KG    B    = 59891.32
   YR =  .25C00044E-01     WN=  .71452809E-01     WCH6   =  .33113046E 03  KG    KEFF = 1.14050
   FR =  .17979232E 02     FS=  .16304966E 02     WCH8   =  .11957465E 05  KG
   FSP=  .16469663E 02     RS=  .26439064E-01     TOTINV=  .52980778E 05  KG
   WKP=  .19551209E 00     YS=  .31889061E-01     TRES   =  .29467764E 04  DAYS
   WNP=  .72174555E-01                            TCYC   =  .73669411E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      8.91405E-01 -3.55834E-02  1.85406E 00  4.88063E-01
2.31730E-03  8.00002E-02  3.02714E-03  1.26014E 01  7.38500E-02  9.58679E-03  1.06985E 01  8.00002E-02  7.48210E-02  5.55767E 00
2.53720E-03  8.00002E-02  3.38257E-03  1.26384E 01  7.38237E-02  9.98260E-03  1.07355E 01  8.00002E-02  7.44887E-02  5.52066E 00
2.81950E-03  8.00002E-02  3.81973E-03  1.26860E 01  7.37913E-02  1.04678E-02  1.07831E 01  8.00002E-02  7.40936E-02  5.47307E 00
3.20520E-03  8.00002E-02  4.38779E-03  1.27512E 01  7.37492E-02  1.10955E-02  1.08483E 01  8.00002E-02  7.36015E-02  5.40786E 00
```

TABLE L.40 Steady-State Flowsheet Characteristics

$R_R = 0.08,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)      PF=     .800      NTAR=   4
   FRLFB=  .010            FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .79999643E-01     WK=  .22096319E 00     WCH5   =  .93189304E 03  KG    B    = 49810.93
   YR =  .49999803E-01     WN=  .11647092E 00     WCH6   =  .66213451E 03  KG    KEFF = 1.12130
   FR =  .21617746E 02     FS=  .19824296E 02     WCH8   =  .11648715E 05  KG
   FSP=  .20024542E 02     RS=  .31994475E-01     TOTINV=  .52970969E 05  KG
   WKP=  .22319515E 00     YS=  .55268507E-01     TRES   =  .24503465E 04  DAYS
   WNP=  .11764739E 00                            TCYC   =  .61258662E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE      9.03613E-01 -1.97418E-03  2.00963E 00  4.75620E-01
2.31730E-03  7.99996E-02  1.28113E-02  1.34492E 01  7.31248E-02  1.52011E-02  1.13802E 01  7.99996E-02  1.09650E-01  8.38477E 00
2.53720E-03  7.99996E-02  1.33470E-02  1.34912E 01  7.30851E-02  1.58250E-02  1.14223E 01  7.99996E-02  1.09272E-01  8.34272E 00
2.81950E-03  7.99996E-02  1.40045E-02  1.35451E 01  7.30364E-02  1.65893E-02  1.14762E 01  7.99996E-02  1.08821E-01  8.28880E 00
3.20520E-03  7.99996E-02  1.48566E-02  1.36188E 01  7.29733E-02  1.75776E-02  1.15499E 01  7.99996E-02  1.08259E-01  8.21512E 00
```

TABLE L.41 Steady-State Flowsheet Characteristics

$R_R = 0.08$, $y_R = 0.08$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .79999641E-01      WK=  .24877397E 00       WCH5   =  .90226054E 03  KG       B    = 40406.43
   YR =  .8CC00066E-01      WN=  .16654501E 00       WCH6   =  .10591808E 04  KG       KEFF = 1.10564
   FR =  .26649227E 02      FS=  .24724770E 02       WCH8   =  .11278307E 05  KG
   FSP=  .24974515E 02      RS=  .37847260E-01       TOTINV=  .52958994E 05  KG
   WKP=  .25128684E 00      YS=  .84470743E-01       TRES   =  .19872619E 04  DAYS
   WNP=  .16822728E 00                               TCYC   =  .49681548E 03  DAYS


    RW           R             Y             F              X             YW            FW            RP            YP            FP


   NONE      9.02753E-01  2.95487E-02  2.19095E 00  4.60426E-01
2.31730E-03  7.99996E-02  2.31664E-02  1.43534E 01  7.23577E-02  2.16347E-02  1.20885E 01  7.99996E-02  1.44937E-01  1.25623E 01
2.53720E-03  7.99996E-02  2.39045E-02  1.44014E 01  7.23031E-02  2.25166E-02  1.21365E 01  7.99996E-02  1.44554E-01  1.25144E 01
2.81950E-03  7.99996E-02  2.48094E-02  1.44627E 01  7.22360E-02  2.35964E-02  1.21978E 01  7.99996E-02  1.44097E-01  1.24531E 01
3.20520E-03  7.99996E-02  2.59804E-02  1.45462E 01  7.21493E-02  2.49916E-02  1.22813E 01  7.99996E-02  1.43526E-01  1.23695E 01
```

TABLE L.42 Steady-State Flowsheet Characteristics

$R_R = 0.08$, $y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .79999931E-01      WK=  .27735816E 00       WCH5   =  .86277534E 03  KG       B    = 31294.39
   YR =  .11999975E 00      WN=  .22870448E 00       WCH6   =  .15882885E 04  KG       KEFF = 1.09187
   FR =  .34408721E 02      FS=  .32317927E 02       WCH8   =  .10784701E 05  KG
   FSP=  .32644372E 02      RS=  .44195672E-01       TOTINV=  .52943059E 05  KG
   WKP=  .28015976E 00      YS=  .12408598E 00       TRES   =  .15386523E 04  DAYS
   WNP=  .23101463E 00                               TCYC   =  .38466308E 03  DAYS


    RW           R             Y             F              X             YW            FW            RP            YP            FP


   NONE      8.83833E-01  6.57637E-02  2.43488E 00  4.38313E-01
2.31730E-03  7.99999E-02  3.63325E-02  1.54056E 01  7.13827E-02  3.01072E-02  1.28740E 01  7.99999E-02  1.86621E-01  1.93472E 01
2.53720E-03  7.99999E-02  3.73272E-02  1.54612E 01  7.13090E-02  3.13235E-02  1.29296E 01  7.99999E-02  1.86257E-01  1.92916E 01
2.81950E-03  7.99999E-02  3.85453E-02  1.55321E 01  7.12188E-02  3.28115E-02  1.30005E 01  7.99999E-02  1.85822E-01  1.92207E 01
3.20520E-03  7.99999E-02  4.01194E-02  1.56284E 01  7.11022E-02  3.47321E-02  1.30969E 01  7.99999E-02  1.85278E-01  1.91244E 01
```

TABLE L.43 Steady-State Flowsheet Characteristics

$R_R = 0.08$, $y_R = 0.20$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .79999926E-01      WK=  .32146507E 00       WCH5   =  .78386789E 03  KG       B    = 18750.23
   YR =  .19999962E 00      WN=  .34717070E 00       WCH6   =  .26455501E 04  KG       KEFF = 1.07115
   FR =  .57428618E 02      FS=  .54957801E 02       WCH8   =  .97983575E 04  KG
   FSP=  .55512931E 02      RS=  .54618983E-01       TOTINV=  .52911102E 05  KG
   WKP=  .32471220E 00      YS=  .20366843E 00       TRES   =  .92133684E 03  DAYS
   WNP=  .35067748E 00                               TCYC   =  .23033421E 03  DAYS

    RW           R             Y             F              X             YW            FW            RP            YP            FP


   NONE      7.97926E-01  1.33785E-01  3.04510E 00  3.84429E-01
2.31730E-03  7.99999E-02  6.37930E-02  1.74298E 01  6.93486E-02  4.71881E-02  1.42203E 01  7.99999E-02  2.58513E-01  4.05731E 01
2.53720E-03  7.99999E-02  6.52533E-02  1.75013E 01  6.92404E-02  4.90595E-02  1.42919E 01  7.99999E-02  2.58226E-01  4.05016E 01
2.81950E-03  7.99999E-02  6.70385E-02  1.75922E 01  6.91082E-02  5.13454E-02  1.43828E 01  7.99999E-02  2.57882E-01  4.04107E 01
3.20520E-03  7.99999E-02  6.93408E-02  1.77151E 01  6.89377E-02  5.42900E-02  1.45056E 01  7.99999E-02  2.57452E-01  4.02978E 01
```

TABLE L.44 Steady-State Flowsheet Characteristics

$R_R = 0.08,\ y_R = 0.28$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .80000435E-01      WK=  .36101304E 00     WCH5   =  .70505769E 03  KG    B    = 10026.80
   YR =  .28000041E 00      WN=  .46636439E 00     WCH6   =  .37015418E 04  KG    KEFF = 1.04893
   FR =  .10739219E 03      FS=  .10428114E 03     WCH8   =  .88131732E 04  KG
   FSP=  .10533449E 03      RS=  .63979132E-01     TOTINV=  .52879091E 05  KG
   WKP=  .36465964E 00      YS=  .28282907E 00     TRES   =  .49239234E 03  DAYS
   WNP=  .47107514E 00                             TCYC   =  .12309809E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP


   NONE      6.37393E-01  2.09516E-01  4.18496E 00  3.07714E-01
2.31730E-03  8.00004E-02  9.86915E-02  1.99916E 01  6.67639E-02  6.50523E-02  1.54947E 01  8.00004E-02  3.20969E-01  8.84745E 01
2.53720E-03  8.00004E-02  1.00505E-01  2.00811E 01  6.66296E-02  6.75819E-02  1.55843E 01  8.00004E-02  3.20782E-01  8.83850E 01
2.81950E-03  8.00004E-02  1.02718E-01  2.01945E 01  6.64657E-02  7.06667E-02  1.56976E 01  8.00004E-02  3.20559E-01  8.82716E 01
3.20520E-03  8.00004E-02  1.05567E-01  2.03470E 01  6.62547E-02  7.46322E-02  1.58502E 01  8.00004E-02  3.20278E-01  8.81191E 01
```

TABLE L.45 Steady-State Flowsheet Characteristics

$R_R = 0.10,\ y_R = 0.05$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010      FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .10000031E 00      WK=  .20597275E 00     WCH5   =  .11434573E 04  KG    B    = 60921.27
   YR =  .50000191E-01      WN=  .10749264E 00     WCH6   =  .66200235E 03  KG    KEFF = 1.13994
   FR =  .17675272E 02      FS=  .15948383E 02     WCH8   =  .11434537E 05  KG
   FSP=  .16109478E 02      RS=  .39002185E-01     TOTINV=  .52959985E 05  KG
   WKP=  .20805328E 00      YS=  .57634181E-01     TRES   =  .29962755E 04  DAYS
   WNP=  .10857843E 00                             TCYC   =  .74906886E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP


   NONE      1.02624E 00 -1.39561E-02  1.90364E 00  5.13543E-01
~~2.31730E-03  1.00000E-01  9.98172E-03  1.11126E 01  9.00019E-02  1.47077E-02  9.16128E 00  1.00000E-01  1.15987E-01  6.73940E 00~~
2.53720E-03  1.00000E-01  1.04819E-02  1.11408E 01  8.99564E-02  1.52996E-02  9.18949E 00  1.00000E-01  1.15602E-01  6.71119E 00
2.81950E-03  1.00000E-01  1.10953E-02  1.11769E 01  8.99007E-02  1.60239E-02  9.22557E 00  1.00000E-01  1.15143E-01  6.67512E 00
3.20520E-03  1.00000E-01  1.18894E-02  1.12260E 01  8.98285E-02  1.69589E-02  9.27470E 00  1.00000E-01  1.14569E-01  6.62598E 00
```

TABLE L.46 Steady-State Flowsheet Characteristics

~~$R_R = 0.10,\ y_R = 0.08$~~

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
~~ FRLFB=  .010             FRLC=   .003      FRLRU=  .010      FRLRP=  .010~~
   RW(I), I=1,NTAR =
      .00231730      .00253720      .00281950      .00320520

~~CALCULATED RESULTS~~

~~ RR =  .99999938E-01      WK=  .22540833E 00     WCH5   =  .11071018E 04  KG    B    = 51906.74~~
   YR =  .80000043E-01      WN=  .15166329E 00     WCH6   =  .10589682E 04  KG    KEFF = 1.12577
~~ FR =  .20744900E 02      FS=  .18917356E 02     WCH8   =  .11071025E 05  KG~~
   FSP=  .19108440E 02      RS=  .44417131E-01     TOTINV=  .52948380E 05  KG
~~ WKP=  .22768519E 00      YS=  .86719407E-01     TRES   =  .25523565E 04  DAYS~~
   WNP=  .15319524E 00                             TCYC   =  .63808912E 03  DAYS

~~  RW           R            Y            F            X            YW           FW           RP           YP           FP~~


   NONE      1.03661E 00  1.75366E-02  2.03499E 00  5.00063E-01
~~2.31730E-03  9.99999E-02  2.07865E-02  1.17005E 01  8.90194E-02  2.10866E-02  9.60890E 00  9.99999E-02  1.54885E-01  9.25187E 00~~
2.53720E-03  9.99999E-02  2.14800E-02  1.17326E 01  8.89563E-02  2.19295E-02  9.64100E 00  9.99999E-02  1.54469E-01  9.21978E 00
~~2.81950E-03  9.99999E-02  2.23293E-02  1.17735E 01  8.88791E-02  2.29603E-02  9.68193E 00  9.99999E-02  1.53973E-01  9.17884E 00~~
3.20520E-03  9.99999E-02  2.34269E-02  1.18291E 01  8.87793E-02  2.42901E-02  9.73750E 00  9.99999E-02  1.53352E-[illegible]  9.12327E 00
```

TABLE L.47 Steady-State Flowsheet Characteristics

$R_R = 0.10,\ y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=  .003        FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720       .00281950      .00320520

CALCULATED RESULTS

   RR =  .99999907E-01       WK=  .25057033E 00      WCH5   =  .10586565E 04  KG    B      = 41231.54
   YR =  .12000024E 00       WN=  .20855709E 00      WCH6   =  .15879897E 04  KG    KEFF = 1.10904
   FR =  .26115932E 02       FS=  .24152929E 02      WCH8   =  .10586575E 05  KG
   FSP=  .24396898E 02       RS=  .51822986E-01      TOTINV=  .52932883E 05  KG
   WKP=  .25310135E 00       YS=  .12618248E 00      TRES   =  .20268425E 04  DAYS
   WNP=  .21066372E 00                               TCYC   =  .50671063E 03  DAYS

    RW           R            Y            F            X           YW           FW           RP           YP           FP

   NONE       1.03286E 00  5.28652E-02  2.22416E 00  4.81222E-01
2.31730E-03  9.99999E-02  3.39302E-02  1.24827E 01  8.78245E-02  2.91415E-02  1.01863E 01  9.99999E-02  1.97326E-01  1.38943E 01
2.53720E-03  9.99999E-02  3.48590E-02  1.25201E 01  8.77400E-02  3.02964E-02  1.02237E 01  9.99999E-02  1.96928E-01  1.38570E 01
2.81950E-03  9.99999E-02  3.59952E-02  1.25677E 01  8.76367E-02  3.17078E-02  1.02713E 01  9.99999E-02  1.96451E-01  1.38094E 01
3.20520E-03  9.99999E-02  3.74618E-02  1.26320E 01  8.75034E-02  3.35269E-02  1.03356E 01  9.99999E-02  1.95854E-01  1.37451E 01
```

TABLE L.48 Steady-State Flowsheet Characteristics

$R_R = 0.10,\ y_R = 0.20$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=  .003        FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720       .00281950      .00320520

CALCULATED RESULTS

   RR =  .99999724E-01       WK=  .28738365E 00      WCH5   =  .96185166E 03  KG    B      = 26460.79
   YR =  .19999985E 00       WN=  .31798577E 00      WCH6   =  .26450961E 04  KG    KEFF = 1.08595
   FR =  .40694176E 02       FS=  .38448489E 02      WCH8   =  .96185431E 04  KG
   FSP=  .38836858E 02       RS=  .63736269E-01      TOTINV=  .52901963E 05  KG
   WKP=  .29028652E 00       YS=  .20565457E 00      TRES   =  .12999885E 04  DAYS
   WNP=  .32119775E 00                               TCYC   =  .32499713E 03  DAYS

    RW           R            Y            F            X           YW           FW           RP           YP           FP

   NONE       9.82118E-01  1.18038E-01  2.65263E 00  4.37003E-01
2.31730E-03  9.99997E-02  6.07426E-02  1.39284E 01  8.53868E-02  4.56320E-02  1.11608E 01  9.99997E-02  2.71382E-01  2.71727E 01
2.53720E-03  9.99997E-02  6.21150E-02  1.39769E 01  8.52621E-02  4.74085E-02  1.12093E 01  9.99997E-02  2.71051E-01  2.71242E 01
2.81950E-03  9.99997E-02  6.37911E-02  1.40383E 01  8.51097E-02  4.95763E-02  1.12707E 01  9.99997E-02  2.70656E-01  2.70628E 01
3.20520E-03  9.99997E-02  6.59502E-02  1.41209E 01  8.49134E-02  5.23651E-02  1.13533E 01  9.99997E-02  2.70159E-01  2.69802E 01
```

TABLE L.49 Steady-State Flowsheet Characteristics

$R_R = 0.10,\ y_R = 0.28$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=  .003        FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
      .00231730      .00253720       .00281950      .00320520

CALCULATED RESULTS

   RR =  .10000000E 00       WK=  .31716653E 00      WCH5   =  .86516128E 03  KG    B      = 16118.96
   YR =  .28000030E 00       WN=  .42858616E 00      WCH6   =  .37009729E 04  KG    KEFF = 1.06622
   FR =  .66803330E 02       FS=  .64171441E 02      WCH8   =  .86516124E 04  KG
   FSP=  .64819638E 02       RS=  .74147692E-01      TOTINV=  .52870986E 05  KG
   WKP=  .32037023E 00       YS=  .28477785E 00      TRES   =  .79144236E 03  DAYS
   WNP=  .43291531E 00                               TCYC   =  .19786059E 03  DAYS

    RW           R            Y            F            X           YW           FW           RP           YP           FP

   NONE       8.70076E-01  1.87094E-01  3.29992E 00  3.78214E-01
2.31730E-03  1.00000E-01  9.21832E-02  1.55543E 01  8.25288E-02  6.31538E-02  1.20625E 01  1.00000E-01  3.36270E-01  5.19170E 01
2.53720E-03 10.00000E-02  9.39422E-02  1.56154E 01  8.23689E-02  6.55657E-02  1.21236E 01  1.00000E-01  3.36028E-01  5.18559E 01
2.81950E-03 10.00000E-02  9.60875E-02  1.56924E 01  8.21739E-02  6.85041E-02  1.22006E 01  1.00000E-01  3.35738E-01  5.17789E 01
3.20520E-03  1.00000E-01  9.88459E-02  1.57956E 01  8.19231E-02  7.22767E-02  1.23037E 01  1.00000E-01  3.35373E-01  5.16758E 01
```

TABLE L.50 Steady-State Flowsheet Chaaracteristics

$R_R = 0.12,\ y_R = 0.08$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .11999977E 00      WK=   .21418810E 00      WCH5   =  .13045507E 04  KG      B    = 60849.10
   YR =  .79999965E-01      WN=   .14181834E 00      WCH6   =  .10587671E 04  KG      KEFF = 1.14023
   FR =  .17696235E 02      FS=   .15922895E 02      WCH8   =  .10871276E 05  KG
   FSP=  .16083732E 02      RS=   .52586879E-01      TOTINV=  .52938376E 05  KG
   WKP=  .21635162E 00      YS=   .89068890E-01      TRES   =  .29915050E 04  DAYS
   WNP=  .14325085E 00                               TCYC   =  .74787625E 03  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE        1.15040E 00  5.95835E-03  1.95030E 00  5.31782E-01
 2.31730E-03  1.20000E-01  1.79071E-02  1.00504E 01  1.05224E-01  2.03803E-02  8.05244E 00  1.20000E-01  1.59774E-01  7.82283E 00
 2.53720E-03  1.20000E-01  1.85563E-02  1.00738E 01  1.05155E-01  2.11828E-02  8.07590E 00  1.20000E-01  1.59362E-01  7.79937E 00
 2.81950E-03  1.20000E-01  1.93507E-02  1.01037E 01  1.05069E-01  2.21634E-02  8.10576E 00  1.20000E-01  1.58870E-01  7.76951E 00
 3.20520E-03  1.20000E-01  2.03766E-02  1.01441E 01  1.04959E-01  2.34269E-02  8.14618E 00  1.20000E-01  1.58253E-01  7.72909E 00
```

TABLE L.51 Steady-State Flowsheet Characteristics

$R_R = 0.12,\ y_R = 0.12$

```
INPUT DATA

   PTH=  1346.0 MW(T)       PF=     .800      NTAR=   4
   FRLFB=  .010             FRLC=   .003      FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730      .00253720      .00281950      .00320520

CALCULATED RESULTS

   RR =  .12000010E 00      WK=   .23174963E 00      WCH5   =  .12474771E 04  KG      B    = 50733.67
   YR =  .11999998E 00      WN=   .19318486E 00      WCH6   =  .15876987E 04  KG      KEFF = 1.12629
   FR =  .21224564E 02      FS=   .19343603E 02      WCH8   =  .10395634E 05  KG
   FSP=  .19538993E 02      RS=   .59293977E-01      TOTINV=  .52923231E 05  KG
   WKP=  .23409053E 00      YS=   .12852589E 00      TRES   =  .24934896E 04  DAYS
   WNP=  .19513623E 00                               TCYC   =  .62337241E 03  DAYS

    RW            R            Y            F            X            YW           FW           RP           YP           FP

   NONE        1.15951E 00  4.12109E-02  2.09321E 00  5.14804E-01
 2.31730E-03  1.20000E-01  3.15661E-02  1.05953E 01  1.03761E-01  2.85109E-02  8.44425E 00  1.20000E-01  2.06426E-01  1.08415E 01
 2.53720E-03  1.20000E-01  3.24459E-02  1.06227E 01  1.03667E-01  2.98240E-02  8.47162E 00  1.20000E-01  2.06004E-01  1.08141E 01
 2.81950E-03  1.20000E-01  3.35213E-02  1.06574E 01  1.03551E-01  3.09829E-02  8.50634E 00  1.20000E-01  2.05500E-01  1.07794E 01
 3.20520E-03  1.20000E-01  3.49082E-02  1.07042E 01  1.03403E-01  3.27324E-02  8.55315E 00  1.20000E-01  2.04867E-01  1.07326E 01
```

TABLE L.52 Steady-State Flowsheet Characteristics

$R_R = 0.12$, $y_R = 0.20$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .12000010E 00    WK=  .26431276E 00    WCH5   =  .11334272E 04  KG    B    = 33853.49
   YR =  .19999988E 00    WN=  .29554647E 00    WCH6   =  .26446594E 04  KG    KEFF = 1.09954
   FR =  .31807647E 02    FS=  .29692660E 02    WCH8   =  .94452187E 04  KG
   FSP=  .29992586E 02    RS=  .72779146E-01    TOTINV=  .52893221E 05  KG
   WKP=  .26698259E 00    YS=  .20783167E 00    TRES   =  .16629089E 04  DAYS
   WNP=  .29853179E 00                          TCYC   =  .41572724E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE       1.13396E 00  1.04422E-01  2.43306E 00  4.75899E-01
2.31730E-03  1.20000E-01  5.81518E-02  1.17230E 01  1.00912E-01  4.44716E-02  9.20108E 00  1.20000E-01  2.81502E-01  2.04028E 01
2.53720E-03  1.20000E-01  5.94507E-02  1.17587E 01  1.00773E-01  4.61781E-02  9.23682E 00  1.20000E-01  2.81145E-01  2.03670E 01
2.81950E-03  1.20000E-01  6.10360E-02  1.18038E 01  1.00603E-01  4.82587E-02  9.28193E 00  1.20000E-01  2.80716E-01  2.03219E 01
3.20520E-03  1.20000E-01  6.30763E-02  1.18643E 01  1.00385E-01  5.09324E-02  9.34241E 00  1.20000E-01  2.80177E-01  2.02614E 01
```

TABLE L.53 Steady-State Flowsheet Chasacteristics

$R_R = 0.12$, $y_R = 0.28$

```
INPUT DATA

   PTH=  1346.0 MW(T)        PF=     .800       NTAR=   4
   FRLFB=  .010              FRLC=   .003       FRLRU=  .010       FRLRP=  .010
   RW(I), I=1,NTAR =
       .00231730       .00253720       .00281950       .00320520

CALCULATED RESULTS

   RR =  .12000018E 00    WK=  .28885999E 00    WCH5   =  .10195031E 04  KG    B    = 21989.25
   YR =  .28C00041E 00    WN=  .39958235E 00    WCH6   =  .37004213E 04  KG    KEFF = 1.08029
   FR =  .48969391E 02    FS=  .46566999E 02    WCH8   =  .84958465E 04  KG
   FSP=  .47037373E 02    RS=  .84311301E-01    TOTINV=  .52863084E 05  KG
   WKP=  .29177777E 00    YS=  .28685428E 00    TRES   =  .10795128E 04  DAYS
   WNP=  .40361853E 00                          TCYC   =  .26987819E 03  DAYS

    RW           R            Y            F            X            YW           FW           RP           YP           FP

   NONE       1.05563E 00  1.69643E-01  2.89209E 00  4.26415E-01
2.31730E-03  1.20000E-01  8.82386E-02  1.29228E 01  9.76889E-02  6.16405E-02  9.89139E 00  1.20000E-01  3.47826E-01  3.65363E 01
2.53720E-03  1.20000E-01  8.99243E-02  1.29680E 01  9.75082E-02  6.39618E-02  9.93666E 00  1.20000E-01  3.47549E-01  3.64911E 01
2.81950E-03  1.20000E-01  9.19789E-02  1.30249E 01  9.72881E-02  6.67874E-02  9.99357E 00  1.20000E-01  3.47217E-01  3.64341E 01
3.20520E-03  1.20000E-01  9.46186E-02  1.31009E 01  9.70053E-02  7.04119E-02  1.00695E 01  1.20000E-01  3.46799E-01  3.63582E 01
```

APPENDIX M

NOMENCLATURE

B	Average discharge burnup, MWD/T
C_A	Unit cost of reprocessing, including conversion of UNH to UO_3, \$/kg fuel fed to reprocessing plant
$C_{AEC}(R)$	Price of UF_6 containing no U-236 and having U-235 to U-238 weight ratio R, based on the AEC scale, \$/kgU
C_C	Unit cost of converting UO_3 to UF_6, \$/kgU fed to conversion
C_{CT}	Cost incurred between purchase of UO_3 and end of conversion to UF_6, excluding inventory charges, \$/kgU purchased
C'_{CT}	Cost incurred between purchase of natural uranium as U_3O_8 and end of conversion to UF_6, excluding inventory charges, \$/kgU purchased
C_D	Price of product from toll enrichment of recycled uranium, based on the AEC scale with U-236 considered as U-238, \$/kgU
$C_E(R)$	Fuel cycle cost when feed containing no U-236 and having U-235 to U-238 weight ratio R is purchased as UF_6 on the AEC price scale, mills/kwhr
C^*_E	Minimum fuel cycle cost realizable when feed containing no U-236 is purchased as UF_6 on the AEC price scale, mills/kwhr

C_F	Unit cost of fabrication, including conversion of UO_3 or UF_6 to UO_2, \$/kgU fabricated
C_K	Price of fissile plutonium, \$/g
C_N	Price of Np-237, \$/g
C_N^I	Price of Np-237 at which the minimum fuel cycle cost C_E^* is the same for both recycle to fabrication and recycle to a diffusion plant, \$/g
$C_N^o(R,y)$	Price of Np-237 at which the U-236 penalty $\delta(R,y)$ equals zero, \$/g
C_{NAT}	Cost of natural uranium as UF_6, \$/kgU
C_R	Price of reactor feed uranium, based on the AEC price scale with U-236 considered as U-238, \$/kgU
C_S	Price of spent uranium, based on the AEC price scale with U-236 considered as U-238, \$/kgU
C_{SH}	Unit cost of post-irradiation shipping, \$/kg fuel shipped
$C_{U_3O_8}$	Price of natural uranium as U_3O_8, \$/lb U_3O_8
C_Δ	Unit cost of separative work, \$/kgU
F	Time-averaged flowrate of makeup uranium fed to fabrication plant, kgU/day
F_B	Time-averaged flowrate of feed uranium to be blended with natural uranium, kgU/day
F_D	Time-averaged flowrate of feed uranium to be pre-enriched by gaseous diffusion, kgU/day

F_{NAT}	Time-averaged flowrate of natural uranium to be blended with feed uranium, kgU/day
F_P	Time-averaged flowrate of uranium product stream from the diffusion plant used to re-enrich recycled uranium, kgU/day
F_R	Time-averaged flowrate of uranium fed to reactor, kgU/day
F_S	Time-averaged flowrate of uranium leaving reprocessing plant, kgU/day
F_T	Time-averaged flowrate of uranium tails stream from the diffusion plant used for pre-enrichment of feed uranium, kgU/day
F_W	Time-averaged flowrate of uranium tails stream from the diffusion plant used to re-enrich recycled uranium, kgU/day
i	Fixed charge rate on working capital, yr^{-1}
I	Total initial loading of uranium in reactor, kg
K	Time-averaged flowrate of fissile plutonium leaving reprocessing plant, kg/day
L	Average load factor for power plant
L_C	Fractional loss of uranium during conversion of UO_3 to UF_6, based on product from conversion
L_C'	Fractional loss of uranium during conversion of U_3O_8 to UF_6, based on product from conversion

L_F	Fractional loss of uranium during fabrication, based on fabricated product
L_{RP}	Fractional loss of Pu and Np during reprocessing, based on material fed to reprocessing plant
L_{RU}	Fractional loss of uranium during reprocessing, based on uranium fed to reprocessing plant
$M(R,y)$	Sum of all fuel cycle costs, exclusive of feed cost, when uranium having U-235 to U-238 weight ratio R and U-236 weight fraction y is used as feed for a basic recycle scheme, \$/day
N	Time-averaged flowrate of Np-237 leaving reprocessing plant, kg/day
P	Net electrical power output of plant, MW
R	Weight ratio of U-235 to U-238 in uranium for which unit feed value is to be determined
R^*	Weight ratio of U-235 to U-238 in feed uranium which gives minimum fuel cycle cost C_E^* when feed containing no U-236 is purchased as UF_6 on the AEC price scale
R_B	Weight ratio of U-235 to U-238 in product stream from blending feed uranium with natural uranium
R_D	Weight ratio of U-235 to U-238 in product stream from the diffusion plant used for pre-enrichment of feed uranium
R_{NAT}	Weight ratio of U-235 to U-238 in natural uranium

R_P	Weight ratio of U-235 to U-238 in product stream from the diffusion plant used to re-enrich recycled uranium
R_R	Weight ratio of U-235 to U-238 in uranium fed to reactor
R_S	Weight ratio of U-235 to U-238 in uranium leaving reprocessing plant
R_T	Weight ratio of U-235 to U-238 in tails stream from the diffusion plant used for pre-enrichment of feed uranium
R_W	Weight ratio of U-235 to U-238 in tails stream from the diffusion plant used to re-enrich recycled uranium
t_C	Time interval between purchase of UO_3 or U_3O_8 and completion of conversion to UF_6, years
t_E	Time interval between delivery of uranium to the AEC for toll enrichment and receipt of product uranium, years
t_F	Average pre-irradiation holdup time for uranium, years
t_{RP}	Average post-irradiation holdup time for plutonium and neptunium, years
t_{RU}	Average post-irradiation holdup time for uranium, years

$V(R,y)$	Unit value of UO_3 having U-235 to U-238 weight ratio R and U-236 weight fraction y, when used as feed for a basic recycle scheme, \$/kgU
$V_B(R,y)$	Maximum unit feed value of UO_3 having U-235 to U-238 weight ratio R and U-236 weight fraction y, when blended with natural uranium, \$/kgU
$V_B(R,y,\epsilon)$	Unit feed value of UO_3 having U-235 to U-238 weight ratio R and U-236 weight fraction y, when blended with natural uranium to form blended product containing weight fraction ϵ of natural uranium, \$/kgU
$V_D(R,y)$	Maximum unit feed value of UO_3 having U-235 to U-238 weight ratio R and U-236 weight fraction y, when pre-enriched by gaseous diffusion, \$/kgU
$V_D(R,y,R_D)$	Unit feed value of UO_3 having U-235 to U-238 weight ratio R and U-236 weight fraction y, when pre-enriched by gaseous diffusion to a U-235 to U-238 weight ratio R_D, \$/kgU
$V_m(R,y)$	The largest of $V(R,y)$, $V_B(R,y)$, and $V_D(R,y)$ for uranium having U-235 to U-238 weight ratio R and U-236 weight fraction y, \$/kgU
x	Weight fraction of U-235 in uranium for which unit feed value is to be determined
y	Weight fraction of U-236 in uranium for which unit feed value is to be determined

y_B	Weight fraction of U-236 in product stream from blending feed uranium with natural uranium
y_D	Weight fraction of U-236 in product stream from the diffusion plant used for pre-enrichment of feed uranium
y_P	Weight fraction of U-236 in product stream from the diffusion plant used to re-enrich recycled uranium
y_R	Weight fraction of U-236 in uranium fed to reactor
y_S	Weight fraction of U-236 in uranium leaving reprocessing plant
y_T	Weight fraction of U-236 in tails stream from the diffusion plant used for pre-enrichment of feed uranium
y_W	Weight fraction of U-236 in tails stream from the diffusion plant used to re-enrich recycled uranium
α	Fraction of total U-236 contained in feed uranium which is present in product stream from the diffusion plant used for feed pre-enrichment
β	Parameter used in U-236 penalty analysis and defined by Equation VII.16, $(\text{kgU/day})^{-1}$
$\delta(R,y)$	U-236 penalty for uranium feed having U-235 to U-238 weight ratio R and U-236 weight fraction y, $/g U-236 in feed; defined by Equation VII.1

$\delta_{ADJ}(R,y)$	Adjusted U-236 penalty for uranium feed having U-235 to U-238 weight ratio R and U-236 weight fraction y, \$/g U-236 in feed stream to fabrication plant; defined by Equation VII.19
$\bar{\delta}$	U-236 penalty level, i.e., approximate value of $\delta(R,y)$ at $R=R^*$, \$/g U-236 in feed
Δ	Average separative work requirement for re-enriching recycled uranium, kgU/day
Δ_D	Average separative work requirement for pre-enrichment of feed uranium, kgU/day
ϵ	Weight fraction of natural uranium in product from blending feed uranium and natural uranium
η	Parameter used in U-236 penalty analysis and defined by Equation VII.17, \$/kgU
ϕ	Separation potential of uranium stream for which unit feed value is to be determined
ϕ_D	Separation potential of product stream from the diffusion plant used for pre-enrichment of feed uranium
ϕ_P	Separation potential of product stream from the diffusion plant used to re-enrich recycled uranium
ϕ_S	Separation potential of uranium leaving reprocessing plant
ϕ_T	Separation potential of tails stream from the diffusion plant used for pre-enrichment of feed uranium

ϕ_W	Separation potential of tails stream from the diffusion plant used to re-enrich recycled uranium

APPENDIX N

REFERENCES

1. "Special Nuclear Materials - Base Charges, Special Charges, Specifications and Packaging", <u>Federal Register</u>, <u>26</u>, 4765 (1961).

2. <u>Nuclear Industry</u>, <u>13</u>(4), 20-21 (1966).

3. <u>Nuclear News</u>, <u>10</u>(6), 18 (1967).

4. T.C. Golden, "The Effect of U-236 on the Value of Fuel Used in Thermal Reactors," MIT, SM Thesis in Nuclear Engineering (September, 1967).

5. D.J. Bauhs, "The Effect of U-236 on the Value of Uranium Used as Feed for a Heavy Water Moderated Organic Cooled Reactor," MIT, SM and Nucl.E. Thesis in Nuclear Engineering (June, 1967).

6. J.A. Ransohoff, "Impact of Isotope Sales on Fuel Cycle Costs and Practices," <u>Vol. 3, Proceedings AIF</u>, 1964 Annual Conference, 180-186.

7. J.A. Ransohoff and J.A. DeFelice, "A Proposed Process for Producing Large Quantities of Np-237 and Pu-238 in Commercial Power Reactors," <u>Trans. Am. Nucl. Soc.</u>, <u>8</u>(2), 334 (1965).

8. R. Nilson and C.W. Showalter, "A Model to Optimize Pu-238 Production by Fuel Recycle," in DP-1066 (Vol. II), 39-52 (1966).

9. D.E. Deonigi and E.A. Eschbach, "Production and Indifference Pricing of Transuranium Isotopes," in DP-1066 (Vol. II), 3-38 (1966).

10. "San Onofre Nuclear Generating Station - Reference Core Design," WCAP-3269-7 (1965).

11. "1000 MWe Closed-Cycle Water Reactor Study," WCAP-2385 (1963).

12. A. de la Garza, G.A. Garrett, and J.E. Murphy, "Some Value Functions for Multicomponent Isotope Separation - Application to a Unit Cost Scale for Uranium-235, 236, 238 Mixtures," K-1455 (1960).

13. J.J. Beaudreau, "Development and Evaluation of the Point Depletion Code CELL," MIT, SM Thesis in Nuclear Engineering (June, 1967).

14. N.B. McLeod, et al, "The Effect of Fuel and Poison Management on Nuclear Power Systems," NYO-9715 (1961).

15. M. Benedict and T.H. Pigford, Nuclear Chemical Engineering, McGraw-Hill Book Co. Inc., New York (1957).

16. Nuclear News, 10(6), 33 (1967).

17. H.W. Graves, Jr., Personal Communication (October, 1965).

18. P.F. Menezes, "Comparison of Observed and Predicted Performance of the First Core of the Yankee Reactor", MIT, SM Thesis in Nuclear Engineering (September, 1964).

19. "Uranium Enrichment Services - Proposed Criteria", Federal Register, 30, 12550 (1965).

20. M.W. Rosenthal, et al, "A Comparative Evaluation of Advanced Converters," ORNL-3686 (1965).

21. "Plutonium and Uranium Enriched in U^{233}-Guaranteed Purchase Prices," Federal Register, 30, 3886 (1965).

22. General Electric Price Handbook, Section 8803, Atomic Power Equipment - Nuclear Fuel (October, 1966).

23. J.B. Burnham, L.G. Merker, and D.E. Deonigi, "Comparative Costs of Oxide Fuel Elements," BNWL-273 (1966).

24. J. Vallance, "Fuel Cycle Economics of Uranium-Fueled Thermal Reactors," A/Conf. 28/P/247 (September, 1964).

25. "Treatment of Certain Nuclear Materials - Charges", Federal Register, 23, 1707 (1958).

26. F.B. Hildebrand, Introduction to Numerical Analysis, McGraw-Hill Book Company, Inc., New York (1956).

27. R.T. Shanstrom, M. Benedict, and C.T. McDaniel, "Fuel Cycles in Nuclear Reactors," NYO-2131 (1959).

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

29. M. Clark and K.F. Hansen, Numerical Methods of Reactor Analysis, Academic Press, New York (1964).

30. A. de la Garza, "A Generalization of the Matched Abundance Ratio Cascade for Multicomponent Isotope Separation," K-1527 (1962).

31. R.C. Mitchell, "A Study of Alternative Cascades for Three Component Isotope Separation," MIT, SM Thesis in Nuclear Engineering (October, 1966).

32. B.F. Rider, et al, "Accurate Nuclear Fuel Burnup Analysis - Sixteenth Quarterly Progress Report: September 1965 - November 1965," GEAP-5060 (1965).

33. S. Pearlstein, "Analysis of (n,2n) Cross Sections for Nuclei of Mass A > 30," BNL-897 (1964).

34. L. Cranberg, et al, <u>Phys. Rev.</u>, <u>103</u>, 662 (1956).

35. J.R. Stehn, et al, "Neutron Cross Sections: Volume III, Z = 88 to 98," BNL-325, 2nd ed., Supp. No.2 (1965).

36. J.R. Stehn, et al, "Neutron Cross Sections: Volume I, Z=1 to 20," BNL-325, 2nd ed., Supp. No. 2 (1964).

37. "Reactor Physics Constants," ANL-5800, 2nd ed. (1963).

38. "Westinghouse Nuclear Design Procedure Manual," (1959).

39. R.F. Barry, "LEOPARD - A Spectrum Dependent Non-Spatial Depletion Code for the IBM-7094," WCAP-3269-26 (1963).

40. M.K. Drake, "A Compilation of Resonance Integrals," <u>Nucleonics</u>, <u>24</u>(8), 108 (1966).

41. D.A. Goellner and J.J. Beaudreau, "Summary Description of the Fuel Depletion Code CELL," MITNE-89 (January, 1968).