A CASH-FLOW STUDY FOR A NON-BASE LOADED POWER REACTOR

by 7214

MICHAEL EUGENE HAWK

B. S., Kansas State University, 1970

A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Nuclear Engineering
KANSAS STATE UNIVERSITY

Manhattan, Kansas

1971

Approved by:

N. Dean Eckhoff
Major Professor

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A_j	total utility load factor for the jth week
B_j	plant load factor for jth week, years 11-20 of operation
C_j	plant load factor for jth week, years 21-30 of operation
CF1	unitized cost for purchase of U_3O_8
CF2	unitized cost for conversion and shipping
CF3	unitized cost for enrichment
CF5	unitized cost for fabrication
CF5A	unitized cost for shipping fabricated fuel elements to the reactor site
CF6	unitized cost of shipping irradiated fuel elements to the reprocessing plant
CF7	unitized cost of reprocessing irradiated fuel
CF8	unitized cost of conversion of reprocessed uranium
CIRU	unitized credit for plutonium
CLETIM	time required to clean the reprocessing plant
CONV	mass of uranium entering the conversion plant
CONVER	0.31245×10^{17} fissions/Mwt sec
COS1	cost for purchase of U_3O_8
COS2	cost for conversion and shipping
COS3	cost for enrichment
COS5	cost for fabrication
COS5A	cost for shipping fabricated fuel elements to the reactor site
COS6	cost for shipping irradiated fuel elements to the reprocessing plant
COS7	cost for reprocessing irradiated fuel
COS8	cost for conversion of reprocessed uranium

CR	unitized credit for scrap and lost uranium from the fabrication process
CRE1	credit for scrap and lost uranium from the fabrication process
CRE2	credit for reprocessed uranium
CRE3	credit for fissile plutonium
DB^2	thermal leakage factor
DELTA	separative duty for enrichment
DELTB	separative duty required to produce one kilogram of uranium enriched to an assay of XE
ENRIC	mass of uranium entering the enrichment plant
E_R	recoverable energy per fission
FE	mass of uranium in the enrichment feed stream that is required to produce one kilogram of uranium at an assay of XE
$FISS_i$	fission rate in the ith region of the core
FLEX	mass of uranium in the scrap and losses stream from the fabrication process
FREAC	mass of uranium in a one-third core load prior to irradiation
FUT	future cash flow
GB25	mass of U-235 entering the reprocessing process
GB26	mass of U-236 entering the reprocessing process
GB28	mass of U-238 entering the reprocessing process
GB41	mass of Pu-241 entering the reprocessing process
GB49	mass of Pu-239 entering the reprocessing process
I	interest rate
K	defined by Eq. (9)
n	number of interest periods
$N_{25}(t)$	nuclide density of U-235 as a function of time
N_{25}^o	initial nuclide density of U-235

$N_{26}(t)$	nuclide density of U-236 as a function of time
N^{o}_{26}	initial nuclide density of U-236
$N_{28}(t)$	nuclide density of U-238 as a function of time
N^{o}_{28}	initial nuclide density of U-238
$N_{40}(t)$	nuclide density of Pu-240 as a function of time
$N_{41}(t)$	nuclide density of Pu-241 as a function of time
$N_{49}(t)$	nuclide density of Pu-239 as a function of time
$N^{25}_{F}(t)$	nuclide density of fission product pairs produced by fission of U-235
$N^{28}_{F}(t)$	nuclide density of fission product pairs produced by fission of U-238
$N^{41}_{F}(t)$	nuclide density of fission product pairs produced by fission of Pu-241
$N^{49}_{F}(t)$	nuclide density of fission product pairs produced by fission of Pu-239
p	resonance escape probability
P	percentage deviations of comparative case cash flows from the reference case cash flows
P_1	fission to resonance non-leakage probability
P_{th}	fission to thermal non-leakage probability
PFSH	mass of uranium entering the fabrication process
PMAX	maximum rated thermal power of the core
$PNOM_j$	plant load factor for the jth week
PUR	mass of U_3O_8 purchased
PURE	mass of fissile plutonium leaving the reprocessing process
PW	present worth of future cash flow
REPTIM	time required to reprocess irradiated fuel
t	time

TAIL — mass of uranium in the tails stream of the enrichment plant

$TOFIS_j$ — total fission rate during the jth week

UCRU — cost for production of one kilogram of uranium at an assay XE (UCRU includes purchase of U_3O_8, conversion and shipping, and enrichment.)

UREP — mass of uranium leaving the reprocessing plant

W — mass of uranium in enrichment tails stream after production of one kilogram of uranium at an assay of XE

X_i — assay of stream i of the enrichment process

XE — assay of uranium leaving the reprocessing process

XF — assay of the feed stream of the enrichment process

XP — assay of the product stream of the enrichment system

XW — assay of the tails stream of the enrichment process

x_j^k — cash flow during the jth year for the kth activity in the reference case

y_j^k — cash flow during the jth year for the kth activity in the comparative case

Greek symbols

α_m — capture to fission ratio for fissile species m

γ — defined by Eq. (10)

ε — fast fission factor

η_m — ratio of the neutrons produced by fission to the number of neutrons absorbed in fissile species m

ν_m — ratio of the number of neutrons produced by fission to the number of neutrons absorbed in fission by fissile species m

ρ — reactivity, $(k_{eff} - 1)/k_{eff}$

σ_m^f — microscopic absorption cross section for species m

Σ_{ST} — macroscopic absorption cross section for core structural components

$\phi(t)$	flux as a function of time
$\phi(X_i)$	defined by Eq. (37)

<u>Subscripts *(m)* for Greek symbols</u>

25	U-235
26	U-236
28	U-238
40	Pu-240
41	Pu-241
49	Pu-239

1.0 INTRODUCTION

As utilities become more committed to nuclear power and more fossil-fired plants are retired, nuclear power reactors will be pressed into peak-load pickup service; therefore, nuclear reactors will deviate strongly from the base-load situation. Consequently, there is some question as to the effect this deviation will have on fuel cycle costs.

Coates (1), in a review of previous work involving fuel cycle costs and cash flows, classified these studies into four categories:

(1) those involving solely the reactor core subsystems;

(2) those involving the reactor core and fuel cycle as a subsystem;

(3) those involving the plant system as a whole;

(4) those involving numerous nuclear plants in the general nuclear economy.

The calculational schemes for these studies grew more complex as automated computing machines became more sophisticated. Schwieger (2) and Fagan (3) have discussed various core physics computer codes which can be integrated into a cash flow study. Also, they have commented on each code's capability and complexity. Bloomster, et.al. (4), Deonigi, et.al. (5), Eschbach, et.al. (6), and Salmon (7) have developed sophisticated techniques for fuel cycle costs calculations. However, all of these different methods assume a constant power generation rate over a finite time period which varies from one year to thirty years.

Consequently, the purpose of this work is to determine the effect that the deviation from the base-load assumption over the thirty year life of a light water reactor will have on:

(1) scheduling of refuel shutdown periods;

(2) present worth of cash flows for U_3O_8 purchase, conversion, enrichment, fabrication, shipping, reprocessing, and uranium and plutonium credits;

(3) total cash flows.

2.0 THEORY

2.1 Burnup

Benedict and Pigford (8) have derived a group of equations which describe fuel burnup under the following assumptions:

a) One group theory is applicable.

b) Burnup is spatially independent.

c) Burnout of fission products is negligible.

d) Microscopic cross-sections are constant.

e) The following reactor parameters remain constant:

(1) fast fission factor, ε,

(2) fission to thermal non-leakage probability, P_{th},

(3) fission to resonance non-leakage probability, P_1,

(4) resonance escape probability, p,

(5) thermal leakage factor, DB^2.

f) Absorption rate of thermal neutrons in cladding and structural materials can be represented by a single term, $\Sigma_{ST}\phi$, where Σ_{ST} is an average macroscopic absorption cross-section and ϕ is the thermal flux.

g) Absorption rate of thermal neutrons in fission products other than xenon and samarium can be represented by a single term, $N_{FF}\sigma_{FF}\phi$, where N_{FF} is the atomic density of all fission products, and σ_{FF} is the microscopic absorption cross-section for the fission products.

h) Absorption rate of thermal neutrons in xenon and samarium is directly proportional to the rate of thermal neutron absorption in all fissionable species and may be represented by the term, $\sum_j r_j N_j \sigma_j \phi$, where

r_j = poison ratio of jth species,

N_j = atomic density of jth species,

σ_j = microscopic absorption cross-section of jth species.

The rate of change of the atomic density of U-235 is given by

$$\frac{dN_{25}(t)}{dt} = -N_{25}(t)\sigma_{25}\phi(t). \tag{1}$$

If $N_{25}(0) = N_{25}^{o}$, then the solution to Eq. (1) is

$$N_{25}(t) = N_{25}^{o} \exp(-\sigma_{25} \int_{o}^{t} \phi(t')dt'). \tag{2}$$

If $\phi(t')$ is a constant,

$$\int_{o}^{t} \phi(t')dt' = \phi t. \tag{3}$$

Equation (2) becomes

$$N_{25}(t) = N_{25}^{o}\exp(-\sigma_{25}\phi t). \tag{4}$$

Since U-236 is produced by absorption of a neutron in U-235 and is consumed by the absorption of a neutron, its rate of change is

$$\frac{dN_{26}(t)}{dt} = \frac{N_{25}(t)\sigma_{25}\alpha_{25}\phi}{1 + \alpha_{25}} - N_{26}(t)\sigma_{26}\phi. \tag{5}$$

The solution to Eq. (5) is

$$N_{26}(t) = C_o[\ \exp(-\sigma_{26}\phi t) - \exp(-\sigma_{25}\phi t)\ ] + N_{26}^o \exp(-\sigma_{26}\phi t), \tag{6}$$

where

N_{26} = atomic density of U-236,

σ_{26} = microscopic absorption cross section of U-236,

$C_o = \dfrac{N_{25}^o \sigma_{25} \alpha_{25}}{(\sigma_{25} - \sigma_{26})(1 + \alpha_{25})}$

α_{25} = capture to fission ratio of U-235,

N_{26}^o = atomic density of U-236 at t = 0.

The rate of change for Pu-239 is

$$\frac{dN_{49}(t)}{dt} = N_{28}(t)\sigma_{28}\phi + \eta_{25}\varepsilon P_1(1 - p)N_{25}(t)\sigma_{25}\phi$$

Absorption of thermal neutrons in U-238 — Absorption of resonance neutrons from U-235 fission in U-238

$$+ \eta_{49}\varepsilon P_1(1 - p)N_{49}(t)\sigma_{49}\phi + \eta_{49}\varepsilon P_1(1 - p)N_{41}(t)\sigma_{41}\phi$$

Absorption of resonance neutrons from Pu-239 fission in U-238 — Absorption of resonance neutrons from Pu-241 fission in U-238

$$- N_{49}(t)\sigma_{49}\phi. \tag{7}$$

Absorption of thermal neutron in Pu-239

If the change in U-238 is negligible,

$$N_{28}(t) = N_{28}^o, \tag{8}$$

where

N_{28}^o = initial charge of U-238.

For the case of no plutonium recycle, the contribution of resonance neutrons from Pu-241 is negligible. Therefore, it can be neglected.

An arrangement of Eq. (7) and definition for fissionable species, m,

$$K_m = \eta_m \varepsilon P_1 (1 - p) \tag{9}$$

and

$$\gamma = 1 - K_{49} \tag{10}$$

yields

$$\frac{dN_{49}(t)}{dt} = N^{o}_{28}\sigma_{28}\phi + K_{25}N_{25}(t)\sigma_{25}\phi - \gamma N_{49}(t)\sigma_{49}\phi. \tag{11}$$

The solution of Eq. (7) is

$$N_{49}(t) = C_1 + C_2\exp(-\sigma_{25}\phi t) - (C_1 + C_2 - C_3)\exp(-\gamma\sigma_{49}\phi t) \tag{12}$$

where

$$C_1 = \frac{N^{o}_{28}\sigma_{28}}{\gamma\sigma_{49}},$$

$$C_2 = \frac{N^{o}_{25}K_{25}\sigma_{25}}{\gamma\sigma_{49} - \sigma_{25}},$$

$$C_3 = N_{49}(0).$$

The rate of change for Pu-240 is due to the non-fissioning absorption of a neutron in Pu-239 and the absorption of a neutron in Pu-240:

$$\frac{dN_{40}(t)}{dt} = \frac{\alpha_{49}N_{49}(t)\sigma_{49}\phi}{1 + \alpha_{49}} - N_{40}(t)\sigma_{40}\phi \tag{13}$$

The solution to Eq. (13) is

$$N_{40}(t) = C_4 + C_5\exp(-\sigma_{25}\phi t) - C_6\exp(-\gamma\sigma_{49}\phi t) - (C_4 + C_5 - C_6 - C_7)\exp(-\sigma_{40}\phi t) \tag{14}$$

where

$$C_4 = \frac{\alpha_{49}\sigma_{49}C_1}{(1 + \alpha_{49})\sigma_{40}},$$

$$C_5 = \frac{\alpha_{49}\sigma_{49}C_2}{(1 + \alpha_{49})(\sigma_{40} - \sigma_{25})},$$

$$C_6 = \frac{\alpha_{49}\sigma_{49}(C_1 + C_2 - C_3)}{(1 + \alpha_{49})(\sigma_{40} - \gamma\sigma_{49})},$$

$$C_7 = N_{40}(0).$$

Pu-241 is produced by the absorption of a neutron in Pu-240 and is depleted by the absorption of a neutron. The rate equation is

$$\frac{dN_{41}(t)}{dt} = N_{40}(t)\sigma_{40}\phi - N_{41}(t)\sigma_{41}\phi. \tag{15}$$

The solution to Eq. (15) is

$$N_{41}(t) = C_8 + C_9\exp(-\sigma_{25}\phi t) + C_{10}\exp(-\sigma_{41}\phi t) + C_{11}\exp(-\gamma\sigma_{49}\phi t) + C_{12}\exp(-\sigma_{40}\phi t) \tag{16}$$

where

$$C_8 = \frac{C_4\sigma_{40}}{\sigma_{41}},$$

$$C_9 = \frac{C_5\sigma_{40}}{\sigma_{41} - \sigma_{25}},$$

$$C_{10} = \left[\left(\frac{C_6}{\sigma_{41} - \gamma\sigma_{49}} + \frac{N^o_{41}}{\sigma_{40}} + \frac{C_4 + C_5 - C_6 - C_7}{\sigma_{41} - \sigma_{40}} - \frac{C_4}{\sigma_{41}} - \frac{C_5}{\sigma_{41} - \sigma_{25}}\right)\right]\sigma_{40},$$

$$C_{11} = \frac{-C_6}{\sigma_{41} - \gamma\sigma_{44}}\sigma_{40},$$

$$C_{12} = \frac{(C_4 + C_5 - C_6 - C_7)\sigma_{40}}{\sigma_{41} - \sigma_{40}},$$

$$N^o_{41} = N_{41}(0).$$

The rate of formation of fission products from U-235 is

$$\frac{dN^{25}_F(t)}{dt} = \frac{N_{25}(t)\sigma_{25}\phi}{1 + \alpha_{25}}. \tag{17}$$

The solution to Eq. (17) is

$$N_F^{25}(t) = \frac{N_{25}^o}{1 + \alpha_{25}} [1 - \exp(-\sigma_{25}\phi t)]. \tag{18}$$

The rate of formation of fission products from Pu-239 is

$$\frac{dN_F^{49}(t)}{dt} = \frac{N_{49}(t)\sigma_{49}\phi}{1 + \sigma_{49}}. \tag{19}$$

Solving Eq. (19) yields

$$N_F^{49}(t) = \frac{\sigma_{49}}{1 + \alpha_{49}}\left[C_1\phi t + \frac{C_2}{\sigma_{25}}[1 - \exp(-\sigma_{25}\phi t)] - [C_1 + C_2 - C_3][1 - \exp(-\gamma\sigma_{49}\phi t)]\right]. \tag{20}$$

Pu-241 fission products are formed according to

$$\frac{dN_F^{41}(t)}{dt} = \frac{N_{41}(t)\sigma_{41}\phi}{1 + \alpha_{41}}. \tag{21}$$

The solution to Eq. (21) is

$$N_F^{41}(t) = \frac{\sigma_{41}}{1 + \alpha_{41}}\left[C_8\phi t + \frac{C_9[1 - \exp(-\sigma_{25}\phi t)]}{\sigma_{25}} + \frac{C_{10}}{\sigma_{41}}[1 - \exp(-\sigma_{41}\phi t)] + \frac{C_{11}}{\gamma\sigma_{49}}[1 - \exp(-\gamma\sigma_{49}\phi t)] + \frac{C_{12}}{\sigma_{40}}[1 - \exp(-\sigma_{40}\phi t)]\right]. \tag{22}$$

From the definitions of ν and ε, a neutron balance on the fast fission of U-238 yields

$$N_F^{28}(t) = \frac{\varepsilon - 1}{\nu_{28} - 1}[\nu_{25}N_F^{25}(t) + \nu_{49}N_F^{49}(t) + \nu_{41}N_F^{41}(t)]. \tag{23}$$

A mass balance on U-238 then yields

$$N_{28}(t) = N_{28}^{o} - N_F^{28}(t) - N_{49}(t) - N_F^{49}(t) - N_{40}(t) - N_{41}(t) - N_F^{41}(t). \qquad (24)$$

For fissionable species m,

$$\mu_m = \eta_m \varepsilon P_{th} p - 1 - r_m; \qquad (25)$$

the total reactivity is then defined:

$$\rho = \frac{\left[\mu_{25}N_{25}(t)\sigma_{25}\phi + \mu_{49}N_{49}(t)\sigma_{49}\phi + \mu_{41}N_{41}(t)\sigma_{41}\phi - DB^2\phi - \Sigma_{ST}\phi - N_{H_2O}(t)\sigma_{H_2O}\phi - N_{28}(t)\sigma_{28}\phi - N_{26}(t)\sigma_{26}\phi - N_{40}(t)\sigma_{40}\phi - [N_F^{25}(t) + N_F^{28}(t) + N_F^{49}(t) + N_F^{41}(t)]\sigma_{FF}\phi\right]}{\varepsilon P_{th} p\phi[\eta_{25}N_{25}(t)\sigma_{25} + \eta_{49}N_{49}(t)\sigma_{49} + \eta_{41}N_{41}(t)\sigma_{41}]}. \qquad (26)$$

2.2 Fuel Cycle

2.2.1 Mass balances

Figure 1 (9) depicts the mass flow through the fuel cycle. If the pre-irradiation material requirements are known, one can back calculate to determine the material needed prior to each activity. These calculations can be performed using the following procedure.

If FREAC is the amount of uranium required prior to irradiation, the amount of uranium needed for fabrication, PFSH, is

$$PFSH = 1.1\ FREAC. \tag{27}$$

The amount of uranium in the excesses and losses stream, FLEX, can be found from the relationship

$$FLEX = 0.1\ FREAC. \tag{28}$$

The uranium requirement, ENRIC, for enrichment is determined by Eq. (29)

$$ENRIC = \frac{PFSH(XP - XW)}{(XF - XW)}, \tag{29}$$

where

XP = product enrichment,

XF = feed enrichment,

XW = tails enrichment.

The amount of uranium lost in the tails stream, TAIL, can be found by a mass balance on the enrichment process

$$TAIL = ENRIC - PFSH. \tag{30}$$

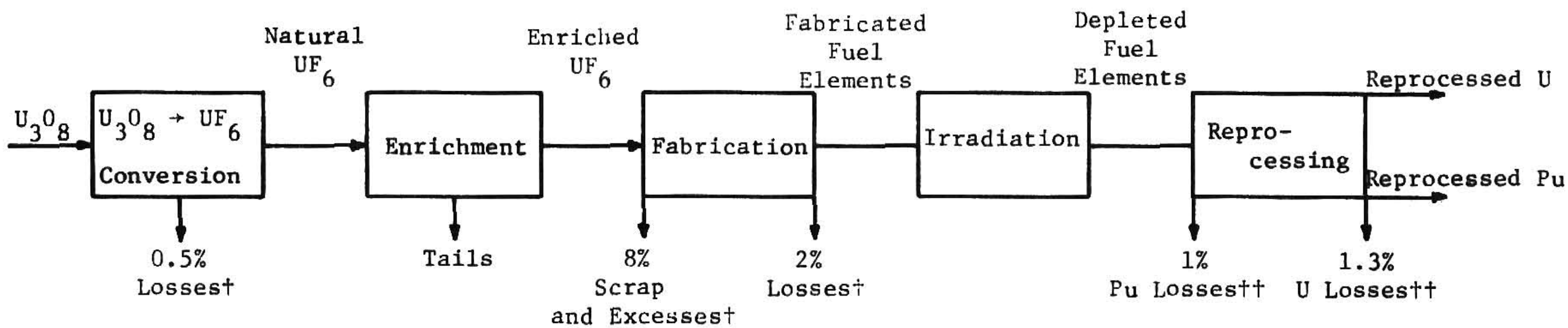
The requirement for conversion, CØNV, is determined by

$$CØNV = 1.005\ ENRIC. \tag{31}$$

Finally the amount of U_3O_8 (in pounds), PUR, is determined by the conversion of Eq. (31):

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.



† Based on Product Stream

†† Based on Feed Stream

Figure 1: Mass Flow Through the Fuel Cycle

$$PUR = C\emptyset NV \times \frac{2.205\ LB}{Kg} \times \frac{1Kg\ U_3O_8}{.848Kg\ U}. \tag{32}$$

To determine the amounts of uranium and plutonium leaving the reprocessing plant, the following procedure can be used. If the amounts of U-235, U-236, and U-238 entering the reprocessing plant are GB25, GB26, and GB28, respectively, the amount of uranium leaving the plant, UREP, can be found from

$$UREP = 0.987(GB25 + GB26 + GB28) \tag{33}$$

Similarly, if GB49 and GB41 represent the amounts of Pu-239 and Pu-241, respectively, entering the reprocessing plant, the amount left after losses, PURE, is determined from Eq. (34)

$$PURE = 0.99(GB49 + GB41) \tag{34}$$

2.2.2 Cash Flow

Table 1 (4) is a list of the fuel cycle activities, the unitized cost for each activity and the duration for each activity. The reprocessing costs were determined by the Nuclear Fuel Service, Incorporated (NFS) model (4). If the material requirements for each activity are known, the cost cash flow can be calculated.

For U_3O_8 purchase, if CF1 is the unitized cost, then the total cost, COS1, can be calculated from

$$COS1 = CF1 \times PUR. \qquad (35)$$

For conversion and shipping, CF2 is the unitized cost, and COS2 is the total cost.

$$COS2 = CF2 \times ENRIC. \qquad (36)$$

For enrichment, the number of kilograms separative work units, DELTA, is defined by

$$DELTA = TAIL \times \phi(XW) + PFSH \times \phi(XP) - ENRIC \times \phi(XF), \qquad (37)$$

where

$$\phi(X_i) = (1 - 2X_i)\log[(1 - X_i)/X_i]$$

The total cost for enrichment, COS3, is determined by Eq. (38) where CF3 is the unitized cost of enrichment.

$$COS3 = CF3 \times DELTA. \qquad (38)$$

The total cost for fabrication is found from Eq. (39) where COS5 is the total cost and CF5 is the unitized cost.

$$COS5 = CF5 \times FREAC. \qquad (39)$$

Equation (40) can be used to determine the total pre-irradiation shipping cost, COS5A, using a unitized cost, CF5A.

$$COS5A = CF5A \times FREAC. \qquad (40)$$

Table 1: Activities, Unitized Costs, and Time Durations for the Fuel Cycle Model

Activity	Unitized Cost†	Duration(Weeks)
U_3O_8 Purchase	\$8/lb U_3O_8	
Conversion and Shipping	\$2.20/KgU	14
Enrichment	\$26/Kg.S.W.U	9
Pre-Fabrication Shipping	0.††	2
Fabrication	\$100/KgU†††	9
Pre-Irradiation Shipping	\$3/KgU	2
Pre-Irradiation Down Time		4
Post-Irradiation Down Time		4
Cooling		17
Pre-Reprocessing Shipping	\$7/KgU	3
Reprocessing	NFS Model	NFS Model
Conversion of Reprocessed Uranium	\$5.60/KgU	
Post-Irradiation Shipping	0.††††	4

† Unitized costs are based on the amount produced during each activity.

†† Included in the fabrication cost.

††† Credits for excesses and losses are paid to the utility at the conclusion of the fabrication process.

†††† Included in the reprocessing costs. Credits for uranium and plutonium are paid to the utility at this time.

The unitized cost for pre-reprocessing shipping charges, CF6, is in terms of dollars per kilogram of uranium loaded into the core. Thus, the total cost for pre-reprocessing shipping, COS6, is found by

$$COS6 = CF6 \times FREAC. \tag{41}$$

In the NFS model for reprocessing costs, the plant capacity is assumed to be 1000Kg of uranium (loaded into the core) per day. The reprocessing time can be determined from

$$REPTIM = FREAC/1000Kg/day. \tag{42}$$

The time involved in cleanup of the plant, CLETIM, is 1/3 of the reprocessing time or eight days, whichever is longer. The total cost for reprocessing, COS7, can then be found from Eq. (43) since the unitized reprocessing cost, CF7, is in dollars per day.

$$COS7 = (REPTIM + CLETIM) \times CF7. \tag{43}$$

The unitized cost for converting uranium in the nitrate form to UF_6, CF8, is based on the amount of uranium leaving the reprocessing plant. The total cost for conversion, COS8, can be determined from

$$COS8 = CF8 \times UREP. \tag{44}$$

Credit for uranium excesses and losses incurred during the fabrication process are based on the pre-fabrication costs. From Eqs. (35), (36) and (38), the unit cost for providing uranium to the fabrication process, CR, can be calculated from

$$CR = (COS1 + COS2 + COS3)/PFSH. \tag{45}$$

The credit for uranium excesses and losses, CRE1, is determined by combining Eqs. (28) and (45)

$$CRE1 = CR \times FLEX. \tag{46}$$

After irradiation, the fuel has an enrichment, XE, calculated by

$$XE = \frac{GB25}{GB25 + GB26 + GB28} \quad (47)$$

Credit for uranium which has not been consumed in irradiation is determined by calculating the cost of purchasing U_3O_8, converting and shipping to the enrichment plant, and enriching to an assay of XE.

In order to produce one kg. of uranium with an assay of XE, FE kilograms of uranium are required as input to the enrichment plant. The resulting amount of tails is W. Equation (48) determines FE while Eq. (49) determines W;

$$FE = \frac{XE - XW}{XF - XW}; \quad (48)$$

$$W = FE - 1. \quad (49)$$

The required feed to the conversion step, FC is calculated from

$$FC = 1.005 \times FE. \quad (50)$$

The amount of U_3O_8 required (in pounds), PURC, is determined from

$$PURC = FC \times \frac{2.205LB}{Kg} \times \frac{1KgU_3O_8}{0.848KgU}. \quad (51)$$

With the above material requirements, the costs can be computed. For enrichment, the separative work units required, DELTB, are calculated by

$$DELTB = W \times \phi(XW) + \phi(XE) - FE \times \phi(XF). \quad (52)$$

The total unit cost, UCRU, involved in U_3O_8 purchase, conversion and shipment, and enrichment can be determined by

$$UCRU = CF1 \times PURC + CF2 \times FE + CF3 \times DELTB. \quad (53)$$

The product of UCRU, the unit cost of uranium at an assay of XE, and UREP provides the credit, CRE2, for the uranium leaving reprocessing plant as shown in

$$CRE2 = UCRU \times UREP. \quad (54)$$

In Eq. (55), the credit for fissile plutonium produced, CRE3, is the product of the unit credit for fissile plutonium, CIRU, and the amount of plutonium credit, PURE.

$$CRE3 = CIRU \times PURE. \tag{55}$$

Once the cash flows are calculated the interest for capital can be determined if the interest rates are known. The interest for any cash flow is the product of the cash flow and the effective interest rate for that cash flow. The interest for the cash flow is then added as a cash flow.

Another method of incorporating the effect of interest charges in an economic study is to determine the present worth of individual cash flow. The present worth of a cash flow is defined as the value at the present time of a cash flow which occurs n interest periods from now. For example, if FUT is the value of a cash flow for U_3O_8 purchases and it occurs n years from the present, the present worth, PW, of FUT for interest rate I is

$$PW = FUT/(1 + I)^n \tag{56}$$

Plant capital costs are amortized over the life of the plant. Since this is a comparative study, the plant capital costs will be the same in each case. Therefore, they will have no effect on the cash flow analysis.

2.2.3 Reactor Model

The reference reactor used in this study is a 134 Mwe pressurized water reactor whose important parameters are listed in Tables 2, 3, and 4 (8). The core was divided into three equal volume regions for out-in refueling. The flux and atomic densities were assumed constant in any region. The reactor was assumed to operate at a constant load factor for the first ten years; shutdowns for refueling occurred on an annual basis. For the last twenty years the reactor operated at varying load factors which were determined by a procedure described below. Refueling shutdown periods occurred when reactivity became zero.

Figure 2, (10) is a display of the total electrical energy generated in 1970 as a function of time. It was assumed that the curve also describes the utility's overall load factor as a function of time. Region I represents the fraction of the utility's total load that is generated by the reference reactor during the second ten years of operation. Region II gives the fraction for the third ten years. Each region is equivalent to 80% of the capacity of the reference reactor.

If A_j is the utility load factor for the jth week, then the reference reactor load factor for the jth week, B_j, is

$$B_j = \frac{(A_j - 0.1)}{(0.45 - 0.1)} 0.8. \tag{57}$$

Equation (57) is subject to the constraint

$$B_j = 0.8, \text{ if } A_j > 0.45. \tag{58}$$

The load factor for the reference reactor during the last ten years, C_j, is

$$C_j = \frac{(A_j - 0.5)0.8;}{(1.0 - 0.5)} \tag{59}$$

Table 2: Properties for Reference Pressurized Water Reactor

Fuel	Slightly enriched UO_2
Enrichment	3.44% U-235
Coolant and Moderator	H_2O, mean temperature 516°F, mean pressure 2000 psia
Reactor Power	480Mwt, 134Mwe
Average Neutron Temperature	908°K
Core Dimensions	Radius, 96.11 cm Height, 234.3 cm
Effective Core Dimensions	Radius, 103.6 cm Height, 249.3 cm
Inventory	U-235 700 kg U-238 19,800 kg
Fast Fission Factor, ε	1.0584
Non-Leakage Probability	
Fission to resonance, P_1	0.9742
Fission to thermal, P_{th}	0.9654
Thermal Leakage Factor, DB^2	1.92×10^{-4} cm^{-1}
Resonance Escape Probability	0.758
Economic Life	30 years

Table 3: Material Properties

Region	Material	Weight (Kg)	Density (g/cm^3)
Fuel	UO_2	23,350	10.7
Cladding	SS-348	6,145	7.78
Structure	Zircaloy	1,293	6.5
Coolant-Moderator	Water	2,670	0.783
	Void	(5,421 in^3)	0

subject to the constraint

$$C_j = 0 \quad \text{if} \quad A_j < 0.5. \tag{60}$$

Once the load factors are known, the flux in any region of the core can be determined. In order to have a flat power distribution, it was assumed that, at any time, the fission rate is constant across the core. The total fission rate for the jth week is

$$TOFIS_j = PNOM_j \times PMAX \times C\emptyset NVER, \tag{61}$$

where

$TOFIS$ = total fission rate, fission/sec,

$PNOM_j$ = the load factor for the jth week,

$PMAX$ = maximum rated thermal power, Mwt,

$C\emptyset NVER$ = conversion constant, $\frac{\text{fission}}{\text{Mwt sec}}$.

Table 4: Effective Nuclide Properties for Thermal Neutrons in the Reference Pressurized Water Reactor

Nuclide	Absorption Cross Section Barns	ν	η	α	r_m
U-235	515	2.47	1.97	0.253	0.0451
U-236	100				
U-238	1.365	2.55			
Pu-239	1690	2.905	1.81	0.600	0.0426
Pu-240	1870				
Pu-241	1590	3.06	2.225	0.3765	0.0541
Fission Product Pairs	31.9				
Water	0.332				
Stainless Steel	2.84				
Zirconium	0.105				

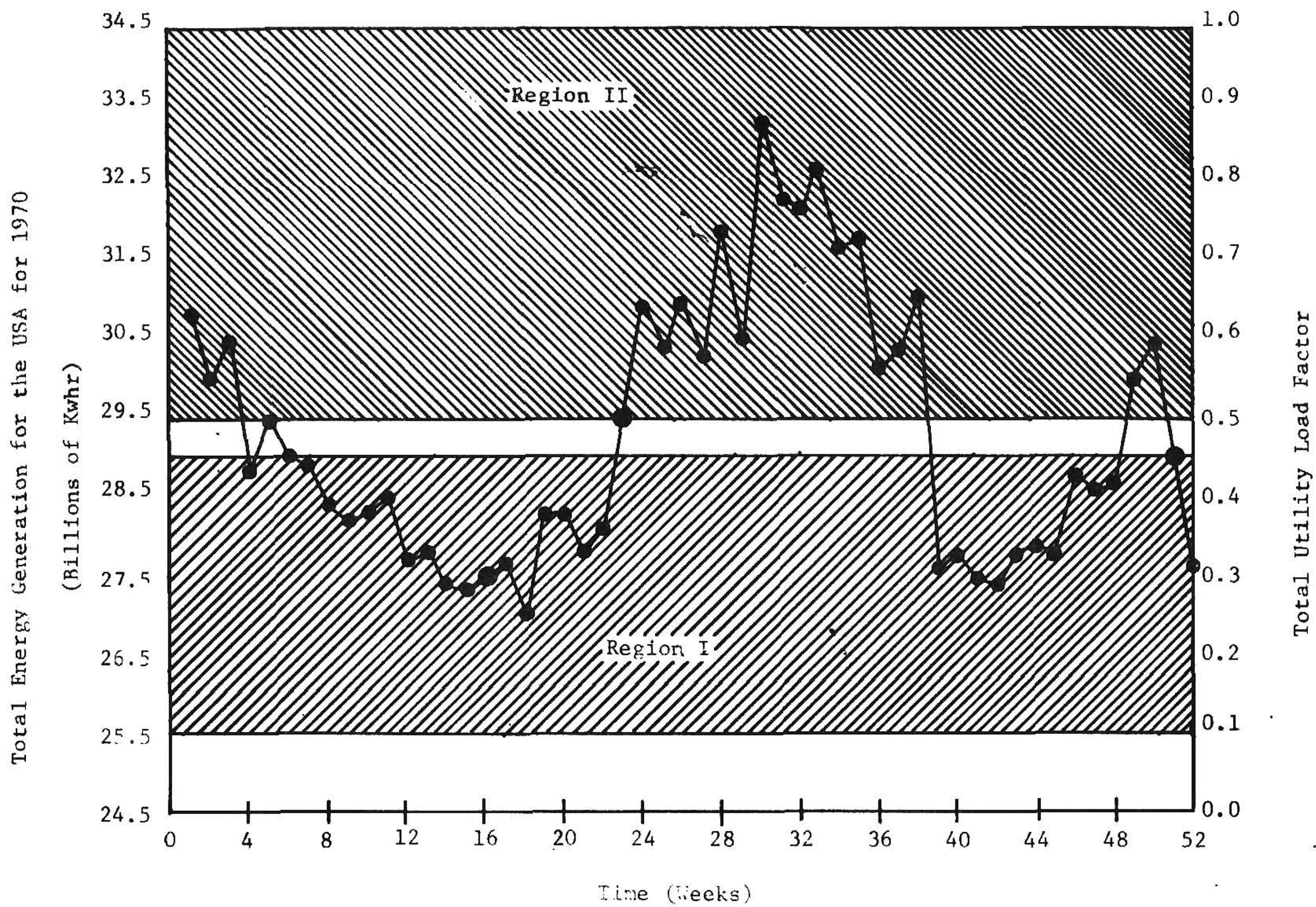


Figure 2: Total Energy Generation for the USA for 1970 and Total Utility Load Factor

CØNVER can be calculated from

$$\text{CØNVER} = \frac{10^6 \text{ watt}}{\text{Mwt}} \times \frac{1 \text{ joule}}{\text{sec watt}} \times \frac{1 \text{ Mev}}{1.6 \times 10^{13} \text{ joule}} \times \frac{\text{fission}}{E_R \text{Mev}}, \qquad (62)$$

where

E_R = recoverable fission energy.

It was assumed that E_R = 200 Mev (11); therefore, CONVER becomes

$$\text{CONVER} = 0.31245 \times 10^{17} \frac{\text{fission}}{\text{Mwt x sec}}. \qquad (63)$$

The fission rate in any region, $FISS_i$, is one-third of TOFIS, $FISS_i$ also has the relationship

$$FISS_i = N_i^{25}\sigma_{25}^f\phi_i + N_i^{49}\sigma_{49}^f\phi_i + N_i^{41}\sigma_{41}^f\phi_i, \qquad (64)$$

where N_i^{25}, N_i^{49}, and N_i^{41} and the atomic densities of U-235, Pu-239, and Pu-241, respectively, in the ith region; σ_{25}^f, σ_{49}^f, and σ_{41}^f are the microscopic fission cross-sections for the respective isotopes; ϕ_i is flux in region i. The solution of Eq. (64) for ϕ_i yields

$$\phi_i = \frac{FISS_i}{N_i^{25}\sigma_f + N_i^{49}\sigma_{49}^f + N_i^{41}\sigma_{41}^f}. \qquad (65)$$

3.0 CALCULATIONAL PROCEDURE

Load factors for the reference reactor were generated by the procedure in section 2.3. Load factors for three comparative cases were also generated by different averaging techniques. For the reference case, power was generated at a constant rate at the particular load factor for one week. For case 1, the load factors from the reference case were averaged from years 1-10, 11-20, 21-30 of operation. For case 2 the reference case load factors were averaged over the years 1-10, 11-30. For case 3, the reference case load factors were averaged over the years 1-30. For comparative cases, the power generation rate was assumed to be constant over the period for which the load factors were averaged. For example, if AV1, AV2, and AV3 are the averages of the load factors from the reference case over years 1-10, 11-20, 21-30, respectively, the power generation rate for the first ten years of operation, POWER, was

$$\mathrm{POWER} = \mathrm{AV1} \times \mathrm{POWE}, \tag{66}$$

where

POWE = maximum electrical power.

For the second and third ten year periods of operation the generation rates were

$$\mathrm{POWER} = \mathrm{AV2} \times \mathrm{POWE}, \tag{67}$$

$$\mathrm{POWER} = \mathrm{AV3} \times \mathrm{POWE}. \tag{68}$$

FUEL, a FØRTRAN IV computer code which incorporated the burnup equations described in section 2.1 was used to calculate startup dates, shutdown dates, and isotopes concentrations. CASH, a FØRTRAN IV computer code, calculated the schedules of fuel processing activities, cash flows, and present worth of cash flows using the methods described in section 2.2.

The present worth of each activity for each comparative case was compared to the reference case by the following method. The percentage deviation from the reference case for each activity of each comparative case was calculated by

$$P = \frac{X_I^k - Y_I^k}{X_I^k}, \tag{69}$$

where

X_I^k = present worth of the total of all cash flows for the kth activity at interest rate I for the reference case,

Y_I^k = present worth of the total of all cash flows for the kth activity for the comparative case at interest I,

k = denotes which activity in the fuel cycle, that is, whether the cash flow is for enrichment, fabrication, and so forth.

Thus, for a particular activity, P determines the effect of the load factor averaging techniques on the present of cash flows for that activity. P was also calculated for the present worth total of all cash flows in the fuel cycle to determine the overall effect of the averaging techniques throughout the fuel cycle.

4.0 RESULTS

Figure 3 is a display of the load factors for the reference case, which were determined by the method described in Section 2.3. For case 1, the average load factors for the 1-10, 11-20, and 21-30 year periods of operation were 0.800, 0.676, and 0.174, respectively. For case 2, the average load factors for the periods 1-10 and 11-30 years of operation were 0.800 and 0.425, respectively. For case 3, the average load factor over the thirty-year life of the plant was 0.550. The reference case, case 1, and case 2 each required 19-1/3 core fuel loadings while case 3 required 21-1/3 core fuel loadings. The difference in core loadings was due to the demand for higher burnup for case 3 over the last ten years of operation. Tables 5-9 are lists of the percentage deviations of cash flows from the reference case at interest rates of four, ten, twelve, sixteen, and eighteen percent, respectively: Tables 10-20 list the cash flow schedule and amounts of cash flow for each activity.

Discussion of Case 1

Case 1 results were very similar to the results from the reference case. For any activity, there was no more than two weeks difference in the schedule. There was a difference in the present worth of the cash flow for shipment to the reactor. This was due to a one week difference in scheduling. For load 17, the reference case listed the cash flow as occurring during the first week of 1990. Case 1 listed the activity as occurring during the last week of 1989. Although the schedules for the two cases were only a week in difference, the cash flows occurred in different years; the result was that the present worth of the cash flow for the reference case was less than the present worth of the cash flow from case 1.

The same scheduling problem occurred in the cash flow for reprocessing

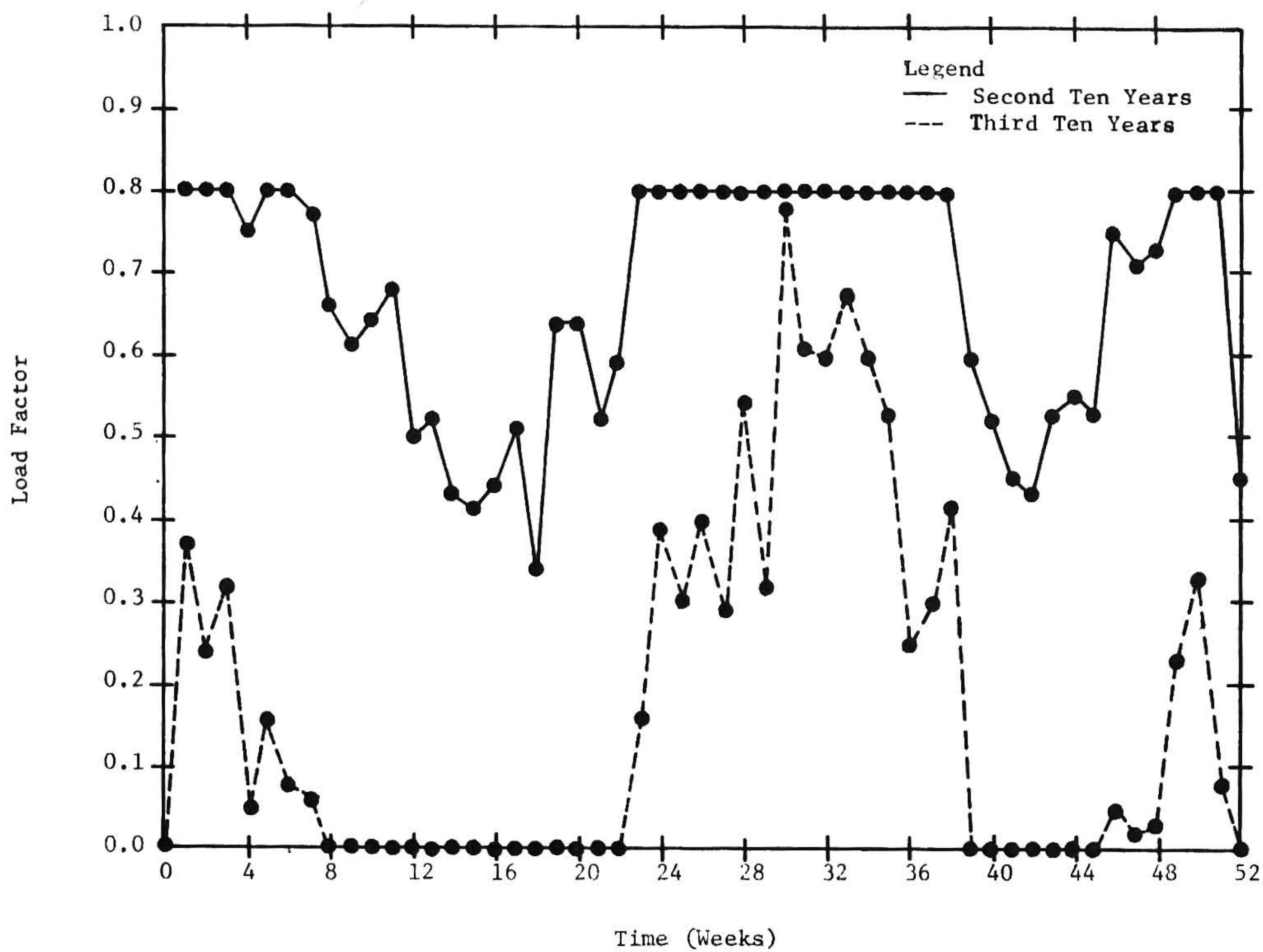


Figure 3: Load Factors for the Reference Case

Table 5: Percentage Deviations From the Reference Case at 4% Interest

Activity	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 3 Corrected (%)
Purchase of U_3O_8	0.00	2.24	-4.05	0.67
Conversion and Shipment	-0.00	2.33	-3.95	0.77
Enrichment	-0.00	2.65	-3.66	1.06
Fabrication	-0.00	2.66	-3.50	1.15
Excess and Scrap Credit	-0.00	2.66	-3.50	1.15
Shipment to Reactor	-0.13	2.53	-3.64	1.02
Shipment to Reprocessing	-0.00	2.75	-4.55	0.56
Reprocessing	-0.20	2.81	-4.77	0.65
Conversion of Uranium	-0.20	2.70	-5.09	0.12
Uranium Credit	0.02	1.35	-28.54	-18.72
Plutonium Credit	0.03	2.52	3.93	7.29
Total	-0.04	2.84	1.71	5.33

Table 6: Percentage Deviations From the Reference Case at 10% Interest

Activity	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 3 Corrected (%)
Purchase of U_3O_8	0.00	2.66	-0.34	1.01
Conversion and Shipment	-0.00	2.69	-0.27	1.08
Enrichment	-0.00	2.97	0.11	1.46
Fabrication	0.00	2.98	0.17	1.47
Excess and Scrap Credit	0.00	2.98	0.17	1.47
Shipment to Reactor	-0.16	2.83	0.02	1.32
Shipment to Reprocessing	0.00	3.81	-0.11	1.41
Reprocessing	-0.39	3.73	-0.38	1.28
Conversion of Uranium	-0.38	3.65	-0.97	0.58
Uranium Credit	-0.00	1.33	-28.30	-25.63
Plutonium Credit	0.01	3.54	9.59	10.59
Total	-0.05	3.24	5.44	6.54

Table 7: Percentage Deviations From the Reference Case at 12% Interest

Activity	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 3 Corrected (%)
Purchase of U_3O_8	0.00	2.49	0.12	1.00
Conversion and Shipment	0.00	2.48	0.16	1.04
Enrichment	0.00	2.73	0.53	1.41
Fabrication	0.00	2.73	0.55	1.40
Excess and Scrap Credit	0.00	2.73	0.55	1.40
Shipment to Reactor	-0.15	2.59	0.41	1.25
Shipment to Reprocessing	0.00	3.71	0.53	1.54
Reprocessing	-0.42	3.59	0.23	1.34
Conversion of Uranium	-0.41	3.51	-0.39	0.63
Uranium Credit	-0.00	1.22	-28.06	-26.35
Plutonium Credit	0.01	3.44	10.61	11.27
Total	-0.05	2.98	5.68	6.42

Table 8: Percentage Deviations From the Reference Case at 16% Interest

Activity	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 3 Corrected (%)
Purchase of U_3O_8	0.00	2.02	0.51	0.89
Conversion and Shipment	0.00	1.97	0.52	0.92
Enrichment	0.00	2.13	0.83	1.21
Fabrication	0.00	2.14	0.79	1.15
Excess and Scrap Credit	0.00	2.14	0.79	1.15
Shipment to Reactor	-0.11	2.03	0.68	1.05
Shipment to Reprocessing	0.00	3.24	1.16	1.59
Reprocessing	-0.43	3.06	0.80	1.30
Conversion of Uranium	-0.43	3.00	0.16	0.60
Uranium Credit	0.00	0.98	-27.47	-26.77
Plutonium Credit	-0.00	2.97	11.94	12.23
Total	-0.05	2.35	5.55	5.88

Table 9: Percentage Deviations From the Reference Case at 18% Interest

Activity	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 3 Corrected (%)
Purchase of U_3O_8	0.00	1.79	0.56	0.81
Conversion and Shipment	0.00	1.71	0.56	0.81
Enrichment	0.00	1.85	0.84	1.09
Fabrication	0.00	1.85	0.78	1.02
Excess and Scrap Credit	0.00	1.85	0.78	1.02
Shipment to Reactor	-0.10	1.75	0.69	0.92
Shipment to Reprocessing	0.00	2.95	1.26	1.54
Reprocessing	-0.43	2.76	0.90	1.23
Conversion of Uranium	-0.42	2.70	0.24	0.53
Uranium Credit	0.00	0.86	-27.14	-26.69
Plutonium Credit	-0.00	2.70	12.38	12.56
Total	-0.04	2.04	5.33	5.55

and in the conversion of reprocessed uranium for load 11. The reference case schedule listed the activities as ending in the first week in 1985; case 1 schedule listed then as ending the last week in 1984. The differences in the uranium and the plutonium credits were due to small differences in isotopic concentrations after irradiation.

Discussion of Case 2

Present worth cash flows for case 2 were somewhat smaller than those for the reference case. The energy generation rate was lower than the reference case during the second ten years; as a result, refuel shutdown periods for case 2 occurred later in the life of the plant than the refuel shutdown periods in the reference case. Since the present worth of a cash flow decreases as the number of interest periods increase, the present worth cash flows for case 2 were less than those for the reference case.

The deviations of case 2 from the reference case increased with increasing interest rates, reached a peak near 10%, and then decreased. Mathematically, one should expect this. For Eq. (69),

$$X_I^k = \sum_{j=1}^{n} \frac{x_j^k}{(1 + I)^j} \tag{70}$$

$$Y_I^k = \sum_{j=1}^{n} \frac{y_j^k}{(1 + i)^j} \tag{71}$$

where

x_j^k = cash flow during jth year for the kth activity in the reference case,

y_j^k = cash flow during jth year for the kth activity in the comparative case,

n = total number of years of plant operation.

Table 10: Cash Flow for U_3O_8 Purchase

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1971	4	1971	4	1971	4	1971	4
2	1971	4	1971	4	1971	4	1971	4
3	1971	4	1971	4	1971	4	1971	4
4	1972	4	1972	4	1972	4	1972	4
5	1973	4	1973	4	1973	4	1973	4
6	1974	4	1974	4	1974	4	1974	4
7	1975	4	1975	4	1975	4	1975	4
8	1976	4	1976	4	1976	4	1976	4
9	1977	4	1977	4	1977	4	1977	4
10	1978	4	1978	4	1978	4	1978	4
11	1979	4	1979	4	1979	4	1979	4
12	1980	4	1980	4	1980	4	1980	4
13	1981	4	1981	4	1981	4	1981	4
14	1983	44	1983	43	1985	20	1984	46
15	1985	22	1985	22	1987	45	1986	34
16	1987	10	1987	9	1990	31	1988	36
17	1989	18	1989	17	1993	50	1991	24
18	1991	7	1991	6	1996	39	1993	30
19	1998	2	1998	4	1999	39	1995	44
20							1998	15
21							2000	28

† All cash flows were for the amount $988,321.94.

Table 11: Cash Flow for Conversion and Shipping

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1971	17	1971	17	1971	17	1971	17
2	1971	17	1971	17	1971	17	1971	17
3	1971	17	1971	17	1971	17	1971	17
4	1972	17	1972	17	1972	17	1972	17
5	1973	17	1973	17	1973	17	1973	17
6	1974	17	1974	17	1974	17	1974	17
7	1975	17	1975	17	1975	17	1975	17
8	1976	17	1976	17	1976	17	1976	17
9	1977	17	1977	17	1977	17	1977	17
10	1978	17	1978	17	1978	17	1978	17
11	1979	17	1979	17	1979	17	1979	17
12	1980	17	1980	17	1980	17	1980	17
13	1981	17	1981	17	1981	17	1981	17
14	1984	5	1984	4	1985	33	1985	7
15	1985	35	1985	35	1988	6	1986	47
16	1987	23	1987	22	1990	44	1988	49
17	1989	31	1989	36	1994	11	1991	37
18	1991	20	1991	19	1996	52	1993	43
19	1998	15	1998	17	1999	50	1996	5
20							1998	28
21							2000	52

† All cash flows were for the amount $104,044.35.

Table 12: Cash Flow for Enrichment

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1971	26	1971	26	1971	26	1971	26
2	1971	26	1971	26	1971	26	1971	26
3	1971	26	1971	26	1971	26	1971	26
4	1972	26	1972	26	1972	26	1972	26
5	1973	26	1973	26	1973	26	1973	26
6	1974	26	1974	26	1974	26	1974	26
7	1975	26	1975	26	1975	26	1975	26
8	1976	26	1976	26	1976	26	1976	26
9	1977	26	1977	26	1977	26	1977	26
10	1978	26	1978	26	1978	26	1978	26
11	1979	26	1979	26	1979	26	1979	26
12	1980	26	1980	26	1980	26	1980	26
13	1981	26	1981	26	1981	26	1981	26
14	1984	14	1984	13	1985	42	1985	16
15	1985	44	1985	44	1988	15	1987	4
16	1987	32	1987	31	1991	1	1989	6
17	1989	40	1989	39	1994	20	1991	46
18	1991	29	1991	28	1997	9	1993	52
19	1998	24	1998	26	2000	6	1996	14
20							1998	37
21							2000	50

† All cash flows were for the amount $1,018,958.02.

Table 13: Cash Flow for Fabrication

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1971	37	1971	37	1971	37	1971	37
2	1971	37	1971	37	1971	37	1971	37
3	1971	37	1971	37	1971	37	1971	37
4	1972	37	1972	37	1972	37	1972	37
5	1973	37	1973	37	1973	37	1973	37
6	1974	37	1974	37	1974	37	1974	37
7	1975	37	1975	37	1975	37	1975	37
8	1976	37	1976	37	1976	37	1976	37
9	1977	37	1977	37	1977	37	1977	37
10	1978	37	1978	37	1978	37	1978	37
11	1979	37	1979	37	1979	37	1979	37
12	1980	37	1980	37	1980	37	1980	37
13	1981	37	1981	37	1981	37	1981	37
14	1984	25	1984	24	1986	1	1985	27
15	1986	3	1986	3	1988	26	1987	15
16	1987	43	1987	42	1991	12	1989	17
17	1989	51	1989	50	1994	31	1992	5
18	1991	40	1991	39	1997	20	1994	11
19	1998	35	1998	37	2000	17	1996	25
20							1998	48
21							2001	9

† All cash flows were for the amount $685,998.78.

Table 14: Cash Flow for Excess and Loss Credits From the Fabrication Process

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1971	37	1971	37	1971	37	1971	37
2	1971	37	1971	37	1971	37	1971	37
3	1971	37	1971	37	1971	37	1971	37
4	1972	37	1972	37	1972	37	1972	37
5	1973	37	1973	37	1973	37	1973	37
6	1974	37	1974	37	1974	37	1974	37
7	1975	37	1975	37	1975	37	1975	37
8	1976	37	1976	37	1976	37	1976	37
9	1977	37	1977	37	1977	37	1977	37
10	1978	37	1978	37	1978	37	1978	37
11	1979	37	1979	37	1979	37	1979	37
12	1980	37	1980	37	1980	37	1980	37
13	1981	37	1981	37	1981	37	1981	37
14	1984	25	1984	24	1986	1	1985	27
15	1986	3	1986	3	1988	26	1987	15
16	1987	43	1987	42	1991	12	1989	17
17	1989	51	1989	50	1994	31	1992	5
18	1991	40	1991	39	1997	20	1994	11
19	1998	35	1998	37	2000	17	1996	25
20							1998	48
21							2001	9

† All cash flows were for the amount $191,934.96.

Table 15: Cash Flow for Pre-Irradiation Shipping

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1971	39	1971	39	1971	39	1971	39
2	1971	39	1971	39	1971	39	1971	39
3	1971	39	1971	39	1971	39	1971	39
4	1972	39	1972	39	1972	39	1972	39
5	1973	39	1973	39	1973	39	1973	39
6	1974	39	1974	39	1974	39	1974	39
7	1975	39	1975	39	1975	39	1975	39
8	1976	39	1976	39	1976	39	1976	39
9	1977	39	1977	39	1977	39	1977	39
10	1978	39	1978	39	1978	39	1978	39
11	1979	39	1979	39	1979	39	1979	39
12	1980	39	1980	39	1980	39	1980	39
13	1981	39	1981	39	1981	39	1981	39
14	1984	27	1984	26	1986	3	1985	29
15	1986	5	1986	5	1988	28	1987	17
16	1987	45	1987	44	1991	14	1989	19
17	1990	1	1989	52	1994	33	1992	7
18	1991	42	1991	41	1997	22	1994	13
19	1998	37	1998	39	2000	19	1996	27
20							1998	50
21							2001	11

† All cash flows were for the amount $20,579.96.

Table 16: Cash Flow for Pre-Reprocessing Shipping

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1973	11	1973	11	1973	11	1973	11
2	1974	11	1974	11	1974	11	1974	11
3	1975	11	1975	11	1975	11	1975	11
4	1976	11	1976	11	1976	11	1976	11
5	1977	11	1977	11	1977	11	1977	11
6	1978	11	1978	11	1978	11	1978	11
7	1979	11	1979	11	1979	11	1979	11
8	1980	11	1980	11	1980	11	1980	11
9	1981	11	1981	11	1981	11	1981	11
10	1982	11	1982	11	1982	11	1982	11
11	1984	51	1984	50	1986	27	1986	1
12	1986	29	1986	29	1988	52	1987	41
13	1988	17	1988	16	1991	30	1989	43
14	1990	25	1990	24	1995	5	1992	31
15	1992	14	1992	13	1997	46	1994	37
16	1999	9	1999	11	2000	43	1996	51
17	2002	16	2002	16	2002	16	1999	22
18	2002	16	2002	16	2002	16	2001	35
19	2002	16	2002	16	2002	16	2002	16
20							2002	16
21							2002	16

† All cash flows were for the amount $48,019.91.

Table 17: Cash Flow for Reprocessing

	Reference Case†		Case 1†		Case 2†		Case 3†	
	Date		Date		Date		Date	
Load	Year	Week	Year	Week	Year	Week	Year	Week
1	1973	13	1973	13	1973	13	1973	13
2	1974	13	1974	13	1974	13	1974	13
3	1975	13	1975	13	1975	13	1975	13
4	1976	13	1976	13	1976	13	1976	13
5	1977	13	1977	13	1977	13	1977	13
6	1978	13	1978	13	1978	13	1978	13
7	1979	13	1979	13	1979	13	1979	13
8	1980	13	1980	13	1980	13	1980	13
9	1981	13	1981	13	1981	13	1981	13
10	1982	13	1982	13	1982	13	1982	13
11	1985	1	1984	52	1986	29	1986	3
12	1986	31	1986	31	1989	2	1987	43
13	1988	19	1988	18	1991	40	1989	45
14	1990	27	1990	26	1995	7	1992	33
15	1992	16	1992	15	1997	48	1994	39
16	1999	11	1999	13	2000	45	1997	1
17	2002	20	2002	20	2002	20	1999	24
18	2002	20	2002	20	2002	20	2001	37
19	2002	20	2002	20	2002	20	2002	20
20							2002	20
21							2002	20

† For the last three loads of each case, the cash flow was $228,639.71. For all the other loads, the cash flow was $356,639.71.

Table 18: Cash Flow for Conversion of Reprocessed Uranium

	Reference Case			Case 1			Case 2			Case 3		
Load	Year	Week	Amount (Dollars)	Year	Week	Amount (Dollars)	Year	Week	Amount (Dollars)	Year	Week	Amount (Dollars)
1	1973	13	37,496.85	1973	13	37,496.85	1973	13	37,496.85	1973	13	37,621.13
2	1974	13	37,132.85	1974	13	37,132.85	1974	13	37,132.85	1974	13	37,354.54
3	1975	13	36,810.82	1975	13	36,810.82	1975	13	36,810.82	1975	13	37,111.35
4	1976	13		1976	13		1976	13		1976	13	
5	1977	13		1977	13		1977	13		1977	13	
6	1978	13		1978	13		1978	13		1978	13	
7	1979	13		1979	13		1979	13		1979	13	
8	1980	13		1980	13		1980	13		1980	13	
9	1981	13		1981	13		1981	13		1981	13	
10	1982	13	↓	1982	13	↓	1982	13	↓	1982	13	↓
11	1985	1	36,398.09	1984	52	36,399.45	1986	29	36,402.36	1986	3	36,478.25
12	1986	31	36,295.65	1986	31	36,296.65	1989	2	36,301.04	1987	43	36,325.45
13	1988	19	36,163.21	1988	18	36,161.14	1991	40	36,166.19	1989	45	36,128.47
14	1990	27	36,301.66	1990	26	36,300.14	1995	7	36,304.68	1992	33	36,325.45
15	1992	16	36,259.91	1992	15	36,254.79	1997	48	36,258.95	1994	39	36,238.76
16	1999	11	36,229.30	1999	13	36,230.95	2000	45	36,227.81	1997	1	36,214.91
17	2002	20	36,547.03	2002	20	36,546.69	2002	20	36,514.98	1999	24	36,277.17
18	2002	20	37,015.96	2002	20	37,019.58	2002	20	36,980.41	2001	37	36,251.42
19	2002	20	37,612.70	2002	20	37,610.95	2002	20	37,572.40	2002	20	36,577.50
20										2002	20	37,121.07
21										2002	20	37,734.24

Table 19: Cash Flow for Uranium Credit

	Reference Case			Case 1			Case 2			Case 3		
Load	Year	Week	Amount (Dollars)	Year	Week	Amount (Dollars)	Year	Week	Amount (Dollars)	Year	Week	Amount (Dollars)
1	1973	17	1,404,201.71	1973	17	1,404,201.71	1973	17	1,404,201.71	1973	17	1,542,322.31
2	1974	17	1,023,747.93	1974	17	1,023,747.93	1974	17	1,023,747.93	1974	17	1,251,347.16
3	1975	17	712,756.46	1975	17	712,756.46	1975	17	712,756.46	1975	17	1,001,966.94
4	1976	17		1976	17		1976	17		1976	17	
5	1977	17		1977	17		1977	17		1977	17	
6	1978	17		1978	17		1978	17		1978	17	
7	1979	17		1979	17		1979	17		1979	17	
8	1980	17		1980	17		1980	17		1980	17	
9	1981	17		1981	17		1981	17		1981	17	
10	1982	17	↓	1982	17	↓	1982	17	↓	1982	17	↓
11	1985	5	354,186.25	1985	4	355,032.64	1986	33	356,634.89	1986	7	418,679.26
12	1986	35	275,263.58	1986	35	275,744.28	1989	6	278,219.73	1987	47	297,007.70
13	1988	23	181,668.16	1988	22	180,519.22	1991	44	182,979.29	1989	49	159,053.54
14	1990	31	279,738.96	1990	30	278,347.74	1995	11	280,933.14	1992	37	297,007.70
15	1992	20	248,404.86	1992	19	245,085.92	1997	52	247,254.29	1994	43	247,528.10
16	1999	15	226,071.07	1999	17	226,701.63	2000	49	225,037.91	1997	5	216,439.01
17	2002	24	476,226.81	2002	24	475,326.42	2002	24	449,035.08	1999	28	260,934.48
18	2002	24	907,644.37	2002	24	910,831.27	2002	24	873,058.79	2001	41	242,239.45
19	2002	24	1,532,761.44	2002	24	1,530,729.29	2002	24	1,487,504.30	2002	24	502,732.03
20										2002	24	1,001,675.07
21										2002	24	1,672,728.63

Table 20: Cash Flows for Plutonium Credit

Load	Reference Case Year	Reference Case Week	Reference Case Amount (Dollars)	Case 1 Year	Case 1 Week	Case 1 Amount (Dollars)	Case 2 Year	Case 2 Week	Case 2 Amount (Dollars)	Case 3 Year	Case 3 Week	Case 3 Amount (Dollars)
1	1973	17	230,212.71	1973	17	230,212.71	1973	17	230,212.71	1973	17	174,945.68
2	1974	17	340,186.73	1974	17	340,186.73	1974	17	340,186.73	1974	17	281,756.74
3	1975	17	380,114.92	1975	17	380,114.92	1975	17	380,114.92	1975	17	344,101.89
4	1976	17		1976	17		1976	17		1976	17	
5	1977	17		1977	17		1977	17		1977	17	
6	1978	17		1978	17		1978	17		1978	17	
7	1979	17		1979	17		1979	17		1979	17	
8	1980	17		1980	17		1980	17		1980	17	
9	1981	17		1981	17		1981	17		1981	17	
10	1982	17	↓	1982	17	↓	1982	17	↓	1982	17	↓
11	1985	5	359,320.19	1985	4	358,996.73	1986	33	358,310.27	1986	7	368,400.60
12	1986	35	342,502.55	1986	35	342,108.71	1989	6	341,673.39	1987	47	346,667.61
13	1988	23	313,271.81	1988	22	313,549.38	1991	44	313,281.52	1989	49	304,945.85
14	1990	31	343,613.43	1990	30	342,753.00	1995	11	342,340.85	1992	37	346,667.61
15	1992	20	333,897.47	1992	19	334,016.33	1997	52	333,541.67	1994	43	334,156.17
16	1999	15	326,862.67	1999	17	326,474.49	2000	49	327,089.54	1997	5	324,997.24
17	2002	24	374,371.56	2002	24	373,442.64	2002	24	371,633.41	1999	28	337,784.65
18	2002	24	359,931.04	2002	24	358,979.20	2002	24	364,758.25	2001	41	332,673.17
19	2002	24	178,965.09	2002	24	179,736.72	2002	24	197,703.44	2002	24	377,041.22
20										2002	24	342,205.54
21										2002	24	115,812.87

Equation (69) can be restated in terms of Eqs. (71) and (72) as

$$P = \frac{\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j} - \sum_{j=1}^{n} \frac{y_j^k}{(1+I)^j}}{\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j}} \tag{72}$$

The first derivative of P with respect to I in Eq. (72) is

$$\frac{dP}{dI} = \frac{1}{\left[\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j}\right]^2} \left[\sum_{j=1}^{n} \frac{(x_j^k - y_j^k)}{(1+I)^j} \sum_{j=1}^{n} \frac{(jx_j^k)}{(1+I)^{j+1}} - \sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j} \sum_{j=1}^{n} \frac{j(x_j^k - y_j^k)}{(1+I)^{j+1}} \right] \tag{73}$$

With dP/dI = 0, Eq. (73) becomes

$$\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j} \sum_{j=1}^{n} \frac{j(x_j^k - y_j^k)}{(1+I)^{j+1}} = \sum_{j=1}^{n} \frac{(x_j^k - y_j^k)}{(1+I)^j} \sum_{j=1}^{n} \frac{jxy}{(1+I)^{j+1}} \tag{74}$$

If Eq. (74) could be solved for I, it would yield a value for which P is a maximum, a minimum, or an inflexion point. Therefore another line of reasoning must be used to determine which it will be. From Tables 10-20, for small I

$$\sum_{j=1}^{n} x_j^k = \sum_{j=1}^{n} y_j^k. \tag{75}$$

Therefore as I approaches zero, P also approaches zero. As i and j become large, $\frac{x_j^k}{(1+I)^j}$ and $\frac{y_j^k}{(1+I)^j}$ approach zero, and for j = 1 - 10,

$$x_j^k = y_j^k. \tag{76}$$

thus forcing P to approach zero. Therefore, since P approaches zero at the upper and lower limits of I and P is known to have a non-zero value between the limits, there must be a value of I for which P is a maximum. For case 2, I lies between 4% and 10% for the maximum value of P.

Discussion of Case 3

The third column of Tables 5-9 lists the percentage deviations of case 3 from the reference case with all 21-1/3 core loadings considered. The fourth column lists the percentage deviations with only the first 19 core loadings considered. Therefore, from Tables 5-9 and Tables 10-20, one discerns that differences in the present worth of cash flows between the reference case and case 3 are caused by two factors: (1) Case 3 demanded two more 1/3 core loadings than did the reference case; and (2) the case 3 cash flows for a 1/3 core load occurred at a later date than the corresponding cash flows from the reference case for the same 1/3 core load. At the interest rate of 4%, the extra cost incurred in the two extra 1/3 core loadings caused a large percentage deviation. As the interest rate increased, the present worths of the cash flows for the last two loadings became negligible since they occurred late in the life of the plant. The difference in scheduling of cash flows for the two cases caused the deviations at higher interest rates. The deviations of case 3 were smaller for the most part than those of case 2 because the case 3 schedule was closer to that of the reference case.

The large percentage deviations for uranium and plutonium credits were caused by the difference in burnup scheduling between the reference case and case 3. For the first ten years of operation, the reactor operated at a load factor of 80% and was shutdown yearly for refueling in the reference cases and cases 1 and 2. However, in case 3, the reactor operated at a load factor of 55%; it also was refueled on an annual basis. Therefore, since the case 3 burnup schedule demanded less energy output than the other three cases, there was more uranium left at the end of an irradiation period. Consequently, the uranium credit cash flows for the years 1-10 in case 3 were much larger than those from the other three cases for the corresponding periods. Case 3 plutonium credits for the same periods were less than those of the other three cases since the fertile U-238 in case 3 had a lower exposure than it did in the other three cases.

Overall, there was essentially no difference in scheduling between the reference case and case 1. Therefore, the present worths of their cash flows and the present worth of total cash flow were nearly identical. The cash flows for case 2 during the second ten years lagged the cash flows from the reference case by as much as 5 years, causing deviations for particular cash flows to deviate by 2%-3%. The deviation for the total present worth of cash flows for case 2 was also on the order of 2%-3%. Case 3 showed marked deviations at low interest rates for particular cash flows and a small deviation for the total present worth of cash flows. As the interest rate increased, deviations for the particular cash flows decreased while the deviation for the total present worth increased. However, even with deviations for uranium credits on the order of 28% and deviations for plutonium credits as high as 12%, the deviation for the total present worth of cash flows was no more than 5.60% for any interest rate.

5.0 CONCLUSIONS

The case 1 averaging technique proved to be accurate for scheduling of cash flow activities. The case 2 technique displayed a marked difference in scheduling of cash flows. Some differences for particular activities were as high as five years. The case 3 technique provided a schedule more compatible with the reference case, but cash flows for particular activities lagged the reference case schedule by as much as three years. Utilities must have an accurate knowledge of the schedule of cash flow activities for financing reasons; therefore, one would tend to dismiss the case 2 and 3 technique as being too inaccurate.

However, all the results of this study are based upon the reference case load scheduling shown in Fig. 3. This schedule deviates strongly from the average load assumption. In the future, utilities will be using more pump-storage facilities and gas turbines to meet extreme peak loads. Thus, nuclear power station load schedules probably will be closer to the average load assumption than the schedule for the reference case used in this study. Therefore, case 2 and 3 techniques may be used for cash flow scheduling if the load schedules do not deviate strongly from the average assumption.

Nonetheless, the case 1 technique proved to be highly accurate. Therefore, for cash flow scheduling purposes, an average load factor may be used for periods of 1-10 years. For periods longer than ten years, the accuracy is wholly dependent upon the degree to which the actual load schedule deviates from the average assumption.

6.0 SUGGESTIONS FOR FURTHER STUDY

Many utilities have operating histories of over seventy years. Consequently they are able to reasonably predict load schedules. An obvious extension of this work would be the use of a more realistic load schedule derived from utility predictions.

Improvements are also possible in the burnup and reactivity calculations. The core could be divided into smaller regions for more accurate prediction of space dependence. Multi-group theory could provide better information on flux shapes, isotopic concentrations, and reactivity. Both improvements would eliminate the necessary assumption that the fission rate distribution is flat across the core.

Another criterion for shutdown should be included to eliminate the possibility of a refuel period occurring during the winter and summer peak load periods. Also, another cash flow factor should be included to account for startup and shutdown costs.

Many utilities are seriously considering the possibility of plutonium recycle, particularly since the U. S. government will no longer be purchasing plutonium after 1971. Therefore, it seems in order to alter the fuel cycle to include the cash flows that would be caused by plutonium recycle.

Finally, another method for including the affect of capital charges should be used since they represent a large fraction of the fuel cycle costs (12).

7.0 ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to Dr. N. D. Eckhoff for his assistance and guidance in this work. Appreciation is given to Dr. C. G. Chezem, Head of the Department of Nuclear Engineering, for his cooperation. Miss Maureen Beaudet is to be acknowledged for her diligent assistance in the preparation of this manuscript. Gratitude is given to the Atomic Energy Commission under whose traineeship program this work was done. Of course, a very warm and special thanks is given to the author's wife, Linda, for her support, understanding, and encouragement.

8.0 LITERATURE CITED

1. Coates, David E.
Studies in Nuclear Power Operations:
I. Optimization of Radial Poison Distribution During Fixed Fuel Operation
II. Cash-Flow Studies of Power Reactor Operations Under Time varying Non-equilibrium Market Conditions. Ph.D. Dissertation. University of Illinois. 1968.

2. Schwieger, Robert G.
Managing Nuclear Fuel Power. 113 (December 1969) No. 12. pp. 175-190.

3. Fagan, John R.
An Optimization Analysis for Fuel Replacement in Large Pressurized Water Reactors. Ph.D. Dissertation. Purdue University. 1968. University Microfilms, Inc. Ann Arbor, Michigan. 1968.

4. Bloomster, C. H., J. H. Nail, D. R. Haffner
PACTOLUS: A Code for Computing Nuclear Power Costs. BNWL-1169. Battelle Memorial Institute, Pacific Northwest Laboratories. Richland, Washington. UC-80 Reactor Technology. January 1970.

5. Deonigi, D. E., et.al.
UCOST: A Computer Code for Calculating the Cost of Enriched Uranium. BNWL-189. Battelle Memorial Institute, Pacific Northwest Laboratories. Richland, Washington. February 1966.

6. Eschbach, E. A., D. E. Deonigi, S. Goldsmith
QUICK: A Simplified Fuel Cost Code. HW-71812. Hanford Atomic Products Operation. Richland, Washington. January 1962.

7. Salmon, Royes
A Procedure and a Computer Code (POWERCO) for Calculating the Cost of Electricity Produced by Nuclear Power Stations. ORNL-3944. Oak Ridge National Laboratory. Oak Ridge, Tennessee. June 1966.

8. Benedict, M. A., et.al.
Nuclear Chemical Engineering. Chapter 3. Fuel Cycles in Thermal Nuclear Reactors. Revised April 1960. To be published.

9. Povejsil, D. J., R. L. Witzke, C. A. DeSalvo
Financial Aspects of the Nuclear Fuel Cycle. Proceedings of the American Power Conference. 29 (1967) pp. 237-249.

10. Electrical World. 175 (April 15, 1971) No. 8. p. 33.

11. Lamarsh, John R.
Introduction to Nuclear Reactor Theory. Addison-Wesley Publishing Co., Inc. Reading, Massachusetts. 1966.

12. Bigge, W. B., M. R. Stepp
Sensitivity Analysis: Big Step in Managing Fuel Cycle Costs. Electrical World. 175 (February 1, 1971) No. 3. pp. 48-49.

9.0 APPENDICES

APPENDIX A

The FUEL Code

A.1 Introduction

The FUEL code calculated the nuclide densities in each of the regions of the core; it also calculates the reactivity at the end of each week of burnup. The code also determines the startup and shutdown dates for each refueling period.

A.2 Input Data Format

Card 1 FØRMAT (6D13.6)

EPSI - fast fission factor

PTH - fission to thermal non leakage probability

PREP - resonance escape probability

DB2 - thermal leakage factor

PMAX - maximum rated thermal power

Card 2 FØRMAT (6D13.6)

P11 - fission to resonance non leakage probability

CØNVER- 0.31245 x 10^{17} fission/Mwt sec

VREG - volume of each region

T - time period considered in one burnup calculation

Card 3 FØRMAT (6D13.6)

ETA25 - η for U-235

RM25 - poison ratio for U-235

SA25 - microscopic absorption cross section of U-235

ALP25 - α for U-235

XNU25 - ν for U-235

Card 4 FØRMAT (6D13.6)

ETA49 - η for Pu-239

RM49 - poison ratio for Pu-239

SA49 - microscopic absorption cross section for Pu-239

ALP49 - α for Pu-239

XNU49 - ν for Pu-239

Card 5 FØRMAT (6D13.6)

ETA41 - η for Pu-241

RM41 - poison ratio for Pu-241

SA41 - microscopic absorption cross section for Pu-241

ALP41 - α for Pu-241

XNU41 - ν for Pu-241

Card 6 FØRMAT (6D13.6)

SA26 - microscopic absorption cross section for U-236

SA28 - microscopic absorption cross section for U-238

SA40 - microscopic absorption cross section for Pu-240

SAFF - microscopic absorption cross section for fission product pairs

SAH20 - microscopic absorption cross section for water

SAST - microscopic absorption cross section for structural components

Card 7 FØRMAT (6D13.6)

ANH2Ø - nuclidic density of water

ANST - nuclidic density of structural components

ANØØ25 - initial nuclidic density of U-235

ANØØ28 - initial nuclidic density of U-238

ANØØ26 - initial nuclidic density of U-236

ANØØ49 - initial nuclidic density of Pu-239

Card 8 FØRMAT (6D13.6)

ANØØ41 - initial nuclidic density of Pu-241

ANØØ40 - initial nuclidic density of Pu-240

ANFØ25 - initial nuclidic density of fission product pairs from U-235 fission

ANFØ28 - initial nuclidic density of fission product pairs from U-238 fission

ANFØ41 - initial nuclidic density of fission product pairs from Pu-241 fission

ANFØ49 - initial nuclidic density of fission product pairs from Pu-239 fission

Card 9-17 FØRMAT (6D13.6)

PNOM(L) - load factor for Lth week of the year during years 1-10 of operation

Card 18-26 FØRMAT (6D13.6)

PAA(L) - load factor for the Lth week of the year during years 21-30 of operation

Card 27-35 FØRMAT (6D13.6)

PBB(L) - load factor for the Lth week of the year during years 21-30 of operation

Card 36 FØRMAT (6D13.6)

XNU28 - ν for U-238

Card 37 FØRMAT (16I5)

NSTA - starting week

NEN1 - number of weeks in years 1-10 of operation

NEN2 - number of weeks in years 1-20 of operation

NENT - total number of weeks of operation

A.3 The FUEL Code Listing

```
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION IBRN(50),NBRN(50),ANO25(3),ANO28(3),ANO26(3),ANO49(3)
      DIMENSION ANO40(3),ANO41(3),ANOF25(3),ANOF49(3),ANOF28(3)
      DIMENSION ANOF41(3),TIMER(3),AN25(3),AN28(3),AN26(3),AN49(3)
      DIMENSION AN40(3),AN41(3),ANF41(3),ANF25(3),ANF49(3),ANF28(3)
      DIMENSION PNOM(52),PAA(52),PBB(52),FLREL(3),PHI(3),EX25(3),EX26(3)
      DIMENSION EXG49(3),EX40(3),C0(3),C1(3),C2(3),C3(3),C4(3),EX41(3)
      DIMENSION C5(3),C6(3),C7(3),C8(3),C9(3),C10(3),C11(3),C12(3)
      DIMENSION CA(3),CB(3),CC(3),CD(3),CE(3),CF(3),CG(3),CH(3),CI(3)
      DIMENSION CK(3),TIM(50),CON25(50),CON26(50),CON28(50),CON49(50)
      DIMENSION CON40(50),CON41(50),FISS(3)
      DIMENSION CONF25(50),CONF49(50),CONF41(50),CONF28(50)
  534 FORMAT(6D13.6)
  535 FORMAT(16I5)
      READ(1,534) EPSI, PTH, PREP, DB2, PMAX
      READ(1,534) P11, CONVER, VREG, T
      READ(1,534) ETA25, RM25, SA25, ALP25, XNU25
      READ(1,534) ETA49, RM49, SA49, ALP49, XNU49
      READ(1,534) ETA41, RM41, SA41, ALP41, XNU41
      READ(1,534) SA26, SA28, SA40, SAFF, SAH2O, SAST
      READ(1,534) ANH2O, ANST, ANO025, ANO028, ANO026, ANO049
      READ(1,534) ANO041, ANO040, ANFO25, ANFO28, ANFO41, ANFO49
      READ(1,534) (PNOM(L), L=1,52)
      READ(1,534) (PAA(L), L=1,52)
      READ(1,534) (PBB(L), L=1,52)
      READ(1,534) XNU28
      READ(1,535) NSTA, NEN1, NEN2, NENT
      WRITE(3,534) EPSI, PTH, PREP, DB2, PMAX
      WRITE(3,534) P11, CONVER,  VREG, T
      WRITE(3,534) ETA25, RM25, SA25, ALP25, XNU25
      WRITE(3,534) ETA49, RM49, SA49, ALP49, XNU49
      WRITE(3,534) ETA41, RM41, SA41, ALP41, XNU41
      WRITE(3,534) SA26, SA28, SA40, SAFF, SAH2O, SAST
      WRITE(3,534) ANH2O, ANST, ANO025, ANO028
      WRITE(3,534) (PNOM(L), L=1,52)
      WRITE(3,534) (PAA(L), L=1,52)
      WRITE(3,534) (PBB(L), L=1,52)
      WRITE(3,534) XNU28
      WRITE(3,535) NSTA, NEN1, NEN2, NENT
      GAMMA = 1.D+0 - ( ETA49*EPSI*P11*(1.D+0 - PREP))
      AMU25 = ETA25 * EPSI * PTH * PREP
      AMU41 = ETA41 * EPSI * PTH * PREP
      AMU49 = ETA49 * EPSI * PTH * PREP
      AKAP25 = ETA25 * EPSI * P11 * (1.D+0 - PREP)
      XMU25 = AMU25 -1.D+0 - RM25
      XMU41 = AMU41 -1.D+0 - RM41
      XMU49 = AMU49 -1.D+0 - RM49
      GAMSIG = GAMMA * SA49
      NC = 0
      K = 1
      J = NSTA + 51
      N = J
    1 IF(J.GT.N) GO TO 7
```

```
      DO 5 I=1,3
    5 IBRN(I) = J + 1
      NBRN(1) = IBRN(1) + 47
      GO TO 10
    7 K = K + 1
      IBRN(K+2) = J + 5
      J = J + 4
   10 J = J + 1
      IF(J.NE.(N+1)) GO TO 17
      DO 14 I=1,3
      AN025(I) = AN0025
      AN028(I) = AN0028
      AN026(I) = AN0026
      AN049(I) = AN0049
      AN040(I) = AN0040
      AN041(I) = AN0041
      ANOF25(I) = ANF025
      ANOF49(I) = ANF049
      ANOF28(I) = ANF028
      ANOF41(I) = ANF041
      TIMER(I) = 0.D+0
   14 CONTINUE
      GO TO 25
   17 IF(NC.EQ.0) GO TO 19
      DO 18 I=2,3
      AN025(I) = AN25(I-1)
      AN028(I) = AN28(I-1)
      AN026(I) = AN26(I-1)
      AN049(I) = AN49(I-1)
      AN040(I) = AN40(I-1)
      AN041(I) = AN41(I-1)
      ANOF41(I) = ANF41(I-1)
      ANOF25(I) = ANF25(I-1)
      ANOF49(I) = ANF49(I-1)
      ANOF28(I) = ANF28(I-1)
   18 CONTINUE
      AN025(1) = AN0025
      AN028(1) = AN0028
      AN026(1) = AN0026
      AN049(1) = AN0049
      AN040(1) = AN0040
      AN041(1) = AN0041
      ANOF25(1) = ANF025
      ANOF49(1) = ANF049
      ANOF28(1) = ANF028
      ANOF41(1) = ANF041
      TIMER(3) = TIMER(2)
      TIMER(2) = TIMER(1)
      TIMER(1) = 0.D+0
      GO TO 25
   19 DO 20 I=1,3
      AN025(I) = AN25(I)
      AN026(I) = AN26(I)
```

```
      ANO28(I) = AN28(I)
      ANO49(I) = AN49(I)
      ANO40(I) = AN40(I)
      ANO41(I) = AN41(I)
      ANOF25(I) = ANF25(I)
      ANOF41(I) = ANF41(I)
      ANOF49(I) = ANF49(I)
      ANOF28(I) = ANF28(I)
   20 CONTINUE
   25 M = J / 52
      L = J - ( M * 52 )
      IF(L.EQ.0) L = 52
      IF(PNOM(L).EQ.0) GO TO 32
      TOFIS = CONVER * PMAX * PNOM(L)
      DO 26 I=1,3
      FISS(I) = (( ANO25(I) * SA25 ) / ( 1.D+0 + ALP25 )) + (( ANO49(I)
     1* SA49) / ( 1.D+0 + ALP49 )) + (( ANO41(I) * SA41 ) / ( 1.D+0 + AL
     2P41 ))
      PHI(I) = ( TOFIS ) / ( FISS(I) * 3.D+0 * VREG )
   26 FLREL(I) = PHI(I)
      PHIBAR = ( PHI(1) + PHI(2) + PHI(3) ) / 3.D+0
      DO 30 I=1,3
      TIMER(I) = TIMER(I) + PHI(I) * T
      EX25(I) = DEXP(-(SA25 * PHI(I) * T ))
      EX26(I) = DEXP(-(SA26 * PHI(I) * T ))
      EX41(I) = DEXP(-(SA41 * PHI(I) * T ))
      EX40(I) = DEXP(-(SA40 * PHI(I) * T ))
      EXG49(I) = DEXP(-( GAMSIG * PHI(I) * T ))
      CO(I) =(ANO25(I) * SA25 * ALP25 ) / (( SA25 - SA26 ) * (1.D+0 + AL
     1P25 ))
      C1(I) = (ANO28(I) * SA28) / GAMSIG
      C2(I) = ( ANO25(I) * AKAP25 * SA25 ) / ( GAMSIG - SA25 )
      C3(I) = ANO49(I)
      C4(I) = ((ALP49 * SA49 ) / (( 1.D+0 + ALP49) * SA40 )) * C1(I)
      C5(I) = (ALP49 * SA49 * C2(I)) / (( 1.D+0 +ALP49 ) * (SA40-SA25))
      C6(I) = (ALP49 * SA49 * ( C1(I) + C2(I) - C3(I))) / (( 1.D+0 + ALP
     149 ) * ( SA40 - GAMSIG ))
      C7(I) = ANO40(I)
      C8(I) = ( C4(I) * SA40 ) / SA41
      C9(I) = ( C5(I) * SA40 ) / ( SA41 - SA25)
      C10(I)= (( C6(I) * SA40 ) / ( SA41 - GAMSIG )) + ( ANO41(I)
     1  ) + (( SA40 * ( C4(I) + C5(I) - C6(I) -C7(I))) / ( SA41 - SA40))
     2 - (( C4(I) * SA40 ) / SA41 ) - (( C5(I) * SA40) / (SA41-SA25))
      C11(I) = - (C6(I) * SA40 ) / (SA41 - GAMSIG)
      C12(I) = (( - C4(I) - C5(I) +C6(I) + C7(I) ) * SA40 )/(SA41-SA40)
      AN41(I) = C8(I) + C9(I)*EX25(I) + C10(I)*EX41(I) + C11(I)*EXG49(I)
     1 + C12(I)*EX40(I)
      AN25(I) = ANO25(I) * EX25(I)
      AN26(I) = ( CO(I) + ANO26(I)) * EX26(I) - CO(I) * EX25(I)
      AN49(I) = C1(I) + C2(I)*EX25(I) - ( C1(I) + C2(I) - C3(I)) * EXG49
     1(I)
      AN40(I) = C4(I) +C5(I) * EX25(I) - C6(I) * EXG49(I) - (C4(I) + C5(
     1I) - C6(I) -C7(I)) * EX40(I)
```

```
      ANF25(I) = (( AN025(I) * (1.D+0 - EX25(I))) / (1.D+0 +ALP25)) +ANO
     1F25(I)
      CA(I) = C1(I) * PHI(I) * T
      CB(I) = ( C2(I) * (1.D+0 - EX25(I)))/ SA25
      CC(I) =(( C1(I) + C2(I) - C3(I)))* (1.D+0 - EXG49(I))/GAMSIG
      CD(I) =(( CA(I) + CB(I) - CC(I))* SA49)/(1.D+0 + ALP49)
      ANF49(I) = CD(I) + ANOF49(I)
      CE(I) = C8(I) * PHI(I) * T
      CF(I) = C9(I) * (1.D+0 - EX25(I)) / SA25
      CG(I) = C10(I) * (1.D+0 - EX41(I))/ SA41
      CH(I) = C11(I) * (1.D+0 - EXG49(I))/GAMSIG
      CI(I) = C12(I) * (1.D+0 - EX40(I)) / SA40
      CK(I) = ((CE(I)+CF(I)+CG(I)+CH(I)+CI(I))*SA41) /(1.D+0 +ALP41)
      ANF41(I) = CK(I) + ANOF41(I)
      ANF28(I) = ((XNU25 * ANF25(I) + XNU49 * ANF49(I) + XNU41* ANF41(I)
     1)*(EPSI - 1.D+0) / (XNU28 - 1.D+0))
      AN28(I) = AN0028 - ANF28(I) -AN49(I) - ANF49(I) - AN40(I) - AN41(I
     1) - ANF41(I)
   30 CONTINUE
      GO TO 36
   32 RHO = 1.D+0
      DO 34 I=1,3
      AN25(I) = AN025(I)
      AN26(I) = AN026(I)
      AN28(I) = AN028(I)
      AN49(I) = AN049(I)
      AN40(I) = AN040(I)
      AN41(I) = AN041(I)
      ANF25(I) = ANOF25(I)
      ANF28(I) = ANOF28(I)
      ANF49(I) = ANOF49(I)
      ANF41(I) = ANOF41(I)
   34 CONTINUE
      GO TO 405
   36 S25 = 0.D+0
      S49 = 0.D+0
      S26 = 0.D+0
      S40 = 0.D+0
      SFF = 0.D+0
      S28 = 0.D+0
      S41 = 0.D+0
      DO 60 I=1,3
      S41 = S41 + AN41(I) * FLREL(I)
      S25 = S25 + AN25(I) * FLREL(I)
      S49 = S49 + AN49(I) * FLREL(I)
      S26 = S26 + AN26(I) * FLREL(I)
      S40 = S40 + AN40(I) * FLREL(I)
      S28 = S28 + AN28(I) * FLREL(I)
      SFF = SFF + (ANF49(I) + ANF25(I) + ANF28(I) + ANF41(I)) *FLREL(I)
   60 CONTINUE
      RHO41 = XMU41 * SA41 *S41
      RHO25 = XMU25 * SA25 * S25
      RHO49 = XMU49*SA49*S49
```

```
      RHO26 = S26 * SA26
      RHO40 = S40 * SA40
      RHOFF = SFF * SAFF
      RHO28 = S28 * SA28
      DRH41 = AMU41 * S41 * SA41
      DRH25 = AMU25 * S25 * SA25
      DRH49 = AMU49 * S49 * SA49
      RLEAK = DB2 * PHIBAR
      RHH20 = ANH20 * SAH20 * PHIBAR
      RHOST = ANST * SAST* PHIBAR
      DRHO = RHO25 + RHC49 + RHO41 - RHO26 - RHO40 - RHOFF - RHO28 - RLE
     1AK - RHH20 - RHOST
      DAHO = DRH25 + DRH49 + DRH41
      RHO = DRHO / DAHO
  400 FORMAT(5X,I4,5X,D20.10,5X,D20.10,5X,D20.10,5X,D20.10)
      WRITE(3,400) J, RHO, FLREL(1), FLREL(2), FLREL(3)
  405 IF(J.GT.NEN1) GO TO 80
      NC = 0
      IF(RHO.LE.0.D+0) GO TO 115
      IF(J.LT.NBRN(K)) GO TO 10
      NC = NBRN(K)
      NBRN(K+1) = NBRN(K) + 52
      TIM(K) = TIMER(3) * 1.D-21
      CON25(K) = AN25(3)
      CON26(K) = AN26(3)
      CON28(K) = AN28(3)
      CON49(K) = AN49(3)
      CON40(K) = AN40(3)
      CON41(K) = AN41(3)
      CONF25(K) = ANF25(3)
      CONF49(K) = ANF49(3)
      CONF41(K) = ANF41(3)
      CONF28(K) = ANF28(3)
   80 IF(J.LT.NEN1) GO TO 7
      IF(J.EQ.NEN1) GO TO 90
      IF(J.LT.NEN2) GO TO 110
      IF(J.EQ.NEN2) GO TO 105
      IF(J.LT.NENT) GO TO 110
      GO TO 200
   90 DO 100 L=1,52
      PNOM(L) = PAA(L)
  100 CONTINUE
      GO TO 7
  105 DO 108 L=1,52
      PNOM(L) = PBB(L)
  108 CONTINUE
  110 NC = 0
      IF(RHO.GT.0.D+0) GO TO 10
  115 IF(J.LT.NEN1) NBRN(K+1) = NBRN(K) + 52
      NBRN(K) = J
      NC = NBRN(K)
      MMM= J + 5
      IF(MMM.GE.NENT) GC TO 200
```

```
      TIM(K) = TIMER(3) * 1.D-21
      CON25(K) = AN25(3)
      CON26(K) = AN26(3)
      CON28(K) = AN28(3)
      CON49(K) = AN49(3)
      CON40(K) = AN40(3)
      CON41(K) = AN41(3)
      CONF25(K) = ANF25(3)
      CONF49(K) = ANF49(3)
      CONF41(K) = ANF41(3)
      CONF28(K) = ANF28(3)
      MAM = J + 4
      IF(MAM.LE.NEN1) GC TO 7
      CO 170 L=1,52
      PNOM(L) = PAA(L)
  170 CONTINUE
      IF(MAM.LE.NEN2) GC TO 7
      DO 180 L=1,52
      PNOM(L) = PBB(L)
  180 CONTINUE
      GO TO 7
  200 I = 3
  201 CON25(K) = AN25(I)
      CON26(K) = AN26(I)
      CON28(K) = AN28(I)
      CON49(K) = AN49(I)
      CON40(K) = AN40(I)
      CON41(K) = AN41(I)
      CONF25(K) = ANF25(I)
      CONF49(K) = ANF49(I)
      CONF41(K) = ANF41(I)
      CONF28(K) = ANF28(I)
      TIM(K) = TIMER(I) * 1.D-21
      NBRN(K) = J
      K=K + 1
      I = I -1
      IF(I.GT.C) GO TO 201
      K = K - 1
      WRITE(3,432)
      WRITE(3,450) (M, IBRN(M), NBRN(M), TIM(M), CON25(M), CON49(M), CON
     141(M), M=1,K)
  432 FORMAT(5X,'LOAD',7X,'STARTING',7X,'ENDING',7X,'FLUX TIME',7X,'URAN
     1IUM-235',7X,'PLUTONIUM-239',7X,'PLUTONIUM-241'/18X,'DATE',10X,'DAT
     2E',10X,'(N/KB)',7X,'CONCENTRATION',7X,'CONCENTRATION',7X,'CONCENTR
     3ATION'///)
  450 FORMAT(5X,I4,9X,I4,10X,I4,5X,D15.10,2X,D15.10,5X,D15.10,5X,D15.10/
     1/)
      WRITE(3,942) (M, CON26(M), CON28(M), CON40(M), CONF25(M), M=1,K)
      WRITE(3,943) (M, CONF49(M), CONF41(M), CONF28(M), M=1,K)
  942 FORMAT(5X,I4,9X,D15.10,9X,D15.10,9X,D15.10,9X,D15.10)
  943 FORMAT(5X,I4,9X,D15.10,9X,D15.10,9X,D15.10)
  537 FORMAT(3I4,3D15.1C)
  538 FORMAT(2D15.10)
```

```
      WRITE(2,537) ( M, IBRN(M), NBRN(M), CON25(M), CON28(M), CON26(M),
     1M=1,K)
      WRITE(2,538) ( CON49(M), CON41(M), M=1,K)
      STOP
      END
```

APPENDIX B

The CASH Code

B.1 Introduction

The CASH code was used to determine the scheduling of cash flows, the amount of each cash flow, the present worth of each cash flow, and the total present worth of all cash flows. It utilizes the burnup data from FUEL.

B.2 Input Data Format

Cards 1-3 FØRMAT (13(2X, A4))

PQ(I) - the letter symbols for each of the twenty-nine cash flow activities

Card 4 FØRMAT (6D13.6)

CF1 - unitized cost for purchase of U_3O_8

CF2 - unitized cost for conversion and shipping

CF3 - unitized cost of enrichment

CF4 - unitized cost of shipping enriched fuel to the fabrication plant

CF5 - unitized cost of fabrication

CF5A - unitized cost of shipping fabricated fuel to the reactor site

Card 5 FØRMAT (6D13.6)

CF7 - unitized cost of reprocessing

CF8 - unitized cost of conversion of reprocessed uranium

CIRU - unitized credit for plutonium

VREG - volume of each region of the core

ANØØ25 - initial nuclidic density of U-235

CF6 - unitized cost of shipping irradiated fuel to the reprocessing plant

Card 6 FØRMAT (6D13.6)

DINT(I) - ith interest rate

Card 7 FØRMAT (6D13.6)

ANØØ28 - initial nuclidic density of U-238

XP - product enrichment of the enrichment plant

XW - tail enrichment of the enrichment plant

XF - feed enrichment of the enrichment plant

Card 8 FØRMAT (16I5)

NYRO - the calendar year prior to the startup year

NINT - number of interest rates

K - number of 1/3 core loads

Card 9-27 FØRMAT (4X, 2I4, 3D15.10)

IBRN(M) - startup week for Mth load

NBRN(M) - shutdown week for Mth load

CØN25(M) - final nuclidic density of U-235 for Mth load

CØN28(M) - final nuclidic density of U-238 for Mth load

CØN26(M) - final nuclidic density of U-236 for Mth load

Card 28-46 FØRMAT (2D15.10)

CØN49(M) - final nuclidic density of Pu-239 for the Mth load

CØN41(M) - final nuclidic density of Pu-241 for the Mth load

B.3 The CASH Code Listing

```
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION NFAB(50),IFAB(50),NSEN(50),ISEN(50),NENR(50),IENR(50)
      DIMENSION IBRN(50),NBRN(50),NLOA(50),ILOA(50),NSFA(50),ISFA(50)
      DIMENSION NCOS(50),ICOS(50),IPUR(50),IUNL(50),NUNL(50),ICOL(50)
      DIMENSION NCOL(50),ISCO(50),NSCO(50),IREP(50),NREP(50),ISRE(50)
      DIMENSION NSRE(50),GB25(50),GB26(50),GB28(50),GB49(50),GB41(50)
      DIMENSION XE(50),F(50),FC(50),PURC(50),UREP(50),PURE(50),COS7(50)
      DIMENSION COS8(50),DELTB(50),UCRU(50),CRE2(50),CRE3(50),TOFLO(50)
      DIMENSION PQ(30),CINT(6),PWF(6,35),PTOFO(6,35),PTOF(6),FIXE(50)
      DIMENSION W(50),CON25(50),CON26(50),CON28(50),CON49(50),CON41(50)
      DIMENSION CFPUR(35),CFCOS(35),CFENR(35),CFSEN(35),CFFAB(35)
      DIMENSION CFSFA(35),CFSCO(35),CFCR1(35),CFREP(35),CFCON(35)
      DIMENSION CFCR2(35),CFCR3(35),TFPUR(5,35),TFCOS(5,35),TFENR(5,35)
      DIMENSION TFSEN(5,35),TFFAB(5,35),TFSFA(5,35),TFSCO(5,35)
      DIMENSION TFCR1(5,35),TFREP(5,35),TFCON(5,35),TFCR2(5,35)
      DIMENSION TFCR3(5,35),TOPUR(5),TOCOS(5),TOENR(5),TOSEN(5),TOCR2(5
      DIMENSION TOSFA(5),TOSCO(5),TOCR1(5),TOREP(5),TOCON(5),TOFAB(5)
      DIMENSION TOCR3(5)
  536 FORMAT(13(2X,A4))
  534 FORMAT(6D13.6)
  535 FORMAT(16I5)
  537 FORMAT(4X,2I4,3D15.10)
  538 FORMAT(2D15.10)
 1013 FORMAT(1H1)
 1117 FORMAT(59X,11H-----------//)
 1023 FORMAT(1H-)
 1003 FORMAT(22X,'SUMMARY OF CASH FLOWS FOR ',I4)
 1033 FORMAT(11X,'--------',14X,'----',8X,'----',9X,'------------')
  999 FORMAT(11X,A4,18X,I4,8X,I4)
 1007 FORMAT(11X,A4,18X,I4,8X,I4,9X,F11.2)
 1119 FORMAT(11X,A4,18X,I4,8X,I4,8X,'-',F11.2)
 1037 FORMAT(1H0)
 1043 FORMAT(28X,'TOTAL CASH FLOW FOR THE YEAR = ',F11.2)
 1121 FORMAT(1X,'INTEREST',2X,D15.10,2X,D15.10,2X,D15.10,2X,D15.10,2X,D.
     15.10//)
 3201 FORMAT(1X,I2,8X,D15.10,2X,D15.10,2X,D15.10,2X,D15.10,2X,D15.10)
 1027 FORMAT(11X,'ACTIVITY',14X,'LOAD',8X,'WEEK',9X,'CASH FLOW($)')
  541 FORMAT(4X,2I4,3D18.10)
  542 FORMAT(2D18.10)
  539 FORMAT(1X,A4,4X,5(2X,D15.10))
 4000 FORMAT(1X,'TOTAL',3X,5(2X,D15.10))
 4001 FORMAT(9X,5(2X,'---------------'))
      READ(5,536)   ( PC(I), I=1,29)
      READ(5,534)   CF1, CF2, CF3, CF4, CF5, CF5A
      READ(5,534)  CF7, CF8, CIRU, VREG, ANO025, CF6
      NINT = 5
      READ(5,534)  ( DINT(I), I=1,NINT )
      READ(5,534)  ANO028, XP, XW, XF
      READ(5,535)   NYRO, NINT, K
      READ(5,537)     ( IBRN(M), NBRN(M), CON25(M), CON28(M), CON26(M), !
     1=1,K)
      READ(5,538)  ( CON49(M), CON41(M), M=1,K)
      WRITE(6,535)  NYRO, NINT, K
```

```
      WRITE(6,536)  ( PC(I), I=1,29)
      WRITE(6,534)  CF1, CF2, CF3, CF4, CF5, CF5A
      WRITE(6,534) CF7, CF8, CIRU, VREG, ANO025, CF6
      WRITE(6,534) ( DINT(I), I=1,NINT )
      WRITE(6,534) ANO028, XP, XW, XF
      WRITE(6,541)   ( IBRN(M), NBRN(M), CON25(M), CON28(M), CON26(M),
     1=1,K)
      WRITE(6,542) ( CON49(M), CON41(M), M=1,K)
      DO 800 M=1,K
      NLOA(M) = IBRN(M) - 1
      ILOA(M) = IBRN(M) -  4
      NSFA(M) = IBRN(M) -  5
      ISFA(M) = IBRN(M) -  6
      NFAB(M) = IBRN(M) -  7
      IFAB(M) = IBRN(M) - 15
      NSEN(M) = IBRN(M) - 16
      ISEV(M) = IBRN(M) - 17
      NENR(M) = IBRN(M) - 18
      IENR(M) = IBRN(M) - 26
      NCOS(M) = IBRN(M) - 27
      ICOS(M) = IBRN(M) - 40
      IPUR(M) = IBRN(M) - 40
      IUNL(M) = NBRN(M) +  1
      ICOL(M) = NBRN(M) +  5
      NCOL(M) = NBRN(M) +   21
      ISCO(M) = NBRN(M) +   22
      NSCO(M) = NBRN(M) +   24
      IREP(M) = NBRN(M) +   25
      NREP(M) = NBRN(M) + 26
      ISRE(M) = NBRN(M) + 27
      NSRE(M) = NBRN(M) + 30
      NUNL(M) = NBRN(M) +  4
  800 CONTINUE
      MAA = K - 2
      DO 900 M=MAA,K
      NREP(M) = NBRN(M) + 28
      ISRE(M) = NBRN(M) + 29
      NSRE(M) = NBRN(M) + 32
  900 CONTINUE
C  MASS BALANCE PRIOR TO IRRADIATION
      GK25 = ( ANO025 * VREG *  .235 D+0 ) / 6.023 D+23
      GK28 = ( ANO028 * VREG *  .238 D+0 ) / 6.023 D+23
      FREAC = GK25 + GK28
      PFSH = 1.1 D+0 * FREAC
      ENRIC = ( PFSH * ( XP - XW )) / ( XF - XW )
      CONV = 1.005 D+0 * ENRIC
      TAIL = ENRIC - PFSH
      PUR = ( CONV * 2.205 D+0 ) /  .848 D+0
C  MASS BALANCE AFTER IRRADIATION
      DO 801 M=1,K
      GB25(M) = ( CON25(M) * VREG * .235 D+0 ) / 6.023 D+23
      GB26(M) = ( CON26(M) * VREG * .236 D+0 ) / 6.023 D+23
      GB28(M) = ( CON28(M) * VREG * .238 D+0 ) / 6.023 D+23
```

```
      GB49(M) = ( CON49(M) * VREG * .239 D+0 ) / 6.023 D+23
      GB41(M) = ( CON41(M) * VREG * .241 D+0 ) / 6.023 D+23
  801 CONTINUE
C  UNITIZED MASS BALANCE FOR U-CREDIT
      DO 803 M=1,K
      XE(M) = GB25(M) / ( GB25(M) + GB26(M) + GB28(M) )
      F(M) = ( XE(M) - XW ) / ( XF - XW )
      W(M) = F(M) - 1.D+0
      FC(M) = F(M) * 1.005 D+0
      PURC(M) = ( FC(M) * 2.205 D+0 ) / .848 D+0
C  MASS BALANCE OUT OF REPROCESSING
      UREP(M) = .987 D+C * ( GB25(M) + GB26(M) + GB28(M) )
      PURE(M) = .99D+0 * ( GB49(M) + GB41(M) )
  803 CONTINUE
C U308 PURCHASE, COST = COS1
      COS1 = CF1 * PUR
C  CONVERSION AND SHIPPING, COST = COS2
      COS2 = CF2 * ENRIC
C  ENRICHMENT, COST = COS3
      FIXP = (1.D+0 - 2.D+0 * XP ) * DLOG(( 1.D+0 - XP ) / XP )
      FIXF = (1.D+0 - 2.D+0 * XF ) * DLOG(( 1.D+0 - XF ) / XF )
      FIXW = (1.D+0 - 2.D+0 * XW ) * DLOG(( 1.D+0 - XW ) / XW )
      DELTA = TAIL * FIXW + PFSH * FIXP - ENRIC * FIXF
      COS3 = CF3 * DELTA
C  PRE-FABRICATION SHIPPING, COST = COS4
      COS4 = CF4 * PFSH
C  FABRICATION, COST = COS5
      COS5 = CF5 * FREAC
      UCR = ( COS1 + COS2 + COS3 + COS4 ) / PFSH
      CRE1 = UCR * 1.D-1 * FREAC
C  PRE-IRRADIATION SHIPPING, COST = COS5A
      COS5A = CF5A * FREAC
C  PRE-REPROCESSING SHIPPING, COST = COS6
      COS6 = CF6 * FREAC
      COSTAA  = ( GK25 + GK28 ) * 1.D-3 * CF7 + 8.D+0 * CF7
      DO 808 M=1,K
C  REPROCESSING, COST = COS7
      COS7(M) = COSTAA
C  CONVERSION, COST = COS8
      COS8(M) = CF8 * UREP(M)
C  URANIUM CREDIT, CREDIT = CRE2
      FIXE(M) = (1.D+0-2.D+0*XE(M) ) * DLOG((1.D+0-XE(M))/XE(M))
      DELTB(M) =  W(M) * FIXW + FIXE(M)  - F(M) * FIXF
      UCRU(M) = CF3 * DELTB(M) + F(M) * CF2  + PURC(M) * CF1
      CRE2(M) = UCRU(M) * UREP(M)
C  PLUTONIUM CREDIT, CREDIT = CRE3
      CRE3(M) = PURE(M) * CIRU
  808 CONTINUE
      COSTBB = ( GK25 + GK28 ) * 3.D-3 * CF7 + 8.D+0 * CF7
      COSTB = COSTBB / 3.D+0
      DO 811 M=MAA,K
      COS7(M) = COSTB
  811 CONTINUE
```

```
C   PRINT OUT OF CASH FLCWS
      WRITE(6,1013)
      DO 1000 L=1,35
      CFPUR(L) = 0.D+0
      CFCOS(L) = 0.D+0
      CFENR(L) = 0.D+0
      CFSEN(L) = 0.D+0
      CFFAB(L) = 0.D+0
      CFSFA(L) = 0.D+0
      CFSCO(L) = 0.D+0
      CFCR1(L) = 0.D+0
      CFREP(L) = 0.D+0
      CFCON(L) = 0.D+0
      CFCR2(L) = 0.D+0
      CFCR3(L) = 0.D+0
      TOFLO(L) = 0.D+0
 1000 CONTINUE
      L = 1
      DO 3000 J=1,1716
      IF(J.NE.1) GO TO 1005
      WRITE(6,1003)  NYRO
      WRITE(6,1023)
      WRITE(6,1027)
      WRITE(6,1033)
      WRITE(6,1037)
 1005 CONTINUE
      DO 2000 M=1,K
      IF(IPUR(M).NE.J) GO TO 1010
      NAZ = IPUR(M) / 52
      NAY =  IPUR(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(1), M, NAY, COS1
      CFPUR(L) = CFPUR(L) + COS1
      TOFLO(L) = TOFLO(L) + COS1
 1010 IF(ICOS(M).NE.J) GO TO 1015
      NAZ = ICOS(M) / 52
      NAY =  ICOS(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(2), M, NAY
 1015 IF(NCOS(M).NE.J) GO TO 1020
      NAZ = NCOS(M) / 52
      NAY =  NCOS(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(3), M, NAY, COS2
      CFCOS(L) = CFCOS(L) + COS2
      TOFLO(L) = TOFLO(L) + COS2
 1020 IF(IENR(M).NE.J) GO TO 1025
      NAZ = IENR(M) / 52
      NAY =  IENR(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(4), M, NAY
 1025 IF(NENR(M).NE.J) GO TO 1030
      NAZ = NENR(M) / 52
```

```
      NAY =  NENR(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(5), M, NAY, COS3
      CFENR(L) = CFENR(L) + COS3
      TOFLO(L) = TOFLO(L) + COS3
 1030 IF(ISEN(M).NE.J) GO TO 1035
      NAZ = ISEN(M) / 52
      NAY =  ISEN(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(6), M, NAY
 1035 IF(NSEN(M).NE.J) GO TO 1040
      NAZ = NSEN(M) / 52
      NAY =  NSEN(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(7), M, NAY, COS4
      CFSEN(L) = CFSEN(L) + COS4
      TOFLO(L) = TOFLO(L) + COS4
 1040 IF(IFAB(M).NE.J) GO TO 1045
      NAZ = IFAB(M) / 52
      NAY =  IFAB(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(8), M, NAY
 1045 IF(NFAB(M).NE.J) GO TO 1050
      NAZ = NFAB(M) / 52
      NAY =  NFAB(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(9), M, NAY, COS5
      CFFAB(L) = CFFAB(L) + COS5
      TOFLO(L) = TOFLO(L) + COS5
      WRITE(6,1119) PQ(29), M, NAY, CRE1
      CFCR1(L) = CFCR1(L) + CRE1
      TOFLO(L) = TOFLO(L) - CRE1
 1050 IF(ISFA(M).NE.J) GO TO 1055
      NAZ = ISFA(M) / 52
      NAY =  ISFA(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(10), M, NAY
 1055 IF(NSFA(M).NE.J) GO TO 1060
      NAZ = NSFA(M) / 52
      NAY =  NSFA(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(11), M, NAY, COS5A
      CFSFA(L) = CFSFA(L) + COS5A
      TOFLO(L) = TOFLO(L) + COS5A
 1060 IF(ILOA(M).NE.J) GO TO 1065
      NAZ = ILOA(M) / 52
      NAY =  ILOA(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(12), M, NAY
 1065 IF(NLOA(M).NE.J) GO TO 1067
      NAZ = NLOA(M) / 52
      NAY =  NLOA(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
```

```
      WRITE(6,999) PQ(13), M, NAY
 1067 IF(IBRN(M).NE.J) GO TO 1068
      NAZ = IBRN(M) / 52
      NAY =  IBRN(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(14), M, NAY
 1068 IF(NBRN(M).NE.J) GO TO 1070
      NAZ = NBRN(M) / 52
      NAY =  NBRN(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(15), M, NAY
 1070 IF(IUNL(M).NE.J) GO TO 1075
      NAZ = IUNL(M) / 52
      NAY =  IUNL(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(16), M, NAY
 1075 IF(NUNL(M).NE.J) GO TO 1080
      NAZ = NUNL(M) / 52
      NAY =  NUNL(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(17), M, NAY
 1080 IF(ICOL(M).NE.J) GO TO 1085
      NAZ = ICOL(M) / 52
      NAY =  ICOL(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(18), M, NAY
 1085 IF(NCOL(M).NE.J) GO TO 1090
      NAZ = NCOL(M) / 52
      NAY =  NCOL(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(19), M, NAY
 1090 IF(ISCO(M).NE.J) GO TO 1095
      NAZ = ISCO(M) / 52
      NAY =  ISCO(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(20), M, NAY
 1095 IF(NSCO(M).NE.J) GO TO 1100
      NAZ = NSCO(M) / 52
      NAY =  NSCO(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(21), M, NAY, COS6
      CFSCO(L) = CFSCO(L) + COS6
      TOFLO(L) = TOFLO(L) + COS6
 1100 IF(IREP(M).NE.J) GO TO 1105
      NAZ = IREP(M) / 52
      NAY =  IREP(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(22), M, NAY
 1105 IF(NREP(M).NE.J) GO TO 1110
      NAZ = NREP(M) / 52
      NAY =  NREP(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,1007) PQ(23), M, NAY, COS7(M)
```

```
      CFREP(L) = CFREP(L) + COS7(M)
      TOFLO(L) = TOFLO(L) + COS7(M)
      WRITE(6,1007) PQ(24), M, NAY, COS8(M)
      CFCON(L) = CFCON(L) + COS8(M)
      TOFLO(L) = TOFLO(L) + COS8(M)
 1110 IF(ISRE(M).NE.J) GO TO 1115
      NAZ = ISRE(M) / 52
      NAY =  ISRE(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(25), M, NAY
 1115 IF(NSRE(M).NE.J) GO TO 1125
      NAZ = NSRE(M) / 52
      NAY =  NSRE(M) - NAZ * 52
      IF(NAY.EQ.0) NAY = 52
      WRITE(6,999) PQ(26), M, NAY
      WRITE(6,1119) PQ(27), M, NAY, CRE2(M)
      CFCR2(L) = CFCR2(L) + CRE2(M)
      TOFLO(L) = TOFLO(L) - CRE2(M)
      WRITE(6,1119) PQ(28), M, NAY, CRE3(M)
      CFCR3(L) = CFCR3(L) + CRE3(M)
      TOFLO(L) = TOFLO(L) - CRE3(M)
 1125 CONTINUE
 2000 CONTINUE
      NAW = J / 52
      NAX = J - NAW * 52
      IF(NAX.NE.0) GO TO 2500
      WRITE(6,1117)
      WRITE(6,1037)
      WRITE(6,1043) TOFLO(L)
      WRITE(6,1013)
      IF(J.EQ.1716) GO TO 2500
      NYR = L + NYRO
      WRITE(6,1003) NYR
      WRITE(6,1023)
      WRITE(6,1027)
      WRITE(6,1033)
      WRITE(6,1037)
      L = L + 1
 2500 CONTINUE
 3000 CONTINUE
C  DETERMINATION OF PRESENT WORTH FACTORS
      DO 3100 I=1,NINT
      PWF(I,1) = 1.D+0
      PWF(I,2) = 1.D+0 / ( 1.D+0 + DINT(I) )
      DO 3050 N=3,L
      PWF(I,N) = PWF(I,2) * PWF(I,N-1)
 3050 CONTINUE
 3100 CONTINUE
      WRITE(6,1013)
      WRITE(6,1121) ( DINT(I), I=1,NINT )
      DO 3200 N=1,L
      WRITE(6,3201)    N, ( PWF(I,N), I=1,NINT)
 3200 CONTINUE
```

```
   10 CONTINUE
C   DETERMINATION OF PRESENT WORTH OF YEAR END CASH FLOWS
      DO 3300 I=1,NINT
      DO 3205 N=1,L
      TFPUR(I,N) = CFPUR(N) * PWF(I,N)
      TFCOS(I,N) = CFCOS(N) * PWF(I,N)
      TFENR(I,N) = CFENR(N) * PWF(I,N)
      TFSEN(I,N) = CFSEN(N) * PWF(I,N)
      TFFAB(I,N) = CFFAB(N) * PWF(I,N)
      TFSFA(I,N) = CFSFA(N) * PWF(I,N)
      TFSCO(I,N) = CFSCO(N) * PWF(I,N)
      TFCR1(I,N) = CFCR1(N) * PWF(I,N)
      TFREP(I,N) = CFREP(N) * PWF(I,N)
      TFCON(I,N) = CFCON(N) * PWF(I,N)
      TFCR2(I,N) = CFCR2(N) * PWF(I,N)
      TFCR3(I,N) = CFCR3(N) * PWF(I,N)
      PTOFO(I,N) = TOFLC(N) * PWF(I,N)
 3205 CONTINUE
 3300 CONTINUE
      DO 3400 I=1,NINT
      TOPUR(I) = 0.D+0
      TOCOS(I) = 0.D+0
      TOENR(I) = 0.D+0
      TOSEN(I) = 0.D+0
      TOFAB(I) = 0.D+0
      TOSFA(I) = 0.D+0
      TOSCO(I) = 0.D+0
      TOCR1(I) = 0.D+0
      TOREP(I) = 0.D+0
      TOCON(I) = 0.D+0
      TOCR2(I) = 0.D+0
      TOCR3(I) = 0.D+0
      PTOF(I) = 0.D+0
      DO 3350 N=1,L
      TOPUR(I) = TOPUR(I) + TFPUR(I,N)
      TOCOS(I) = TOCOS(I) + TFCOS(I,N)
      TOENR(I) = TOENR(I) + TFENR(I,N)
      TOSEN(I) = TOSEN(I) + TFSEN(I,N)
      TOFAB(I) = TOFAB(I) + TFFAB(I,N)
      TOSFA(I) = TOSFA(I) + TFSFA(I,N)
      TOSCO(I) = TOSCO(I) + TFSCO(I,N)
      TOCR1(I) = TOCR1(I) + TFCR1(I,N)
      TOREP(I) = TOREP(I) + TFREP(I,N)
      TOCON(I) = TOCON(I) + TFCON(I,N)
      TOCR2(I) = TOCR2(I) + TFCR2(I,N)
      TOCR3(I) = TOCR3(I) + TFCR3(I,N)
      PTOF(I) = PTOF(I) + PTOFO(I,N)
 3350 CONTINUE
 3400 CONTINUE
      WRITE(6,1013)
      WRITE(6,1121)  ( CINT(I), I=1,NINT )
      WRITE(6,1037)
      WRITE(6,539) PQ(1),    ( TOPUR(I), I=1,NINT )
```

```
      WRITE(6,539) PQ(3),    ( TOCOS(I), I=1,NINT )
      WRITE(6,539) PQ(5),    ( TOENR(I), I=1,NINT )
      WRITE(6,539) PQ(7),    ( TOSEN(I), I=1,NINT )
      WRITE(6,539) PQ(9),    ( TOFAB(I), I=1,NINT )
      WRITE(6,539) PQ(11),   ( TOSFA(I), I=1,NINT )
      WRITE(6,539) PQ(21),   ( TOSCO(I), I=1,NINT )
      WRITE(6,539) PQ(29),   ( TOCR1(I), I=1,NINT )
      WRITE(6,539) PQ(23),   ( TOREP(I), I=1,NINT )
      WRITE(6,539) PQ(24),   ( TOCON(I), I=1,NINT )
      WRITE(6,539) PQ(27),   ( TOCR2(I), I=1,NINT )
      WRITE(6,539) PQ(28),   ( TOCR3(I), I=1,NINT )
      WRITE(6,4001)
      WRITE(6,1037)
      WRITE(6,4000)    ( PTOF(I), I=1,NINT )
      WRITE(6,1013)
 5000 CONTINUE
      STOP
      END
```

A CASH-FLOW STUDY FOR A NON-BASE LOADED POWER REACTOR

by

MICHAEL EUGENE HAWK

B. S., Kansas State University, 1970

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Nuclear Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1971

ABSTRACT

As utilities become more committed to nuclear power and more fossil-fired plants are retired, nuclear power reactors will be pressed into peak-load pickup service; therefore, nuclear reactors will deviate strongly from the base-load situation. Consequently, there is some question as to the effect this deviation will have on fuel cycle costs.

The purpose of this work was to determine the effect that the deviation from the base load assumption over the thirty year life of a light water reactor will have on:

(1) Scheduling of refuel shutdown periods;

(2) Present worth of cash flows for U_3O_8 purchase, conversion, enrichment, fabrication, shipping, reprocessing, and uranium and plutonium credits;

(3) Total cash flows.

Cash flows were determined for four cases of burnup. For the reference case, power was generated at a constant rate at a particular load factor for one week. For the first comparative case, the load factors from the reference case were averaged from years 1-10, 11-20, 21-30 of operation. For the second comparative case, the reference case load factors were averaged over the years 1-10 and 11-30. For the comparative cases, the power generation rate was assumed to be constant over the period for which the load factors were averaged.

The case 1 averaging technique proved to be accurate for scheduling of cash flow activities. The case 2 technique displayed a marked difference in scheduling of cash flows. Some differences for particular activities were as high as five years. The case 3 technique provided a schedule more

compatible with the reference case, but cash flows for particular activities lagged the reference case schedule by as much as three years. Utilities must have an accurate knowledge of the schedule of cash flow activities for financing reasons; therefore, one would tend to dismiss the case 2 and 3 technique as being too inaccurate.

However, all the results of this study are based upon the reference case load scheduling. This schedule deviates strongly from the average load assumption. In the future, utilities will be using more pump-storage facilities and gas turbines to meet extreme peak loads. Thus, nuclear power station load schedules probably will be closer to the average load assumption than the schedule for the reference case used in this study. Therefore, case 2 and 3 techniques may be used for cash flow scheduling if the load schedules do not deviate strongly from the average assumption.

Nonetheless, the case 1 technique proved to be highly accurate. Therefore, for cash flow scheduling purposes, an average load factor may be used for periods of 1-10 years. For periods longer than ten years, the accuracy is wholly dependent upon the degree to which the actual load schedule deviates from the average assumption.