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

by 2

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Major Professor
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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 \( U_3 O_8 \)

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 \( 0.31245 \times 10^{17} \) fissions/Mwt sec

COS1 cost for purchase of \( U_3 O_8 \)

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 \(i\)th 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
\(N_{25}^0\) initial nuclide density of U-235
$N_{26}(t)$ nuclide density of U-236 as a function of time

$N_{26}^0$ initial nuclide density of U-236

$N_{28}(t)$ nuclide density of U-238 as a function of time

$N_{28}^0$ 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

$N_{F}^{25}(t)$ nuclide density of fission product pairs produced by fission of U-235

$N_{F}^{28}(t)$ nuclide density of fission product pairs produced by fission of U-238

$N_{F}^{41}(t)$ nuclide density of fission product pairs produced by fission of Pu-241

$N_{F}^{49}(t)$ 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 $j$th week

$PUR$ mass of $U_{308}$ 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 \(j\)th week
UCRU cost for production of one kilogram of uranium at an assay
XE (UCRU includes purchase of \(\text{U}_3\text{O}_8\), 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 \(j\)th year for the \(k\)th activity in the
reference case
\(y_j^k\) cash flow during the \(j\)th year for the \(k\)th activity in the
comparative case

Greek symbols
\(\alpha_m\) capture to fission ratio for fissile species \(m\)
defined by Eq. (10)
\(\gamma\) fast fission factor
\(\eta_m\) ratio of the neutrons produced by fission to the number
of neutrons absorbed in fissile species \(m\)
\(\nu_m\) ratio of the number of neutrons produced by fission to the
number of neutrons absorbed in fission by fissile species
\(m\)
\(\rho\) reactivity, \((k_{\text{eff}} - 1)/k_{\text{eff}}\)
\(\sigma_m\) microscopic absorption cross section for species \(m\)
\(E_{ST}\) macroscopic absorption cross section for core structural components
\( \phi(t) \) flux as a function of time

\( \phi(X_i) \) defined by Eq. (37)

**Subscripts \((m)\) for Greek symbols**

- 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 $\text{U}_3\text{O}_8$ 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, \( \epsilon \),

(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 \( \Sigma_{ST} \) is an average macroscopic absorption cross-section and \( \phi \) 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 \( \sigma_{FF} \) 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

\[ r_j = \text{poison ratio of jth species}, \]

\[ N_j = \text{atomic density of jth species}, \]

\[ \sigma_j = \text{microscopic absorption cross-section of jth species}. \]

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

\[ \frac{dN_{25}(t)}{dt} = -N_{25}(t)\sigma_{25} \phi(t). \]  \hspace{1cm} (1)

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

\[ N_{25}(t) = N_{25}^0 \exp(-\sigma_{25} \int_0^t \phi(t')dt'). \] \hspace{1cm} (2)

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

\[ \int_0^t \phi(t')dt' = \phi t. \] \hspace{1cm} (3)

Equation (2) becomes

\[ N_{25}(t) = N_{25}^0 \exp(-\sigma_{25} \phi t). \] \hspace{1cm} (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

\[ \frac{dN_{26}(t)}{dt} = \frac{N_{25}(t)\sigma_{25} \alpha_{26} \phi}{1 + \alpha_{25}} - N_{26}(t) \sigma_{26} \phi. \] \hspace{1cm} (5)

The solution to Eq. (5) is

...
\[ N_{26}(t) = C_0 \left[ \exp(-\sigma_{26} \phi t) - \exp(-\sigma_{25} \phi t) \right] + N_{26}^0 \exp(-\sigma_{26} \phi t), \] (6)

where

\[ N_{26} = \text{atomic density of U-236}, \]
\[ \sigma_{26} = \text{microscopic absorption cross section of U-236}, \]
\[ C_0 = \frac{N_{25}^0 \sigma_{25}}{(\sigma_{25} - \sigma_{26})(1 + \alpha_{25})} \]
\[ \alpha_{25} = \text{capture to fission ratio of U-235}, \]
\[ N_{26}^0 = \text{atomic density of U-236 at } t = 0. \]

The rate of change for Pu-239 is

\[ \frac{dN_{49}(t)}{dt} = N_{28}(t)\sigma_{28} \phi + \eta_{25}\varepsilon P_1 (1 - p)N_{25}(t)\sigma_{25} \phi \]
\[ \text{Absorption of thermal neutrons in U-238} \]
\[ + \eta_{49}\varepsilon P_1 (1 - p)N_{49}(t)\sigma_{49} \phi + \eta_{49}\varepsilon P_1 (1 - p)N_{41}(t)\sigma_{41} \phi \]
\[ \text{Absorption of resonance neutrons from Pu-239} \]
\[ \text{fission in U-238} \]
\[ - N_{49}(t)\sigma_{49} \phi. \] (7)

If the change in U-238 is negligible,

\[ N_{28}(t) = N_{28}^0, \] (8)

where

\[ N_{28}^0 = \text{initial charge of U-238}. \]

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, \( m \),
\[ K_m = \eta_m e^{P_1(1 - p)} \]  

and

\[ \gamma = 1 - K_{49} \]  

yields

\[ \frac{dN_{49}(t)}{dt} = N_{28}^O \sigma_{28} \phi + K_{25} N_{25}(t) \sigma_{25} \phi - \gamma N_{49}(t) \sigma_{49} \phi. \]  

The solution of Eq. (7) is

\[ N_{49}(t) = C_1 + C_2 e^{(-\sigma_{25} \phi t)} - (C_1 + C_2 - C_3) e^{(-\gamma \sigma_{49} \phi t)} \]  

where

\[ C_1 = \frac{N_{28}^O \sigma_{28}}{\gamma \sigma_{49}}, \]

\[ C_2 = \frac{K_{25} \sigma_{25}}{\gamma \sigma_{49} - \sigma_{25}}, \]

\[ C_3 = N_{49}(0). \]

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:

\[ \frac{dN_{40}(t)}{dt} = \alpha_{49} N_{49}(t) \sigma_{49} \phi - N_{40}(t) \sigma_{40} \phi \]  

The solution to Eq. (13) is

\[ N_{40}(t) = C_4 + C_5 e^{(-\sigma_{25} \phi t)} - C_6 e^{(-\gamma \sigma_{49} \phi t)} - (C_4 + C_5 - C_6 - C_7) e^{(-\sigma_{40} \phi t)} \]  

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

\[
C_8 = \frac{C_4 \sigma_{40}}{\sigma_{41}},
\]

\[
C_9 = \frac{C_5 \sigma_{40}}{\sigma_{41} - \sigma_{25}}.
\]

\[
C_{10} = \left[ \frac{C_6}{\sigma_{41} - \gamma \sigma_{49}} + \frac{N_{40}^0}{\sigma_{40}} + \frac{C_4}{\sigma_{41} - \sigma_{40}} + \frac{C_5 - C_6 - C_7}{\sigma_{41} - \sigma_{25}} \right] \sigma_{40},
\]

\[
C_{11} = \frac{-C_9}{\sigma_{41} - \gamma \sigma_{44}} \sigma_{40},
\]

\[
C_{12} = \frac{(C_4 + C_5 - C_6 - C_7) \sigma_{40}}{\sigma_{41} - \sigma_{40}}.
\]

\[
N_{41}^0 = N_{41}(0).
\]

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

\[ N_F^{25}(t) = \frac{N_0^{25}}{1 + \alpha_{25}} [1 - \exp(-\sigma_{25}\phi t)]. \]  
(18)

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

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

Solving Eq. (19) yields

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

Pu-241 fission products are formed according to

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

The solution to Eq. (21) is

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

From the definitions of \( \nu \) and \( \varepsilon \), a neutron balance on the fast fission of U-238 yields

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

A mass balance on U-238 then yields
\[ N_{28}(t) = N_{28}^0 - N_{28}^{28}(t) - N_{49}(t) - N_{49}^{49}(t) - N_{40}(t) - N_{41}(t) - N_{41}^{41}(t). \] (24)

For fissionable species \( m \),
\[ \mu_m = \eta_m \epsilon_{th} \rho - 1 - r_m. \] (25)

the total reactivity is then defined:
\[
\rho = \left[ \mu_{25} N_{25}(t) \sigma_{25}^\phi + \mu_{49} N_{49}(t) \sigma_{49}^\phi + \mu_{41} N_{41}(t) \sigma_{41}^\phi 
- B_2^2 \phi - \Sigma_{st}^\phi - N_{28}(t) \sigma_{28}^\phi - N_{26}(t) \sigma_{26}^\phi 
- N_{40}(t) \sigma_{40}^\phi - \left[ N_{25}(t) + N_{28}^{28}(t) + N_{49}^{49}(t) + N_{41}^{41}(t) \right] \sigma_{FF}^\phi \right] \\
\frac{\epsilon_{th} \rho}{\eta_{25} N_{25}(t) \sigma_{25}^\phi + \eta_{49} N_{49}(t) \sigma_{49}^\phi + \eta_{41} N_{41}(t) \sigma_{41}^\phi}. \] (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

\[ \text{PFSH} = 1.1 \times \text{FREAC}. \]  \hspace{1cm} (27)

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

\[ \text{FLEX} = 0.1 \times \text{FREAC}. \]  \hspace{1cm} (28)

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

\[ \text{ENRIC} = \frac{\text{PFSH}(\text{XF} - \text{XW})}{(\text{XF} - \text{XW})}, \]  \hspace{1cm} (29)

where

- \( \text{XP} \) = product enrichment,
- \( \text{XF} \) = feed enrichment,
- \( \text{XW} \) = tails enrichment.

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

\[ \text{TAIL} = \text{ENRIC} - \text{PFSH}. \]  \hspace{1cm} (30)

The requirement for conversion, C\( \text{ONV} \), is determined by

\[ \text{C\( \text{ONV} \)} = 1.005 \times \text{ENRIC}. \]  \hspace{1cm} (31)

Finally the amount of \( \text{U}_3\text{O}_8 \) (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.
Figure 1: Mass Flow Through the Fuel Cycle
\[ \text{PUR} = \text{CONV} \times \frac{2.205 \text{ LB}}{\text{Kg}} \times \frac{1 \text{ Kg}}{0.848 \text{ Kg U}} \text{ U}_{238} \]  

(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

\[ \text{UREP} = 0.987(\text{GB25} + \text{GB26} + \text{GB28}) \]  

(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)

\[ \text{PURE} = 0.99(\text{GB49} + \text{GB41}) \]  

(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 $U_{3.08}$ purchase, if $C_{F1}$ is the unitized cost, then the total cost, $C_{OS1}$, can be calculated from

$$C_{OS1} = C_{F1} \times \text{PUR}.$$  
(35)

For conversion and shipping, $C_{F2}$ is the unitized cost, and $C_{OS2}$ is the total cost.

$$C_{OS2} = C_{F2} \times \text{ENRIC}.$$  
(36)

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

$$\text{DELTA} = TAIL \times \phi(XW) + PFSH \times \phi(XP) - \text{ENRIC} \times \phi(XF).$$  
(37)

where

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

The total cost for enrichment, $C_{OS3}$, is determined by Eq. (38) where $C_{F3}$ is the unitized cost of enrichment.

$$C_{OS3} = C_{F3} \times \text{DELTA}.$$  
(38)

The total cost for fabrication is found from Eq. (39) where $C_{OS5}$ is the total cost and $C_{F5}$ is the unitized cost.

$$C_{OS5} = C_{F5} \times \text{FREAC}.$$  
(39)

Equation (40) can be used to determine the total pre-irradiation shipping cost, $C_{OS5A}$, using a unitized cost, $C_{F5A}$.

$$C_{OS5A} = C_{F5A} \times \text{FREAC}.$$  
(40)
Table 1: Activities, Unitized Costs, and Time Durations for the Fuel Cycle Model

<table>
<thead>
<tr>
<th>Activity</th>
<th>Unitized Cost†</th>
<th>Duration(Weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_3O_8$ Purchase</td>
<td>$8/\text{lb }U_3O_8$</td>
<td></td>
</tr>
<tr>
<td>Conversion and Shipping</td>
<td>$2.20/\text{KgU}$</td>
<td>14</td>
</tr>
<tr>
<td>Enrichment</td>
<td>$26/\text{Kg. S.W. U}$</td>
<td>9</td>
</tr>
<tr>
<td>Pre-Fabrication Shipping</td>
<td>0.††</td>
<td>2</td>
</tr>
<tr>
<td>Fabrication</td>
<td>$100/\text{KgU}^{+++}$</td>
<td>9</td>
</tr>
<tr>
<td>Pre-Irradiation Shipping</td>
<td>$3/\text{KgU}$</td>
<td>2</td>
</tr>
<tr>
<td>Pre-Irradiation Down Time</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Post-Irradiation Down Time</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Cooling</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Pre-Reprocessing Shipping</td>
<td>$7/\text{KgU}$</td>
<td>3</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>NFS Model</td>
<td>NFS Model</td>
</tr>
<tr>
<td>Conversion of Reprocessed Uranium</td>
<td>$5.60/\text{KgU}$</td>
<td></td>
</tr>
<tr>
<td>Post-Irradiation Shipping</td>
<td>0.††††</td>
<td>4</td>
</tr>
</tbody>
</table>

† 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

\[ \text{COS6} = \text{CF6} \times \text{FREAC}. \]  
(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

\[ \text{REPTIM} = \frac{\text{FREAC}}{1000\text{Kg/day}}. \]  
(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.

\[ \text{COS7} = (\text{REPTIM} + \text{CLETIM}) \times \text{CF7}. \]  
(43)

The unitized cost for converting uranium in the nitrate form to UF₆, CF8, is based on the amount of uranium leaving the reprocessing plant. The total cost for conversion, COS8, can be determined from

\[ \text{COS8} = \text{CF8} \times \text{UREP}. \]  
(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

\[ \text{CR} = \frac{\text{COS1} + \text{COS2} + \text{COS3}}{\text{PPSH}}. \]  
(45)

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

\[ \text{CRE1} = \text{CR} \times \text{FLEX}. \]  
(46)

After irradiation, the fuel has an enrichment, EX, calculated by
\[ \text{XE} = \frac{\text{GB25}}{\text{GB25} + \text{GB26} + \text{GB28}} \]  

Credit for uranium which has not been consumed in irradiation is determined by calculating the cost of purchasing $\text{U}_3\text{O}_8$, 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:

\[ \text{FE} = \frac{\text{XE} - \text{W}}{\text{XF} - \text{W}} \]

\[ \text{W} = \text{FE} - 1. \]

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

\[ \text{FC} = 1.005 \times \text{FE}. \]

The amount of $\text{U}_3\text{O}_8$ required (in pounds), PURC, is determined from

\[ \text{PURC} = \frac{\text{FC} \times 2.205\text{LB} \times 1\text{KgU}_3\text{O}_8}{0.848\text{KgU}}. \]

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

\[ \text{DELTB} = \text{W} \times \phi(\text{XW}) + \phi(\text{XE}) - \text{FE} \times \phi(\text{XF}). \]

The total unit cost, UCRU, involved in $\text{U}_3\text{O}_8$ purchase, conversion and shipment, and enrichment can be determined by

\[ \text{UCRU} = \text{CF1} \times \text{PURC} + \text{CF2} \times \text{FE} + \text{CF3} \times \text{DELTB}. \]

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

\[ \text{CRE2} = \text{UCRU} \times \text{UREP}. \]

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.

\[ C_{RE3} = CIRU \times PURE. \] (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

\[ PW = \frac{FUT}{(1 + I)^n} \] (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 MW(e) 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 \( j \)th week, then the reference reactor load factor for the \( j \)th week, \( B_j \), is

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

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>Slightly enriched $\text{U}_2\text{O}_3$</td>
</tr>
<tr>
<td>Enrichment</td>
<td>3.44% U-235</td>
</tr>
<tr>
<td>Coolant and Moderator</td>
<td>$\text{H}_2\text{O}$, mean temperature 516°F, mean pressure 2000 psia</td>
</tr>
<tr>
<td>Reactor Power</td>
<td>480Mwt, 134Mwe</td>
</tr>
<tr>
<td>Average Neutron Temperature</td>
<td>908°K</td>
</tr>
<tr>
<td>Core Dimensions</td>
<td>Radius, 96.11 cm</td>
</tr>
<tr>
<td></td>
<td>Height, 234.3 cm</td>
</tr>
<tr>
<td>Effective Core Dimensions</td>
<td>Radius, 103.6 cm</td>
</tr>
<tr>
<td></td>
<td>Height, 249.3 cm</td>
</tr>
<tr>
<td>Inventory</td>
<td>U-235 700 kg</td>
</tr>
<tr>
<td></td>
<td>U-238 19,800 kg</td>
</tr>
<tr>
<td>Fast Fission Factor, $\epsilon$</td>
<td>1.0584</td>
</tr>
<tr>
<td>Non-Leakage Probability</td>
<td></td>
</tr>
<tr>
<td>Fission to resonance, $P_{1}$</td>
<td>0.9742</td>
</tr>
<tr>
<td>Fission to thermal, $P_{th}$</td>
<td>0.9654</td>
</tr>
<tr>
<td>Thermal Leakage Factor, $DB^2$</td>
<td>$1.92 \times 10^{-4}$ cm$^{-1}$</td>
</tr>
<tr>
<td>Resonance Escape Probability</td>
<td>0.758</td>
</tr>
<tr>
<td>Economic Life</td>
<td>30 years</td>
</tr>
</tbody>
</table>
Table 3: Material Properties

<table>
<thead>
<tr>
<th>Region</th>
<th>Material</th>
<th>Weight (Kg)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>UO₂</td>
<td>23,350</td>
<td>10.7</td>
</tr>
<tr>
<td>Cladding</td>
<td>SS-348</td>
<td>6,145</td>
<td>7.78</td>
</tr>
<tr>
<td>Structure</td>
<td>Zircaloy</td>
<td>1,293</td>
<td>6.5</td>
</tr>
<tr>
<td>Coolant-Moderator</td>
<td>Water</td>
<td>2,670</td>
<td>0.783</td>
</tr>
<tr>
<td></td>
<td>Void</td>
<td>(5,421 in³)</td>
<td>0</td>
</tr>
</tbody>
</table>

subject to the constraint

\[ C_j = 0 \text{ if } A_j < 0.5. \]  \hspace{1cm} (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

\[ \text{TOFIS}_j = \text{PNOM}_j \times \text{PMAX} \times \text{CØNVER}, \] \hspace{1cm} (61)

where

- \( \text{TOFIS} \) = total fission rate, fission/sec,
- \( \text{PNOM}_j \) = the load factor for the jth week,
- \( \text{PMAX} \) = maximum rated thermal power, Mwt,
- \( \text{CØNVER} \) = conversion constant, fission.

\( \text{Mwt sec} \)
Table 4: Effective Nuclide Properties for Thermal Neutrons in the Reference Pressurized Water Reactor

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Absorption Cross Section</th>
<th>$\nu$</th>
<th>$\eta$</th>
<th>$\alpha$</th>
<th>$r_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-235</td>
<td>515</td>
<td>2.47</td>
<td>1.97</td>
<td>0.253</td>
<td>0.0451</td>
</tr>
<tr>
<td>U-236</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-238</td>
<td>1.365</td>
<td>2.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu-239</td>
<td>1690</td>
<td>2.905</td>
<td>1.81</td>
<td>0.600</td>
<td>0.0426</td>
</tr>
<tr>
<td>Pu-240</td>
<td>1870</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu-241</td>
<td>1590</td>
<td>3.06</td>
<td>2.225</td>
<td>0.3765</td>
<td>0.0541</td>
</tr>
<tr>
<td>Fission Product Pairs</td>
<td>31.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0.332</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>2.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.105</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2: Total Energy Generation for the USA for 1970 and Total Utility Load Factor
CONVER can be calculated from

\[
\text{CONVER} = \frac{10^6 \text{ watt}}{\text{Mwt}} \times \frac{1 \text{ joule}}{\text{sec watt}} \times \frac{1 \text{ Mev}}{1.6 \times 10^{13} \text{ joule}} \times \frac{\text{fission}}{E_R \text{ Mev}}
\]  (62)

where

\[ E_R = \text{recoverable fission energy}. \]

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

\[
\text{CONVER} = 0.31245 \times 10^{17} \frac{\text{fission}}{\text{Mwt x sec}}
\]  (63)

The fission rate in any region, \( \text{FISS}_i \), is one-third of TOFIS, \( \text{FISS}_i \) also has the relationship

\[
\text{FISS}_i = N_{i25}^f \phi_i + N_{i49}^f \phi_i + N_{i41}^f \phi_i,
\]  (64)

where \( N_{i25}^f \), \( N_{i49}^f \), and \( N_{i41}^f \) and the atomic densities of U-235, Pu-239, and Pu-241, respectively, in the \( i \)th region; \( \sigma_{25}^f \), \( \sigma_{49}^f \), and \( \sigma_{41}^f \) are the microscopic fission cross-sections for the respective isotopes; \( \phi_i \) is flux in region \( i \). The solution of Eq. (64) for \( \phi_i \) yields

\[
\phi_i = \frac{\text{FISS}_i}{N_{i25}^f + N_{i49}^f + N_{i41}^f} \frac{f_{25}^f}{\sigma_{25}^f} + \frac{f_{49}^f}{\sigma_{49}^f} + \frac{f_{41}^f}{\sigma_{41}^f}
\]  (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

\[ \text{POWER} = \text{AV1} \times \text{POWE}, \]  

(66)

where

\[ \text{POWE} = \text{maximum electrical power}. \]

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

\[ \text{POWER} = \text{AV2} \times \text{POWE}, \]  

(67)

\[ \text{POWER} = \text{AV3} \times \text{POWE}. \]  

(68)

FUEL, a FORTRAN 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 FORTRAN 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

$$P = \frac{x_k^I - y_k^I}{x_k^I},$$

(69)

where

$$x_k^I = \text{present worth of the total of all cash flows for the } k\text{th activity at interest rate } I \text{ for the reference case},$$

$$y_k^I = \text{present worth of the total of all cash flows for the } k\text{th activity for the comparative case at interest } I,$$

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

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

<table>
<thead>
<tr>
<th>Activity</th>
<th>Case 1 (%)</th>
<th>Case 2 (%)</th>
<th>Case 3 (%)</th>
<th>Case 3 Corrected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase of $\text{U}_3\text{O}_8$</td>
<td>0.00</td>
<td>2.24</td>
<td>-4.05</td>
<td>0.67</td>
</tr>
<tr>
<td>Conversion and Shipment</td>
<td>-0.00</td>
<td>2.33</td>
<td>-3.95</td>
<td>0.77</td>
</tr>
<tr>
<td>Enrichment</td>
<td>-0.00</td>
<td>2.65</td>
<td>-3.66</td>
<td>1.06</td>
</tr>
<tr>
<td>Fabrication</td>
<td>-0.00</td>
<td>2.66</td>
<td>-3.50</td>
<td>1.15</td>
</tr>
<tr>
<td>Excess and Scrap Credit</td>
<td>-0.00</td>
<td>2.66</td>
<td>-3.50</td>
<td>1.15</td>
</tr>
<tr>
<td>Shipment to Reactor</td>
<td>-0.13</td>
<td>2.53</td>
<td>-3.64</td>
<td>1.02</td>
</tr>
<tr>
<td>Shipment to Reprocessing</td>
<td>-0.00</td>
<td>2.75</td>
<td>-4.55</td>
<td>0.56</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>-0.20</td>
<td>2.81</td>
<td>-4.77</td>
<td>0.65</td>
</tr>
<tr>
<td>Conversion of Uranium</td>
<td>-0.20</td>
<td>2.70</td>
<td>-5.09</td>
<td>0.12</td>
</tr>
<tr>
<td>Uranium Credit</td>
<td>0.02</td>
<td>1.35</td>
<td>-28.54</td>
<td>-18.72</td>
</tr>
<tr>
<td>Plutonium Credit</td>
<td>0.03</td>
<td>2.52</td>
<td>3.93</td>
<td>7.29</td>
</tr>
<tr>
<td>Total</td>
<td>-0.04</td>
<td>2.84</td>
<td>1.71</td>
<td>5.33</td>
</tr>
</tbody>
</table>
Table 6: Percentage Deviations From the Reference Case at 10% Interest

<table>
<thead>
<tr>
<th>Activity</th>
<th>Case 1 (%)</th>
<th>Case 2 (%)</th>
<th>Case 3 (%)</th>
<th>Case 3 Corrected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase of $U_3O_8$</td>
<td>0.00</td>
<td>2.66</td>
<td>-0.34</td>
<td>1.01</td>
</tr>
<tr>
<td>Conversion and Shipment</td>
<td>-0.00</td>
<td>2.69</td>
<td>-0.27</td>
<td>1.08</td>
</tr>
<tr>
<td>Enrichment</td>
<td>-0.00</td>
<td>2.97</td>
<td>0.11</td>
<td>1.46</td>
</tr>
<tr>
<td>Fabrication</td>
<td>0.00</td>
<td>2.98</td>
<td>0.17</td>
<td>1.47</td>
</tr>
<tr>
<td>Excess and Scrap Credit</td>
<td>0.00</td>
<td>2.98</td>
<td>0.17</td>
<td>1.47</td>
</tr>
<tr>
<td>Shipment to Reactor</td>
<td>-0.16</td>
<td>2.83</td>
<td>0.02</td>
<td>1.32</td>
</tr>
<tr>
<td>Shipment to Reprocessing</td>
<td>0.00</td>
<td>3.81</td>
<td>-0.11</td>
<td>1.41</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>-0.39</td>
<td>3.73</td>
<td>-0.38</td>
<td>1.28</td>
</tr>
<tr>
<td>Conversion of Uranium</td>
<td>-0.38</td>
<td>3.65</td>
<td>-0.97</td>
<td>0.58</td>
</tr>
<tr>
<td>Uranium Credit</td>
<td>-0.00</td>
<td>1.33</td>
<td>-28.30</td>
<td>-25.63</td>
</tr>
<tr>
<td>Plutonium Credit</td>
<td>0.01</td>
<td>3.54</td>
<td>9.59</td>
<td>10.59</td>
</tr>
<tr>
<td>Total</td>
<td>-0.05</td>
<td>3.24</td>
<td>5.44</td>
<td>6.54</td>
</tr>
</tbody>
</table>
Table 7: Percentage Deviations From the Reference Case at 12% Interest

<table>
<thead>
<tr>
<th>Activity</th>
<th>Case 1 (%)</th>
<th>Case 2 (%)</th>
<th>Case 3 (%)</th>
<th>Case 3 Corrected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase of $^{3}O_{8}$</td>
<td>0.00</td>
<td>2.49</td>
<td>0.12</td>
<td>1.00</td>
</tr>
<tr>
<td>Conversion and Shipment</td>
<td>0.00</td>
<td>2.48</td>
<td>0.16</td>
<td>1.04</td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.00</td>
<td>2.73</td>
<td>0.53</td>
<td>1.41</td>
</tr>
<tr>
<td>Fabrication</td>
<td>0.00</td>
<td>2.73</td>
<td>0.55</td>
<td>1.40</td>
</tr>
<tr>
<td>Excess and Scrap Credit</td>
<td>0.00</td>
<td>2.73</td>
<td>0.55</td>
<td>1.40</td>
</tr>
<tr>
<td>Shipment to Reactor</td>
<td>-0.15</td>
<td>2.59</td>
<td>0.41</td>
<td>1.25</td>
</tr>
<tr>
<td>Shipment to Reprocessing</td>
<td>0.00</td>
<td>3.71</td>
<td>0.53</td>
<td>1.54</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>-0.42</td>
<td>3.59</td>
<td>0.23</td>
<td>1.34</td>
</tr>
<tr>
<td>Conversion of Uranium</td>
<td>-0.41</td>
<td>3.51</td>
<td>-0.39</td>
<td>0.63</td>
</tr>
<tr>
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<td>-0.00</td>
<td>1.22</td>
<td>-28.06</td>
<td>-26.35</td>
</tr>
<tr>
<td>Plutonium Credit</td>
<td>0.01</td>
<td>3.44</td>
<td>10.61</td>
<td>11.27</td>
</tr>
<tr>
<td>Total</td>
<td>-0.05</td>
<td>2.98</td>
<td>5.68</td>
<td>6.42</td>
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</table>
Table 8: Percentage Deviations From the Reference Case at 16% Interest

<table>
<thead>
<tr>
<th>Activity</th>
<th>Case 1 (%)</th>
<th>Case 2 (%)</th>
<th>Case 3 (%)</th>
<th>Case 3 Corrected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase of $\text{U}_3\text{O}_8$</td>
<td>0.00</td>
<td>2.02</td>
<td>0.51</td>
<td>0.89</td>
</tr>
<tr>
<td>Conversion and Shipment</td>
<td>0.00</td>
<td>1.97</td>
<td>0.52</td>
<td>0.92</td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.00</td>
<td>2.13</td>
<td>0.83</td>
<td>1.21</td>
</tr>
<tr>
<td>Fabrication</td>
<td>0.00</td>
<td>2.14</td>
<td>0.79</td>
<td>1.15</td>
</tr>
<tr>
<td>Excess and Scrap Credit</td>
<td>0.00</td>
<td>2.14</td>
<td>0.79</td>
<td>1.15</td>
</tr>
<tr>
<td>Shipment to Reactor</td>
<td>-0.11</td>
<td>2.03</td>
<td>0.68</td>
<td>1.05</td>
</tr>
<tr>
<td>Shipment to Reprocessing</td>
<td>0.00</td>
<td>3.24</td>
<td>1.16</td>
<td>1.59</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>-0.43</td>
<td>3.06</td>
<td>0.80</td>
<td>1.30</td>
</tr>
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<td>Conversion of Uranium</td>
<td>-0.43</td>
<td>3.00</td>
<td>0.16</td>
<td>0.60</td>
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<td>0.98</td>
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</tr>
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<td>2.97</td>
<td>11.94</td>
<td>12.23</td>
</tr>
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<tr>
<td>Activity</td>
<td>Case 1 (%)</td>
<td>Case 2 (%)</td>
<td>Case 3 (%)</td>
<td>Case 3 Corrected (%)</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Purchase of U₃O₈</td>
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<td>0.81</td>
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<tr>
<td>Conversion and Shipment</td>
<td>0.00</td>
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<td>1.09</td>
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</tr>
<tr>
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<td>1.85</td>
<td>0.78</td>
<td>1.02</td>
</tr>
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<td>1.54</td>
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<tr>
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<td>0.86</td>
<td>-27.14</td>
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<tr>
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<td>-0.00</td>
<td>2.70</td>
<td>12.38</td>
<td>12.56</td>
</tr>
<tr>
<td>Total</td>
<td>-0.04</td>
<td>2.04</td>
<td>5.33</td>
<td>5.55</td>
</tr>
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</table>
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),

\[ x^k_I = \sum_{j=1}^{n} \frac{x^k_j}{(1 + i)^j} \]  

(70)

\[ y^k_I = \sum_{j=1}^{n} \frac{y^k_j}{(1 + i)^j} \]  

(71)

where

- \( x^k_j \) = cash flow during jth year for the kth activity in the reference case,
- \( y^k_j \) = 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 U₃O₈ Purchase

<table>
<thead>
<tr>
<th>Load</th>
<th>Reference Case† Date</th>
<th>Case 1† Date</th>
<th>Case 2† Date</th>
<th>Case 3† Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>Week</td>
<td>Year</td>
<td>Week</td>
</tr>
<tr>
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<tr>
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<td>1975</td>
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<td>8</td>
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<tr>
<td>21</td>
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<td></td>
</tr>
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</table>

† All cash flows were for the amount $988,321.94.
<table>
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<th>Reference Case† Date</th>
<th>Case 1† Date</th>
<th>Case 2† Date</th>
<th>Case 3† Date</th>
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</thead>
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† All cash flows were for the amount $104,044.35.
Table 12: Cash Flow for Enrichment

<table>
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<th>Load</th>
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<th>Case 2† Date</th>
<th>Case 3† Date</th>
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† All cash flows were for the amount $1,018,958.02.
### Table 13: Cash Flow for Fabrication

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<th>Case 2† Date</th>
<th>Case 3† Date</th>
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</thead>
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<td>Year</td>
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<td>Week</td>
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<tr>
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</table>

† All cash flows were for the amount $685,998.78.
Table 14: Cash Flow for Excess and Loss Credits
From the Fabrication Process

<table>
<thead>
<tr>
<th>Load</th>
<th>Reference Case† Date</th>
<th>Case 1† Date</th>
<th>Case 2† Date</th>
<th>Case 3† Date</th>
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</thead>
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† All cash flows were for the amount $191,934.96.
Table 15: Cash Flow for Pre-Irradiation Shipping

<table>
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<th>Load</th>
<th>Reference Case† Date</th>
<th>Case 1† Date</th>
<th>Case 2† Date</th>
<th>Case 3† Date</th>
</tr>
</thead>
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</tr>
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</tr>
<tr>
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</table>

† All cash flows were for the amount $20,579.96.
Table 16: Cash Flow for Pre-Reprocessing Shipping

<table>
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<tr>
<th>Load</th>
<th>Reference Case† Date</th>
<th>Case 1† Date</th>
<th>Case 2† Date</th>
<th>Case 3† Date</th>
</tr>
</thead>
<tbody>
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<td>Week</td>
</tr>
<tr>
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<td>2002</td>
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<tr>
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</table>

† All cash flows were for the amount $48,019.91.
Table 17: Cash Flow for Reprocessing

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<th>Case 2† Date</th>
<th>Case 3† Date</th>
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</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td>2002</td>
</tr>
</tbody>
</table>

† 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>
<thead>
<tr>
<th>Load</th>
<th>Reference Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Amount (Dollars)</td>
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<tr>
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<td>1974</td>
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<td>37,132.85</td>
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<tr>
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<td>13</td>
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Table 18: Cash Flow for Conversion of Reprocessed Uranium
<table>
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<th>Reference Case Amount (Dollars)</th>
<th>Case 1 Year Week Amount (Dollars)</th>
<th>Case 2 Year Week Amount (Dollars)</th>
<th>Case 3 Year Week Amount (Dollars)</th>
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<td>1973 17 1,404,201.71</td>
<td>1973 17 1,404,201.71</td>
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<tr>
<td>2</td>
<td>1974 17 1,023,747.93</td>
<td>1974 17 1,023,747.93</td>
<td>1974 17 1,023,747.93</td>
<td>1974 17 1,251,347.16</td>
</tr>
<tr>
<td>3</td>
<td>1975 17 712,756.46</td>
<td>1975 17 712,756.46</td>
<td>1975 17 712,756.46</td>
<td>1975 17 1,001,966.94</td>
</tr>
<tr>
<td>5</td>
<td>1977 17</td>
<td>1977 17</td>
<td>1977 17</td>
<td>1977 17</td>
</tr>
<tr>
<td>7</td>
<td>1979 17</td>
<td>1979 17</td>
<td>1979 17</td>
<td>1979 17</td>
</tr>
<tr>
<td>10</td>
<td>1982 17</td>
<td>+</td>
<td>1982 17</td>
<td>+</td>
</tr>
<tr>
<td>11</td>
<td>1985 5  354,186.25</td>
<td>1985 4  355,032.64</td>
<td>1986 33  356,634.89</td>
<td>1986 7  418,679.26</td>
</tr>
<tr>
<td>12</td>
<td>1986 35  275,263.58</td>
<td>1986 35  275,744.28</td>
<td>1989 6  278,219.73</td>
<td>1987 47  297,007.70</td>
</tr>
<tr>
<td>13</td>
<td>1988 23  181,666.16</td>
<td>1988 22  180,519.22</td>
<td>1991 44  182,979.29</td>
<td>1989 49  159,053.54</td>
</tr>
<tr>
<td>14</td>
<td>1990 31  279,738.96</td>
<td>1990 30  278,347.74</td>
<td>1995 11  280,933.14</td>
<td>1992 37  297,007.70</td>
</tr>
<tr>
<td>16</td>
<td>1999 15  226,071.07</td>
<td>1999 17  226,701.63</td>
<td>2000 49  225,037.91</td>
<td>1997 5  216,439.01</td>
</tr>
<tr>
<td>17</td>
<td>2002 24  476,226.81</td>
<td>2002 24  475,326.42</td>
<td>2002 24  449,035.08</td>
<td>1999 28  260,934.48</td>
</tr>
<tr>
<td>19</td>
<td>2002 24  1,532,761.44</td>
<td>2002 24  1,530,729.29</td>
<td>2002 24  1,487,504.30</td>
<td>2002 24  502,732.03</td>
</tr>
<tr>
<td>20</td>
<td>2002 24  1,001,675.07</td>
<td>2002 24  1,001,675.07</td>
<td>2002 24  1,672,728.63</td>
<td></td>
</tr>
</tbody>
</table>
Table 20: Cash Flows for Plutonium Credit

<table>
<thead>
<tr>
<th>Load</th>
<th>Reference Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>Week</td>
<td>Amount (Dollars)</td>
<td>Year</td>
</tr>
<tr>
<td>1</td>
<td>1973</td>
<td>17</td>
<td>230,212.71</td>
<td>1973</td>
</tr>
<tr>
<td>2</td>
<td>1974</td>
<td>17</td>
<td>340,186.73</td>
<td>1974</td>
</tr>
<tr>
<td>4</td>
<td>1976</td>
<td>17</td>
<td>176,914.81</td>
<td>1976</td>
</tr>
<tr>
<td>5</td>
<td>1977</td>
<td>17</td>
<td>117,500.00</td>
<td>1977</td>
</tr>
<tr>
<td>6</td>
<td>1978</td>
<td>17</td>
<td>78,500.00</td>
<td>1978</td>
</tr>
<tr>
<td>7</td>
<td>1979</td>
<td>17</td>
<td>62,000.00</td>
<td>1979</td>
</tr>
<tr>
<td>8</td>
<td>1980</td>
<td>17</td>
<td>50,000.00</td>
<td>1980</td>
</tr>
<tr>
<td>9</td>
<td>1981</td>
<td>17</td>
<td>36,500.00</td>
<td>1981</td>
</tr>
<tr>
<td>10</td>
<td>1982</td>
<td>17</td>
<td>□</td>
<td>1982</td>
</tr>
<tr>
<td>11</td>
<td>1985</td>
<td>5</td>
<td>359,320.19</td>
<td>1985</td>
</tr>
<tr>
<td>13</td>
<td>1988</td>
<td>23</td>
<td>313,271.81</td>
<td>1988</td>
</tr>
<tr>
<td>14</td>
<td>1990</td>
<td>31</td>
<td>343,613.43</td>
<td>1990</td>
</tr>
<tr>
<td>16</td>
<td>1999</td>
<td>15</td>
<td>328,686.27</td>
<td>1999</td>
</tr>
<tr>
<td>17</td>
<td>2002</td>
<td>24</td>
<td>374,371.56</td>
<td>2002</td>
</tr>
<tr>
<td>18</td>
<td>2002</td>
<td>24</td>
<td>359,931.04</td>
<td>2002</td>
</tr>
<tr>
<td>19</td>
<td>2002</td>
<td>24</td>
<td>178,965.09</td>
<td>2002</td>
</tr>
</tbody>
</table>
Equation (69) can be restated in terms of Eqs. (71) and (72) as

\[
P = \frac{\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j} - \sum_{j=1}^{n} \frac{y_j^k}{(1+I)^j}}{\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j}}
\]

(72)

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

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

(73)

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

\[
\sum_{j=1}^{n} \frac{x_j^k}{(1+I)^j} \sum_{j=1}^{n} \frac{j(x_j^k - y_j^k)}{(1+I)^{j+1}} = \sum_{j=1}^{n} \frac{(x_j^k - y_j^k)}{(1+I)^j} \sum_{j=1}^{n} \frac{jx_j^k}{(1+I)^{j+1}}
\]

(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 \( I \)

\[
\sum_{j=1}^{n} x_j^k = \sum_{j=1}^{n} y_j^k.
\]

(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 \( j = 1 - 10 \),

\[
x_j^k = y_j^k.
\]

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.
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11. Lamarsh, John R.
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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

FÖRMAT (6D13.6)

EPSI - fast fission factor

PTH - fission to thermal non leakage probability

PREP - resonance escape probability

DB2 - thermal leakage factor

P MAX - maximum rated thermal power

Card 2

FÖRMAT (6D13.6)

P11 - fission to resonance non leakage probability

$\text{CONVER} = 0.31245 \times 10^{17}$ fission/Mwt sec

VREG - volume of each region

T - time period considered in one burnup calculation

Card 3

FÖRMAT (6D13.6)

ETA25 - $\eta$ for U-235

RM25 - poison ratio for U-235

SA25 - microscopic absorption cross section of U-235

ALP25 - $\alpha$ for U-235

XNU25 - $\nu$ for U-235
Card 4

FØRMAT (6D13.6)

ETA49 - \( \eta \) for Pu-239

RM49 - poison ratio for Pu-239

SA49 - microscopic absorption cross section for Pu-239

ALP49 - \( \alpha \) for Pu-239

XNU49 - \( \nu \) for Pu-239

Card 5

FØRMAT (6D13.6)

ETA41 - \( \eta \) for Pu-241

RM41 - poison ratio for Pu-241

SA41 - microscopic absorption cross section for Pu-241

ALP41 - \( \alpha \) for Pu-241

XNU41 - \( \nu \) 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

FORMAT (6D13.6)

ANØø41 - initial nuclidic density of Pu-241

ANØø40 - initial nuclidic density of Pu-240

ANØø25 - initial nuclidic density of fission product pairs from U-235 fission

ANØø28 - initial nuclidic density of fission product pairs from U-238 fission

ANØø41 - initial nuclidic density of fission product pairs from Pu-241 fission

ANØø49 - initial nuclidic density of fission product pairs from Pu-239 fission

Card 9-17

FORMAT (6D13.6)

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

Card 18-26

FORMAT (6D13.6)

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

Card 27-35

FORMAT (6D13.6)

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

Card 36

FORMAT (6D13.6)

XNU28 - v for U-238

Card 37

FORMAT (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

```fortran
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION IBRN(50), NBRN(50), ANQ25(3), ANQ28(3), ANQ26(3), ANQ49(3)
DIMENSION ANQ40(3), ANQ41(3), ANQ25(3), ANQ49(3), ANQ28(3)
DIMENSION ANQF41(3), TIMER(3), ANQ25(3), ANQ28(3), ANQ26(3), ANQ49(3)
DIMENSION ANQ40(3), ANQ41(3), ANQF41(3), ANQ25(3), ANQ49(3), ANQ28(3)
DIMENSION PNOM(52), PAA(52), PBB(52), FLREL(3), PHI(3), EX25(3), EX26(3)
DIMENSION EX49(3), EX40(3), CU(3), CL(3), C2(3), C3(3), C4(3), EX41(3)
DIMENSION CE1(3), CE2(3), CE3(3), CE4(3), CE5(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 CON25(50), CON49(50), CON41(50), CON28(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, SAH20, SAST
READ(1,534) ANH20, ANST, ANO025, 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, SAH20, SAST
WRITE(3,534) ANH20, 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 = 1.0*D+0 - ( ETA49*EPSI*P11*(1.0*D+0 - PREP))
AMU25 = ETA25 * EPSI * PTH * PREP
AMU41 = ETA41 * EPSI * PTH * PREP
AMU49 = ETA49 * EPSI * PTH * PREP
AKAP25 = ETA25 * EPSI * P11 * (1.0*D+0 - PREP)
XMU25 = AMU25 -1.0*C+0 - RM25
XMU41 = AMU41 -1.0*C+0 - RM41
XMU49 = AMU49 -1.0*C+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(I) = IBRN(I) + 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
GO 14 I=1,3
AN025(I) = AN0025
AN028(I) = AN0028
AN026(I) = AN0026
AN049(I) = AN0049
AN040(I) = AN0040
AN041(I) = AN0041
ANOF25(I) = ANFO25
ANOF49(I) = ANFO45
ANOF28(I) = ANFO28
ANOF41(I) = ANFO41
TIMER(I) = .D+0
14 CONTINUE
GO TO 25
17 IF(YC.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(I) = AN0025
AN028(I) = AN0028
AN026(I) = AN0026
AN049(I) = AN0049
AN040(I) = AN0040
AN041(I) = AN0041
ANOF25(I) = ANFO25
ANOF49(I) = ANFO45
ANOF28(I) = ANFO28
ANOF41(I) = ANFO41
TIMER(3) = TIMER(2)
TIMER(2) = TIMER(1)
TIMER(1) = .D+0
GO TO 25
19 DO 25 I=1,3
AN025(I) = AN25(I)
AN026(I) = AN26(I)
AN028(I) = AN28(I)
AN049(I) = AN49(I)
AN040(I) = AN40(I)
AN041(I) = AN41(I)
AN025(I) = ANF25(I)
AN041(I) = ANF41(I)
AN049(I) = ANF49(I)
AN028(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) = (( AN025(I) * SA25 ) / ( 1.D0 + ALP25 )) + (( AN049(I) * SA49 ) / ( 1.D0 + ALP49 )) + (( AN041(I) * SA41 ) / ( 1.D0 + ALP41 ))
   PHI(I) = ( TUFIS ) / ( FISS(I) * 3.D0 * VREG )
   26 CONTINUE
   FLREL(I) = PHI(I)
   PHIBAR = ( PHI(1) + PHI(2) + PHI(3) ) / 3.D0
   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 ))
     C0(I) = (AN025(I) * SA25 + ALP25 ) / ( ( SA25 - SA26 ) * ( 1.D0 + ALP125 ))
     C1(I) = (AN028(I) * SA28 ) / GAMSIG
     C2(I) = ( AN025(I) * AKAP25 + SA25 ) / ( GAMSIG - SA25 )
     C3(I) = AN049(I)
     C4(I) = ( (ALP49 * SA49 ) / ( 1.D0 + ALP49 ) * SA40 ) * C1(I)
     C5(I) = ( ALP49 * SA49 * C2(I) ) / ( 1.D0 + ALP49 ) * (SA40 - SA25)
     C6(I) = ( ALP49 * SA49 * ( C1(I) + C2(I) - C3(I) ) ) / ( 1.D0 + ALP149 ) * ( SA49 - GAMSIG )
     C7(I) = AN040(I)
     C8(I) = ( C4(I) * SA40 ) / SA41
     C9(I) = ( C5(I) * SA40 ) / ( SA41 - SA25)
     C10(I) = ( ( C6(I) * SA40 ) / ( SA41 - GAMSIG ) ) + ( AN041(I)
     C11(I) = ( ( C6(I) * SA40 ) / ( 1 - C4(I) - C5(I) - C6(I) - C7(I) ) ) / ( SA41 - SA40 )
     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)
     C12(I)*EX40(I)
     AN25(I) = AN025(I) * EX25(I)
     AN26(I) = ( C0(I) + AN026(I) ) * EX26(I) - C0(I) * EX25(I)
     AN49(I) = C1(I) + C2(I)*EX25(I) - ( C1(I) + C2(I) - C3(I) ) * EXG49(I)
     AN40(I) = C4(I) + C5(I) * EX25(I) - C6(I) * EXG49(I) - ( C4(I) + C5(I) - C6(I) - C7(I) ) * EX40(I)
ANF25(I) = ((( AN025(I) * (1.0+0 - EX25(I))) / (1.0+0 +ALP25)) +ANO1F25(I))
CA(I) = C1(I) * PHI(I) * T
CB(I) = ( C2(I) * (1.0+0 - EX25(I)))/ SA25
CC(I) =(( C1(I) * C2(I) - C3(I))* (1.0+0 - EXG49(I))/GAMSIG
CD(I) =(( CA(I) + CB(I) - CC(I))* SA49)/(1.0+0 + ALP49)
ANF49(I) = CD(I) + ANOF49(I)
CE(I) = C8(I) * PHI(I) * T
CF(I) = C9(I) * (1.0+0 - EX25(I)) / SA25
CG(I) = C10(I) * (1.0+0 - EX41(I))/ SA41
CH(I) = C11(I) * (1.0+0 - EXG49(I))/GAMSIG
CI(I) = C12(I) * (1.0+0 - EX40(I)) / SA40
CK(I) = ((CE(I)+CF(I)+CG(I)+CH(I)+CI(I))*SA41) / (1.0+0 +ALP41)
ANF41(I) = CK(I) + ANOF41(I)
ANF28(I) = (((XNU25 * ANF25(I) + XNU49 * ANF49(I) + XNU41* ANF41(I))
1) * (EPSI - 1.0+0) - (XNU28 - 1.0+0))
AN28(I) = ANU028 - ANF28(I) - AN49(I) - ANF49(I) - AN40(I) - AN41(I)
- ANF41(I)
30 CONTINUE
GO TO 36
32 RHO = 1.0+0
DO 34 I=1,3
AN25(I) = ANU25(I)
AN26(I) = ANU26(I)
AN28(I) = ANO28(I)
AN49(I) = ANU49(I)
AN40(I) = ANU40(I)
AN41(I) = ANO41(I)
ANF25(I) = ANOF25(I)
ANF28(I) = ANOF28(I)
ANF49(I) = ANOF49(I)
ANF41(I) = ANOF41(I)
34 CONTINUE
GO TO 405
36 S25 = 0.0+0
S49 = 0.0+0
S26 = 0.0+0
S40 = 0.0+0
SFF = 0.0+0
S28 = 0.0+0
S41 = 0.0+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 = XNU41 * SA41 *S41
RHO25 = XNU25 * SA25 * S25
RHO49 = XNU49*SA49*S49
RH026 = S26 * SA26
RH040 = S40 * SA4C
RH0FF = SFF * SAFF
RH028 = 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 = RHQ25 + RHC49 + RHQ41 - RHQ26 - RHQ40 - RHOFF - RHQ28 - RLE

DAHO = DRH25 + DRH49 + DRH41
RH = DRHO / DAHO

FORM(5X,14,5X,D20.10,5X,D20.10,5X,D20.10,5X,D20.10)
WRITE(3,400) J, RHO, FLREL(1), FLREL(2), FLREL(3)

4 5 IF(J.GT.NEN1) GO TO 80

NC = 0
IF(RHO.LE.0.0D+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) * 1.0D-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.0.0D+0) GO TO 10

115 IF(J.LT.NEN1) NBRN(K+1) = NBRN(K) + 52
NBRN(K) = J
NC = NBRN(K)

Mmx = J + 5
IF(Mmx.GE.NENT) GC TO 200
TIM(K) = TIMER(3) * 1.D-21
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)
MAM = J + 4
IF(MAM.LE.NEN1) GC TO 7
L0 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
IUM-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(2D15.1C)
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

F0RMAT (13(2X, A4))

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

Card 4

F0RMAT (6D13.6)

CF1 - unitized cost for purchase of U\textsubscript{3}O\textsubscript{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

F0RMAT (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
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), ILDA(50), NSFA(50), ISFA(50)
DIMENSION NCOS(50), ICOS(50), IPUR(50), IUNL(50), NUNL(50), ICOL(50)
DIMENSION NCUL(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), COS(50)
DIMENSION COS8(50), DELT8(50), WCUR(50), CRE2(50), CRE3(50), TOFL0(50)
DIMENSION PQI(30), RINT(6), PWF(6,35), PTOF(6,35), PTOF(6), FIXE(50)
DIMENSION W(50), CCN25(50), CON26(50), CON28(50), CON49(50), QON41(50)
DIMENSION CFPUR(35), CFPOS(35), CFENER(35), CFSEN(35), CFAB(35)
DIMENSION CFPSA(35), CFSCD(35), CFSPR(35), CFREP(35), CFCON(35)
DIMENSION CFPR2(35), CFPRK(35), TFPUR(5,35), TFCOS(5,35), TFENR(5,35)
DIMENSION TFSFA(5,35), TFFAB(5,35), TFSFA(5,35), TFCOS(5,35)
DIMENSION TFR1(5,35), TFRP(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), TOCSU(5), TOCR1(5), TDREP(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-)
1063 FORMAT(22X,'SUMMARY OF CASH FLOWS FOR ',I4)
1033 FORMAT(11X,'-------------',14X,'--------',8X,'---------',9X,'-------------')
999 FORMAT(11X,AI4,18X,I4,8X,I4)
1007 FORMAT(11X,AI4,18X,I4,8X,I4,9X,F11.2)
1119 FORMAT(11X,AI4,18X,I4,8X,I4,8X,'-1',F11.2)
1073 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,D15.10,2X,D15.10,2X,D15.10,2X,D15.10)
3271 FORMAT(1X,I2,8X,I15.10,2X,I15.10,2X,I15.10,2X,I15.10,2X,I15.10,2X,I15.10,2X,I15.10)
1027 FORMAT(11X,'ACTIVITIES',14X,'LOAD',8X,'WEEK',9X,'CASH FLOW($)')
541 FORMAT(4X,2I4,3D18.10)
542 FORMAT(2D18.10)
539 FORMAT(1X,AI4,4X,5(2X,D15.10))
4020 FORMAT(1X,'TOTAL',3X,5(2X,D15.10))
4031 FORMAT(9X,5(2X,'----------'))
READ(5,536) ( PG(I), I=1,29)
READ(5,534) CF1, CF2, CF3, CF4, CF5, CF5A
READ(5,534) CF7, CF8, CIRU, VREG, ANDO25, CF6
NINT = 5
READ(5,534) ( DINT(I), I=1,NINT )
READ(5,534) ANDO28, XP, TX, XF
READ(5,535) NYRO, NINT, K
READ(5,537) ( IBRN(M), NBRN(M), CON25(M), CON28(M), CON26(M), 1)
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, AN0025, CF6
WRITE(6,534)  ( DIAT(I), I=1,NINT )
WRITE(6,534)  AN0028, XP, XW, XF
WRITE(6,541)  ( IBRN(M), NBRN(M), CON25(M), CON28(M), CON26(M),
               I=1,K)
WRITE(6,542)  ( CON49(M), CON41(M), M=1,K)
CO 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 = ( ANOU25 * VREG * .235 D+0 ) / 6.023 D+23
GK28 = ( ANOU28 * VREG * .238 D+0 ) / 6.023 D+23
FREAC = GK25 + GK28
PFSH = 1.1 D+3 * FREAC
ENRIC = ( PFSH * ( XP - XW )) / ( XF - XW )
CONV = 1.005 D+0 * ENRIC
TAIL = ENRIC - PFSH
PUR = ( CONV * 2.205 D+1 ) / .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**

**C**

**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.C05 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, CUST = COS1**

**COS1 = CF1 * PUR**

**C CONVERSION AND SHIPPING, COST = COS2**

**COS2 = CF2 * ENRIC**

**C ENRICHMENT, COST = COS3**

**FIXP = (1.D+U - 2.D+0 * XP ) * DLOG(( 1.D+0 - XP ) / XP )**

**FIXF = (1.D+U - 2.D+0 * XF ) * DLOG(( 1.D+0 - XF ) / XF )**

**FIXW = (1.D+U - 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**

**COS1 = UCR * 1.D-1 * FREAC**

**C PRE-IRRADIATION SHIPPING, COST = COS5A**

**COS5A = CF5A * FREAC**

**C PRE-REPROCESSING SHIPPING, COST = COS6**

**COS6 = CF6 * FREAC**

**COSAA = ( GK25 + GK28 ) * 1.D-3 * CF7 + 8.D+0 * CF7**

**DO 808 M=1,K**

**C REPROCESSING, COST = COS7**

**COS7(M) = COSAA**

**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**

**COS3(M) = PURE(M) * CIRU**

**B2B 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 FLOWS
WRITE(6,1013)
DO 1000 L=1,35
CFPUR(L) = O.D+0
CFCOS(L) = O.D+0
CFENR(L) = O.D+0
CFSEN(L) = O.D+0
CFFAB(L) = O.D+0
CFSFA(L) = O.D+0
CFSCO(L) = O.D+0
CFCR1(L) = O.D+0
CFREP(L) = O.D+0
CFCR2(L) = O.D+0
CFCR3(L) = O.D+0
TOFLO(L) = G.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(I), M, NAY, COS1
CFPUR(L) = CFPUR(L) + COS1
TOFLO(L) = TOFLO(L) + COS1
1010 IF(ICS(M) .NE. J) GO TO 1015
NAZ = ICS(M) / 52
NAY = ICS(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(2), 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(ENR(M) .NE. J) GO TO 1030
NAZ = ENR(M) / 52
1030
NAY = NENR(M) - NAZ * 52
IF(NAY.EQ.0) NAY = 52
WRITE(6,1037) 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.J) NAY = 52
WRITE(6,999) PQ(6), M, NAY
1035 IF(ISEN(M).NE.J) GO TO 1040
NAZ = NSEN(M) / 52
NAY = NSEN(M) - NAZ * 52
IF(NAY.EQ.J) NAY = 52
WRITE(6,1037) 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.J) NAY = 52
WRITE(6,999) PQ(8), M, NAY
1045 IF(IFAB(M).NE.J) GO TO 1050
NAZ = NFAB(M) / 52
NAY = NFAB(M) - NAZ * 52
IF(NAY.EQ.J) NAY = 52
WRITE(6,1037) PQ(9), M, NAY, COS5
CFIFAB(L) = CFIFAB(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.J) NAY = 52
WRITE(6,999) PQ(10), M, NAY
1055 IF(ISFA(M).NE.J) GO TO 1060
NAZ = NSFA(M) / 52
NAY = NSFA(M) - NAZ * 52
IF(NAY.EQ.J) NAY = 52
WRITE(6,1037) 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.J) 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.J) NAY = 52
1067 WRITE(6,999) PQ(13), M, NAY
1068 IF( IBRN(M).NE.J) GO TO 1068
NAY = IBRN(M) / 52
IF (NAY.EQ.0) NAY = 52
WRITE(6,999) PQ(14), M, NAY
1068 IF(NBRN(M).NE.J) GO TO 1070
NAY = 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
NAY = 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
NAY = 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
NAY = 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
NAY = 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
NAY = 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
NAY = NSCO(M) / 52
NAY = NSCO(M) - NAZ * 52
IF(NAY.EQ.0) NAY = 52
WRITE(6,1007) PQ(21), M, NAY, COS6
CFSOC(L) = CFSOC(L) + COS6
TFSOC(L) = TFSOC(L) + COS6
1100 IF(IREP(M).NE.J) GO TO 1105
NAY = 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
NAY = 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
NAZ = J - NAW * 52
IF(NAX.NE.0) GO TO 2500
WRITE(6,1117)
WRITE(6,1037)
WRITE(6,1043) TOFLO(L)
WRITE(6,1013)
WRITE(6,1019)
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) = 1.0*D+0
PWF(I,2) = 1.0*D+0 / ( 1.0*D+0 + DINT(I) )
DO 3500 N=3,L
PWF(I,N) = PWF(I,2) * PWF(I,N-1)
3500 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)
TFSAI(I,N) = CFSAI(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)
PTOF0(I,N) = TOFLC(N) * PWF(I,N)
3205 CONTINUE
3300 CONTINUE
DO 3400 I=1,NINT
TOPUR(I) = 0.0+0
TOCOS(I) = 0.0+0
TOENR(I) = 0.0+0
TOSEN(I) = 0.0+0
TOFAB(I) = 0.0+0
TOFAI(I) = 0.0+0
TOSCO(I) = 0.0+0
TOCR1(I) = 0.0+0
TOREP(I) = 0.0+0
TOCON(I) = 0.0+0
TOCR2(I) = 0.0+0
TOCR3(I) = 0.0+0
PTOF(I) = 0.0+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)
TOFAI(I) = TOFAI(I) + TFSAI(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) + PTOF0(I,N)
3350 CONTINUE
3400 CONTINUE
WRITE(6,1013)
WRITE(6,1121) ( CINT(I), I=1,NINT )
WRITE(6,1037)
WRITE(6,539) PQ(I), ( TOPUR(I), I=1,NINT )
WRITE(6,539) PQ(3),   ( TOGOS(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(23),  ( TOCR1(I), I=1,NINT )
WRITE(6,539) PQ(29),  ( TOCR1(I), I=1,NINT )
WRITE(6,539) PQ(23),  ( TUREP(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

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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 $^{3}$O$_{8}$ 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.