A CRITIQUE AND SIMPLIFICATION OF NUCLEAR FUEL CYCLE ECONOMICS CALCULATIONS

by

MARK WILLIAM ZIMMERMANN
B.A., Point Loma College
(1982)

Submitted to the Department of Nuclear Engineering in Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August, 1983

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Accepted by: Signature redacted
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Submitted to the Department of Nuclear Engineering on August 17, 1983, in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Engineering.

ABSTRACT

The objective of the present work was to review, compare and critique methodologies used for nuclear fuel cycle economics calculations, and to extend some of the prior work done at MIT in a way which could make it more attractive as a generalized way to both teach and carry out engineering economic studies of the nuclear fuel cycle.

The discounting theory, programming, simplifying assumptions, and errors induced as a result of those assumptions, were examined for six state-of-the-art computer programs. Also, three sets of numerical comparisons between codes were reviewed. It was found that the MITCOST II program, developed some years ago at MIT, was the most suitable of the more elaborate codes.

A rigorous derivation of a "Direct Plus Carrying Charge Model (DCC)" based on a simple transformation of the time span variable was carried out and shown to be an exact and simple alternative approach to the generation and presentation of nuclear fuel costs. Approximate prescriptions for levelizing over long time spans in the presence of price escalation were also derived and evaluated.

An interactive computer program, DCC, in the BASIC language for microcomputer use, was prepared to implement the model for convenient use in teaching and research applications.

Thesis Supervisor: Michael J. Driscoll
Title: Professor of Nuclear Engineering

Thesis Reader: David D. Lanning
Title: Professor of Nuclear Engineering
ACKNOWLEDGEMENTS

I would like to thank Professor Michael J. Driscoll for his helpful suggestions, critical review and support during the course of this thesis. I would also like to thank Professor David D. Lanning, who served as the Reader of this thesis.
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CHAPTER 1
INTRODUCTION

1.1 Foreword

Commercial nuclear power has been a reality now for almost a quarter century, and a major contribution to its acceptance by utilities has been its inexpensive fuel costs, compared to fossil options. Indeed, these costs must be low to offset the higher capital costs of the nuclear units. Hence accurate evaluation of the contribution of the nuclear fuel cycle to the cost of electricity has been of interest among the nuclear community for several decades, and a variety of methodologies have been developed to do such computations. No one approach, however, has gained general acceptance.

Accordingly it is the purpose of the present thesis to review this prior work, compare and critique some of the available computer programs, and extend some of the prior work done at MIT in a way which could make it more attractive as a generalized way to both teach and carry out engineering economic studies of the nuclear fuel cycle.

The work reviewed and reported here is in the realm of engineering economics, which is concerned with the evaluation of future alternatives with an acceptable degree of uncertainty, and not with accounting economics, which is concerned with the precise documentation of historical costs - although there is appreciable activity and interest in this latter area: for example the accounting code FUELMACS [B-5]. Also, codes that develop material balances for nuclear fuel cycles will not be discussed; for a critical review of such codes, the reader is referred to Ref. [T-1].
1.2 Background

Most of the methods used for fuel cost calculations have been embodied in computer programs used by utilities, vendors, architect engineers, and government laboratories. There is, however, no industry standard for these calculations as yet, and only cursory treatment in most textbooks, nor has any comprehensive review of the available tools in this area been published.

To illustrate the anarchy in the field, the following brief roster of state-of-the-art applications is cited; a more detailed dissection of the referenced programs will be presented in the body of the thesis.

GACOST is an updated version of the earlier code PWCOST [L-1]. Both were developed at General Atomic.

GEM is an updated version of CINCAS [C-2]; both GEM and CINCAS were developed at the University of Illinois and Commonwealth Edison. GEM calculates batch, yearly, and multiple-batch levelized fuel costs. Another code, GEM II, calculates the cycle levelized fuel costs. A third code, GEM III, incorporates both GEM and GEM II as subroutines, and also does sensitivity calculations. GEM III is presently in use at Commonwealth Edison.

MITCOST II, a code developed at MIT for detailed fuel cycle economic analysis, is a more general and versatile code than its predecessors, MITCOST [C-4], MITCOST 1 [W-2], and MITCOST-C [R-1].

NFCOST was prepared for the Electric Power Research Institute (EPRI) by Nuclear Associates International Corporation. The code is presently in use at American Electric Power Service Corporation, where it has been modified several times.
LNFC was prepared for the Office of Energy Source Analysis of the Energy Information Administration in the U.S. Department of Energy by the Orkand Corporation for use in fuel cycle planning studies.

Finally, a highly simplified program, ENUF, was programmed at MIT for use as a teaching tool, based on the theory of the SIMMOD model, developed by Abbaspour [A-1] for fuel cycle economic studies as part of the NASAP effort.

1.3 Purpose and Outline of Present Work

It is the purpose of the present thesis to do a critical review of publicly available computer programs designed to do nuclear fuel cycle cost calculations, and to derive and evaluate the features of an alternative approach, designated here as the Direct Plus Carrying Charge Model (DCC).

The codes included in this study are listed in column one of Table 1.1. This list was culled from a much larger compilation developed in a survey of the literature. The codes have been selected with the following criteria in mind: currency (i.e. < 10 years old and now in active use - and in general the last version of a historical sequence is preferred); variety (examples from organizations of different types: utilities/vendors/academia), and the availability of detailed documentation. Column two lists their expanded titles (where known), from which the abbreviated designators in column one were derived. Column three of Table 1.1 lists the user's manual or comparable documentation corresponding to each code.

In Chapter 2, the codes will be described, and listings of the key features will be presented. The codes will then be critiqued according to theoretical and programming aspects, assumptions and errors induced,
### TABLE 1.1
REPRESENTATIVE ROSTER OF RECENT FUEL CYCLE ECONOMICS PROGRAMS

<table>
<thead>
<tr>
<th>Code</th>
<th>Full Title</th>
<th>User's Manual/Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>Direct Plus Carrying Charge</td>
<td>This thesis.</td>
</tr>
</tbody>
</table>
and a comparison of several codes carried out. The computer code DCC is derived and compared to ENUF/SIMMOD in Chapter 3, so it will not be included in the critique of Chapter 2.

Chapter 3 will suggest the simplicity, and examine the accuracy of the Direct Plus Carrying Charge Model by repeating Abbaspour's derivation of SIMMOD, followed by a derivation of further simplifications leading to the Direct Plus Carrying Charge Model. The results of the Model will then be compared to the computer code ENUF/SIMMOD.

Chapter 4 will summarize the results and list the conclusions. Also, there will be recommendations for further work. Finally, six appendices are included: four dealing with several fine points, expanding upon material in the body of the thesis; and the last two documenting the DCC Computer Program.
CHAPTER 2
CRITIQUE OF FUEL CYCLE ECONOMICS CODES

2.1 Introduction

The key features of the representative computer programs identified in Chapter 1 will be summarized in this chapter as the various aspects of the codes are discussed. Key theoretical aspects of the codes will be critiqued first: specifically the tax treatment and the degree of detail used in describing cash flows. Next, the programming aspects will be critiqued. This section will include a listing of the descriptive characteristics of the codes as well as focus on the details of the input and output parameters. The next section will include a listing of the major assumptions in each code and the corresponding errors that result. Preceding the chapter summary will be a comparison between the codes GEM and MITCOST, NFCOST and GACOST, and ENUF/SIMMOD and MITCOST II.

2.2 Theoretical Aspects

2.2.1 Explicit Tax Treatment

Table 2.1 lists the tax categories that each code handles. Of the seven codes, only MITCOST II treats all forms of taxes explicitly. The four taxes provided for in MITCOST II are [C-6]:

1. Federal Income Tax, \( T_F \)
2. State Income Tax, \( T_S \)
3. State Gross Revenues Tax, \( T_R \)
4. Local Property Tax, \( T_P \)

For a batch of fuel \( k \) in period \( n \), the taxes are defined as (all cash flows in dollars):
<table>
<thead>
<tr>
<th>Type of Tax</th>
<th>GACOST</th>
<th>GEM</th>
<th>MITCOST II</th>
<th>NFCOST</th>
<th>LNFC</th>
<th>ENUF/ SIMMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Federal Income Tax</td>
<td>$X^1$</td>
<td>$X$</td>
<td>$X$</td>
<td></td>
<td></td>
<td>$X^3$</td>
</tr>
<tr>
<td>2. State Income Tax</td>
<td></td>
<td>$X$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. State Gross Revenue Tax</td>
<td></td>
<td></td>
<td>$X$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Local Property Taxes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Tax Fraction Method</td>
<td>$X^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$X$</td>
</tr>
</tbody>
</table>

1 - or a combined equivalent federal and state income tax.

2 - see section 2.2.1.

3 - a composite tax rate, see section 2.2.1.
\[ T_F, k, n = \tau_F (S_k, n + PIR_k, n - C_k, n - D_k, n - B_k, n) \]
\[ - T_S, k, n - T_R, k, n - T_P, k, n \]  \hspace{1cm} (2.1)

\[ T_S, k, n = \tau_S (S_k, n + PIR_k, n - C_k, n - D_k, n - B_k, n) \]
\[ - T_R, k, n - T_P, k, n ) \] \hspace{1cm} (2.2)

\[ T_R, k, n = \tau_R (S_k, n + PIR_k, n ) \] \hspace{1cm} (2.3)

\[ T_P, k, n = \tau_P (V_k, n ) \] \hspace{1cm} (2.4)

where

\[ S_k, n = \text{gross revenues from the sale of electricity produced by batch } k \text{ in period } n; \]
\[ C_k, n = \text{current expenses for batch } k \text{ in period } n; \]
\[ D_k, n = \text{depreciation taken for batch } k \text{ in period } n; \]
\[ B_k, n = \text{interest paid to bondholders for batch } k \text{ in period } n; \]
\[ V_k, n = \text{outstanding principal of batch } k \text{ in period } n; \]
\[ PIR_k, n = \text{post-irradiation fuel credits for batch } k \text{ not taken as part of the depreciation reserve in period } n; \]
\[ \tau_F = \text{annual federal income tax rate, } yr^{-1}; \]
\[ \tau_S = \text{annual state income tax rate, } yr^{-1}; \]
\[ \tau_R = \text{annual state gross revenues tax rate, } yr^{-1}; \]
\[ \tau_P = \text{per period local property tax rate, } yr^{-1}. \]

The assumptions are that:

1. The federal income taxes are not deductable from state income taxes.
2. The local property taxes are proportional to the outstanding principal for a particular batch \( k \) at the end of period \( n \).

The economics code GEM provides for a combined federal and state tax. The sum of income tax payments and cost of money payments over a period \( n \) is given by:

\[
T_n = \left[ \frac{i(1-b)\tau_{CR}}{(1-\tau_{CR})} \right] V_n,
\]

where:
- \( i = \) equity return rate;
- \( b = \) debt-to-total capital ratio;
- \( \tau_{CR} = \) combined federal and state income tax rate;
- \( V_n = \) outstanding principal in period \( n \).

For background information necessary to the formulation of Eq. (2.5) and other relations displayed in this chapter, the reader is referred to the engineering economics text by Smith [S-5]. By applying the definitions of the cost of money and the discount rate, and with some rearrangement, one arrives at the following equation:

\[
T_n = \left[ \frac{x}{1-\tau_{CR}} \right] V_n,
\]

where \( x \) is the discount rate, as derived by Vondy in his benchmark report [R-2] of the mid-sixties on the discounted cash flow technique. Equation (2.6) uses the "tax fraction method" for accounting for taxes; as defined here "the tax fraction method" is a method that provides for the effect of taxes by the inclusion of the factor \( 1/(1-\tau) \) in the calculation.

ENUF/SIMMOD uses the tax fraction method, where the tax rate is a composite tax rate that accounts for the effect of all taxes combined.

GACOST, NFCOST, and LNFCC have no provision for taxes.
Presumably one can use the crude approximation of an "after-tax" or "tax-adjusted" rate of return. For long-lived investments (i.e., as $N \rightarrow \infty$ in the present worth factor):

$$ATRR \approx \frac{1}{2} BTRR,$$  \hspace{1cm} (2.7)

where:

- $ATRR$ = the after tax rate of return; and
- $BTRR$ = the before tax rate of return.

Because nuclear fuel is relatively short-lived, depreciation and annual capital recovery play a significant role, and the approximation is therefore not very good.

An accurate simulation of taxes is a requirement for a definitive analysis in any engineering study. The fact that the codes GACOST, NFCOST, and LNFCC do not have any provision for taxes is a very limiting factor. GEM and ENUF/SIMMOD will be compared to the codes MITCOST and MITCOST II, respectively, in sections 2.5.1 and 2.5.3 of this chapter. It will be shown that the results are in good agreement, and thus the tax fraction method is satisfactory. However, the treatment of taxes in MITCOST II is the best of all the codes if one doesn't wish to make the simplification of using only a single composite tax rate.

2.2.2 Degree of Detail on Cash Flows

Table 2.2 lists four types of depreciation, and the type provided for in each code. Only MITCOST II provides for all four. ENUF/SIMMOD treats depreciation implicitly. For a derivation of how this is done, the reader is referred to pp 27-29 of the report by Abbaspour [A-1]. The user's manual for LNFCC makes no mention of how depreciation is treated.

The most logical form of depreciation for nuclear fuel is "energy
TABLE 2.2  
DEPRECIATION TREATMENTS PERMITTED IN VARIOUS  
FUEL CYCLE ECONOMICS CODES  

<table>
<thead>
<tr>
<th>Type of Depreciation</th>
<th>GACOST</th>
<th>GEM</th>
<th>MITCOST II</th>
<th>NFCOST</th>
<th>LNFCC</th>
<th>ENUF/SIMMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Depreciation&lt;sup&gt;1&lt;/sup&gt;</td>
<td>X&lt;sup&gt;2&lt;/sup&gt;</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Straight Line Depreciation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sum-of-the-year's Digits Depreciation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Declining Balance Depreciation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 - Principal plus interest minus net salvage.  
2 - Also available is the outdated method of the investment principal minus net salvage.  
3 - Implicitly.
depreciation", in which the residual value of the fuel decreases in direct proportion to the total amount of energy extracted from the fuel as of a given time. Since nuclear reactors are typically base-load units, they are operated continuously at full power - hence straight line depreciation is essentially equivalent to energy depreciation. This relationship is not exact because reactor operation is interrupted by both unplanned and planned (e.g. refueling) outages. Moreover, the energy generated by a given fuel assembly is not known with exactitude - it is a computed rather than a measured quantity. All-in-all, therefore, these two types of depreciation may be regarded as synonymous.

The method of depreciation employed is also subject to regulatory approval; in most jurisdictions in the U.S., straight line depreciation is preferred for a utility's capital units. Also, in the Electric Power Research Institute's (EPRI) Technical Assessment Guide (TAG) [E-1], straight line depreciation is the only method considered. Therefore, the lack of sum-of-the-year's-digits and double declining balance methods, provided for in MITCOST II, and not included in any of the other codes, does not necessarily imply that the other codes are less accurate in their analysis. It can be concluded that all of the codes treat depreciation adequately, except perhaps for LNFCC.

Table 2.3 shows that escalation is treated in the three advanced economic codes GACOST, GEM, and MITCOST II, and in the simple code ENUF/SIMMOD. It is not treated in NFCOST and LNFCC. NFCOST and LNFCC therefore lack the ability to treat such factors as escalation due to resource depletion, and de-escalation due to improvements in design or manufacturing technology.

Basic to the understanding of cash flow analysis is the understand-
**TABLE 2.3**  
SPECIAL FEATURES OF FUEL CYCLE ECONOMICS PROGRAMS

<table>
<thead>
<tr>
<th>Feature</th>
<th>GACOST</th>
<th>GEM</th>
<th>MITCOST II</th>
<th>NFCOST</th>
<th>LNFCC</th>
<th>ENUF/SIMMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accommodation of Escalation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Accommodation of Fuel Leasing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accommodation of Recycle</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

a. The price of Electricity can not be escalated.
ing of the work by Vondy [R-2]. The method that he developed consists of writing a cash flow balance for each period \( n \) so as to be able to calculate the outstanding principal (net investment) for batch \( k \) at the beginning of period \( n+1 \). The outstanding principal for batch \( k \) is then required to go to zero at the end of the period in which the last cash flow pertaining to batch \( k \) occurs [C-6]. The reader is referred to Appendix A for a review of Vondy's original presentation [R-2], augmented for completeness and clarity.

All of the codes used a variation of Vondy's approach. In GACOST, the net fuel cost (i.e. the numerator of Vondy's equation without tax depreciation) is calculated first. Next, the net fuel cost is depreciated for each cycle. Finally, the revenue requirements per cycle are calculated by incremental depreciation. There are four options available for calculating the fuel value at the beginning and end of each reload interval. All of the options are based on the replacement value and not on the salvage value of the fuel.

The code GEM does a calculation similar to that in GACOST. However, three distinct types of economic analysis are used, each yielding identical results. The three types are cash flow, allocated costs, and yearly cash flow. The cash flow analysis divides batch life into three periods, which are pre-irradiation, irradiation time, and post-irradiation time. The levelized cash flow for the transactions is calculated for each time period. The allocated cost analysis divides the transactions into expense and inventory costs, which will be referred to later in this section as direct costs and carrying charge costs. The yearly cash flow analysis calculates the cash flow for each transaction on a year by year basis.
In MITCOST II, the taxable terms for fuel credits have been separated from the other terms so that the payment schedule for taxes need not coincide with the expense or credit payments. MITCOST II also calculates the fuel cost for a batch which is not being discharged at the end of the irradiation period by one of two methods. The two methods are the Inventory Value Method (IVM) and the Energy Value Method (EVM). On a conceptual level, the outstanding difference between the IVM and the EVM is that in the IVM the value of the fuel is related to what it could be sold for as salvage, while the EVM values the fuel according to the energy it is capable of producing in the future [C-6]. This feature, applied when fuel will produce more energy in the future, is a logical and useful option.

All of the codes divide the revenue requirements into "expense" and "working capital charges", the latter also referred to as "carrying charges". The nomenclature differs in almost every code and one should be careful to determine the precise definitions. An expense is the component of the revenue requirement for goods and services that are usually used in one year or less. Since nuclear fuel typically lasts for several years, it is treated as an investment, and expense in this context refers to the capital investment in the fuel. The expense is sometimes referred to as the "direct cost". The carrying charges are the revenue needed to support the investment and equal to the sum of:

- Return on Debt
- Return on Equity
- Income Taxes
- Depreciation
- Property Tax
- Insurance (not accounted for in the codes)
The revenue requirement is the sum of the direct cost (DC) and the carrying charges (CC). That is:

\[
\text{Revenue requirement} = \text{DC} + \text{CC} \quad (2.8)
\]

The codes NFCOST and LNFCC specify a "carrying charge rate". The carrying charge rate is the amount of revenue per dollar of investment that must be collected per unit time from customers in order to pay the carrying charges on that investment. It is expressed as a decimal that is multiplied by the original investment to obtain a dollar amount.

Since ENUF/SIMMOD is based on the Simple Model (SIMMOD), which will be discussed in Chapter 3, the discussion of the cash flow analysis for ENUF/SIMMOD will be deferred until then. Table 2.4 lists the levelized fuel costs and the units output by each code.

Table 2.5 lists some of the other features in the codes. MITCOST II is the most versatile code with respect to the number of tax and billing periods. Also, tax payments can occur at times different from those at which billing occurs.

2.2.3 Fine Points

The most common methods for determining levelized costs are the Pseudo-Cash-Flow-Formulation and the Present-Worth-Cost method. Although the two methods are conceptually correct, levelized costs based on each method are not precisely equivalent. F. Correa found in his work ([C-5] and Appendix B) that the former model favors, by a few percent, alternatives that present a low annual cost to initial investment ratio. He concluded, therefore, that for a valid comparison of levelized costs for similar economic alternatives, the present-worth-cost method should be used.
**TABLE 2.4**
OUTPUT CATEGORIES FOR SEVERAL FUEL CYCLE CODES

<table>
<thead>
<tr>
<th>Code</th>
<th>Levelized Fuel Costs: (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GACOST</td>
<td>batch cycle, and lifetime (mills/kWhr)</td>
</tr>
<tr>
<td>GEM</td>
<td>batch, yearly, multiple batch (cents/OBTU, mills/kWhr)</td>
</tr>
<tr>
<td>MITCOST II</td>
<td>sublot, batch, period (user specifies) (mills/kWhr)</td>
</tr>
<tr>
<td>NFCOST</td>
<td>operational year, calendar year (cents/OBTU, mills/kWhr)</td>
</tr>
<tr>
<td>LNFCC</td>
<td>batch (only one allowed) (mills/kWhr)</td>
</tr>
<tr>
<td>ENUF/SIMMOD</td>
<td>period (mills/kWhr)</td>
</tr>
</tbody>
</table>
TABLE 2.5
OTHER FEATURES OF FUEL CYCLE ECONOMICS PROGRAMS

<table>
<thead>
<tr>
<th>Feature</th>
<th>GACOST</th>
<th>GEM</th>
<th>MITCOST II</th>
<th>NFCOST</th>
<th>LNFCC</th>
<th>ENUF/ SIMMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Number of Batches permitted per case</td>
<td>32</td>
<td>50</td>
<td>33</td>
<td>20&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1</td>
<td>∞&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum Number of Sublots permitted per batch</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum Number of Transactions permitted</td>
<td>7</td>
<td>12</td>
<td>25</td>
<td>20&lt;sup&gt;b&lt;/sup&gt;</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Number of Tax Payment periods permitted</td>
<td>-</td>
<td>1</td>
<td>1, 2, 3, 4, 6, 12</td>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1</td>
</tr>
<tr>
<td>Number of Billing (Revenue) periods permitted</td>
<td>-</td>
<td>1</td>
<td>1, 2, 3, 4, 6, 12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1</td>
</tr>
</tbody>
</table>

a - Tax payments can occur at times different from those at which billing occurs.
b - Modified to 50 for use at American Electric Power (AEP).
c - i.e. doesn't treat explicitly.
d - Essentially infinite, but all are identical except for item-by-item escalation.
Another non-trivial distinction is that while sometimes constant dollar transactions and a deflated discount rate are used in lieu of then-current dollars and the actual market discount rate (alternative procedures which are mathematically equivalent under certain circumstances), there is one important exception. When tax deductions related to depreciation are involved, this transformation breaks down and is no longer exact. For a discussion of this, the reader is referred to Appendix C.

Finally, it should be noted that one does not obtain equivalent results by deflating the bond and stock rates of return to find a deflated discount rate as opposed to deflating the discount rate itself. Appendix D shows this mathematically.

2.3 Programming Aspects

Table 2.6 compares some programming aspects. Note that neither GACOST, MITCOST II, nor NFCOST is written in double precision, which may present a problem should these codes be run on computers having a short word length.

The GACOST code is a very flexible computer program, with numerous options available, but the input description is overwhelming and much time is required to become familiar with the code. Also, the program would be difficult to modify because the programming of the code is difficult to follow.

The input data for MITCOST II is more clearly grouped than in either GACOST or GEM. The data for each case in MITCOST II is divided into eight groups according to the type of parameter and the input requirements of the parameter. Each group is further divided into data sets which contain a specific type of data, which may only apply to one
<table>
<thead>
<tr>
<th>Feature</th>
<th>GACOST</th>
<th>GEM</th>
<th>MITCOST II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine original version was written for:</td>
<td>UNIVAC/1108</td>
<td>IBM/360</td>
<td>IBM/360</td>
</tr>
<tr>
<td>Programming language:</td>
<td>FORTRAN IV</td>
<td>FORTRAN IV</td>
<td>FORTRAN IV</td>
</tr>
<tr>
<td>Precision:</td>
<td>Single</td>
<td>Double</td>
<td>Single</td>
</tr>
<tr>
<td>Core Size (words (60 bits/word)) required to compile/load: (decimal)</td>
<td>23K/~73K</td>
<td>23K/~66K</td>
<td>?/32K</td>
</tr>
<tr>
<td>Compiling time (sec):</td>
<td>77</td>
<td>45</td>
<td>-</td>
</tr>
<tr>
<td>Typical running time:</td>
<td>~1.8</td>
<td>~0.3 ~0.7</td>
<td>-</td>
</tr>
<tr>
<td>(sec/batch)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of card images:</td>
<td>7800</td>
<td>4500</td>
<td>2000</td>
</tr>
</tbody>
</table>
### TABLE 2.6 (continued)

**COMPARISON OF PROGRAMMING FEATURES**

<table>
<thead>
<tr>
<th>Feature</th>
<th>NFCOST</th>
<th>LNFCC</th>
<th>ENUF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine original version was written for:</td>
<td>IBM 370/3033</td>
<td>IBM 370/168</td>
<td>Tektronix 4051</td>
</tr>
<tr>
<td>Programming language:</td>
<td>FORTRAN IV</td>
<td>FORTRAN IV</td>
<td>BASIC</td>
</tr>
<tr>
<td>Precision:</td>
<td>Single</td>
<td>-</td>
<td>Single</td>
</tr>
<tr>
<td>Core Size (# bytes) required to compile/load-execute:</td>
<td>296K/136K</td>
<td>128K/128K</td>
<td>-/15K</td>
</tr>
<tr>
<td>Compiling time (sec):</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Typical running time: (sec/batch)</td>
<td>0.13</td>
<td>1 - 100</td>
<td>~0.5</td>
</tr>
<tr>
<td>Number of card images:</td>
<td>4300</td>
<td>0(^a)</td>
<td>0(^b)</td>
</tr>
</tbody>
</table>

- \(^a\) - On a 9-track magnetic tape.
- \(^b\) - On a Scotch DC 300A data cartridge.
sublot, or to several batches. Table 2.7 lists the output of MITCOST II. The reader should compare this with the output of NFCOST listed in Table 2.8. NFCOST was not designed to be a detailed fuel cycle code such as MITCOST II and therefore contains a less detailed output. However, it is possible that NFCOST may contain all the information the user may need.

NFCOST avoids the construction of the "segment or batch scheme" required for the GACOST input. The segment scheme, originally conceived to calculate HTGR (High Temperature Gas Cooled Reactor) costs, is an awkward contrivance when used to represent the PWR (Pressurized Water Reactor) situation. NFCOST was modified at American Electric Power so that the user can more readily input existing fuel contract data and avoid the laborious task of "number crunching" before inputting data.

The codes LNFCC and ENUF/SIMMOD require no input files. Input is supplied after a default listing of parameter values. These may be changed when the user is prompted to enter parameter symbols and their new values. The user may decide the number of changes to be made in accordance with what is being examined.

2.4 Assumptions and Errors Induced as a Result

Since all the codes use some form of Vondy's method, it might be instructive to state the original assumptions of Vondy and then review how one code, MITCOST II, was changed in order to improve on the assumptions. The assumptions inherent in Vondy's approach are the following:

1. Return to investors is paid at the same time as taxes.
2. The use of a discrete present worth factor is acceptable.
3. Taxes are paid on cash flows simultaneously with the cash flow itself.
The output of MITCOST II [C-6] consists of the following:

(a) A tabulation of the energy production data.
(b) A tabulation of the mass flows.
(c) A tabulation of all other input quantities.
(d) A table for each sublot giving the lag time, absolute time, unit cost, quantity, direct cost, and discounted cost.
(e) A tabulation of the direct and discounted energy production per sublot.
(f) The levelized unit nuclear fuel cost and revenue requirement per sublot.
(g) A tabulation of the direct and discounted transaction costs for each batch.
(h) The levelized unit nuclear fuel cost and revenue requirement per batch.
(i) A tabulation of the direct and discounted transaction costs over the reactor life.
(j) The overall levelized unit nuclear fuel cost and the overall revenue requirement.
(k) A tabulation of parameters related to the levelization of the advance payment for a fixed-commitment separative work contract.
(l) A summary table of the levelized unit nuclear fuel cost and the revenue requirement per sublot and per batch.
(m) A summary table of the levelized unit nuclear fuel cost and the revenue requirement per period.
(n) A quarterly cash flow tabulation per sublot, per batch, and overall.
### TABLE 2.8

**SYNOPSIS OF NFCOST OUTPUT**

- (a) Input variable listing.
- (b) Case ground rules and dates.
- (c) Working capital charge rates.
- (d) Mass balance and energy output data.
- (e) Batch-by-batch input description and calculations.
- (f) Annual fuel cost summary for all batches.
- (g) Levelized annual fuel costs.
- (h) Selected batch summaries.
An investigation was made by A. Croff, the author of MITCOST II, to explore the feasibility of eliminating the first assumption. Since the assumption results in only a slight perturbation on reality, and MITCOST II was not intended to be an accounting code, it was not deemed necessary.

Croff does eliminate the second assumption by replacing the discrete present worth factor \((1 + x')^{-n}\) by an instantaneous present worth factor \((1 + x')^{t_R - t_k, n}\), where \(t_R\) is an arbitrary selected reference time and \(t_k, n\) is the time at which cash flow \(n\) occurs. The discount rate is changed from a "per period" basis to a "per year" basis, and \(t\) is in years. In Vondy's equation, the indices on the summations were changed to reflect the fact that:

1. the summations are now over cash flow, not periods; and
2. the cash flows are independent of each other.

This results in an equation which is sensitive to small changes in the time at which cash flows occur.

Croff also eliminates the third assumption because he concludes that it is too restrictive. By separating terms representing cash flows other than taxes from terms representing the taxes paid on these cash flows, he nullifies the assumption.

Other assumptions are made in MITCOST II in order to use the Energy Value Method (EVM) and the Inventory Value Method (IVM) for determining the value of fuel that will be used in the next irradiation period. The three inputs assumed to be known are:

1. The initial (pre-irradiation) cost of the batch and the times at which these costs are incurred.
2. The energy production history of the batch up to the end of
the present irradiation period.

3. The isotopic composition of the batch at the end of the present irradiation period.

Another assumption of MITCOST II is that all parameters are assumed to be invariant throughout the life of the reactor, except for lead times.

Table 2.9 lists the assumptions in GACOST. There are also assumptions related to what GACOST refers to as "cumulative throughput - learning by unit or batch of units strategy", but they will not be detailed here.

A key assumption built into NFCOST is that there are two different carrying charge rates: one for the period of irradiation, and a different one for non-irradiation periods.

A fundamental assumption of LNFCC regarding cycle costs is that discounting over half of a cycle's time span is equivalent to levelizing over an entire cycle: this assumption can only be exact for a linearized present worth factor (simple interest).

The assumptions of the simple model (SIMMOD), on which ENUF is based, are as follows:

1. Only equilibrium batches are considered. Equilibrium batches are defined as those batches which have equal in-core residence times and equal charge and discharge enrichments.

2. Revenue and depreciation charges are assumed to occur at the midpoint of the irradiation period.

Abbaspour concluded [A-1] that two-thirds of the difference in fuel cycle costs between ENUF/SIMMOD and MITCOST II is a result of the first assumption, and that approximately one-fifth of the discrepancy
**TABLE 2.9**

**ASSUMPTIONS IN GACOST**

1. Progress payments which occur after a segment commences to produce energy do not contribute to the pre-irradiation working capital expenses.

2. The "buyback cycle" differs from the normal cycle in that, after the cooling time, ownership of the discharged fuel is assumed to be with the fuel vendor.

3. In the calculation of the total fuel cycle cost per batch, the batch is assumed to produce an amount of energy $E$ during this interval. It is further assumed that this energy is produced uniformly during the period and that it is equivalent to producing an amount of energy $E$ at the midpoint of the interval.

4. There are three alternative treatments for calculating how much of the reactor's total energy a batch produces during a reload interval. The first method assumes that a batch's energy production is proportional to its volume and all batches are assumed to occupy the same volume fraction of the core, i.e., all batches are the same size such that, at equilibrium, each batch's mass flow is identical to that of the other batches.

5. The post-irradiation working capital expenses are assumed to be paid at the time the reprocessed spent fuel is sold in the middle of the reprocessing interval.

6. The expenses associated with storing the spent fuel and shipping it are assumed to occur at the midpoint of the storage period and shipping intervals, respectively.

7. When escalation is calculated based on labor and material escalations, the labor and material costs are usually assumed to follow the escalation experienced by representative labor and material cost indices.
between the codes is a result of the second assumption.

2.5 **Comparison of Codes**

2.5.1 **GEM and MITCOST**

A comparison between GEM and MITCOST, the earlier version of MITCOST II, was done by Brehm and Spriggs [B-4]. They also modified the two codes and did a comparison to correct some of the errors and inconsistencies between the two codes. The results of their comparison are shown in Table 2.10. There is a 0.13 percent difference between the modified versions of the codes obtained for the batch levelized fuel cost. This can be considered good agreement.

2.5.2 **NFCOST and GACOST**

A comparison between NFCOST and GACOST was made by American Electric Power in 1981 for two proposals by Exxon and Westinghouse to fabricate fuel. The comparison was made for four categories of results: expenses, working capital charges, total costs, and levelized annual costs. It was found that NFCOST and GACOST were very close to each other in the area of tabulated expenses. For working capital charges, the differences between GACOST and NFCOST were larger, but generally within 1.5 percent of each other. Tables 2.11 and 2.12 show a comparison of the annual levelized fuel cycle costs for the Exxon and Westinghouse Contracts, respectively.

The difference in the working capital charges was reduced to 0.01 percent by compensating for what NFCOST requires the user to input as an "equivalent full value period" (EFVP) to represent the time of payment. For example, say a contract required seven equal payments for fabrication, starting 6 months before delivery, with one every month, ending at the time of delivery. NFCOST input requires the user to say
### TABLE 2.10

**Comparision Between Original and Modified Versions of GEM and MITCOST**

<table>
<thead>
<tr>
<th>Item</th>
<th>Original MITCOST</th>
<th>Modified MITCOST</th>
<th>Original GEM</th>
<th>Modified GEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Batch Levelized Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mills/kwhe)</td>
<td>5.3223</td>
<td>5.3524</td>
<td>5.3402</td>
<td>5.3458</td>
</tr>
<tr>
<td><strong>Non-time-valued Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(10^6 \text{ $})$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium Ore</td>
<td>7.3483</td>
<td>7.3377</td>
<td>7.3483</td>
<td></td>
</tr>
<tr>
<td>Fabrication</td>
<td>2.5520</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium Credit</td>
<td>1.7339</td>
<td>1.6429</td>
<td>1.6480</td>
<td>1.6511</td>
</tr>
<tr>
<td>Plutonium Credit</td>
<td>2.5491</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td>0.4983</td>
<td>0.4917</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reprocessing</td>
<td>2.9900</td>
<td>2.9503</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Discounted Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(10^9 \text{ kwhe})$</td>
<td>2.3271</td>
<td>2.3351</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Discounted Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(10^7 \text{ $})$</td>
<td>1.2386</td>
<td>1.2456</td>
<td>1.2470</td>
<td>1.2483</td>
</tr>
</tbody>
</table>

*Reported in Reference [B-4].
TABLE 2.11
AEP'S COMPARISON OF NFCOST AND GACOST
FOR AN EXXON CONTRACT*
Yearly Levelized Annual Fuel Cycle Costs

<table>
<thead>
<tr>
<th>Time (yrs)</th>
<th>GACOST Total (mills/hwhr)</th>
<th>NFCOST Total (mills/hwhr)</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 1.0</td>
<td>4.310</td>
<td>4.431</td>
<td>2.8</td>
</tr>
<tr>
<td>0.0 - 2.0</td>
<td>4.711</td>
<td>4.811</td>
<td>2.1</td>
</tr>
<tr>
<td>0.0 - 3.0</td>
<td>5.056</td>
<td>5.144</td>
<td>1.7</td>
</tr>
<tr>
<td>0.0 - 4.0</td>
<td>5.270</td>
<td>5.346</td>
<td>1.4</td>
</tr>
<tr>
<td>0.0 - 5.0</td>
<td>5.308</td>
<td>5.376</td>
<td>1.3</td>
</tr>
<tr>
<td>0.0 - 6.0</td>
<td>5.338</td>
<td>5.403</td>
<td>1.2</td>
</tr>
<tr>
<td>0.0 - 7.0</td>
<td>5.441</td>
<td>5.505</td>
<td>1.2</td>
</tr>
<tr>
<td>0.0 - 8.0</td>
<td>5.601</td>
<td>5.671</td>
<td>1.2</td>
</tr>
<tr>
<td>0.0 - 9.0</td>
<td>5.779</td>
<td>5.848</td>
<td>1.2</td>
</tr>
<tr>
<td>0.0 - 10.0</td>
<td>5.967</td>
<td>6.034</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 11.0</td>
<td>6.155</td>
<td>6.227</td>
<td>1.2</td>
</tr>
<tr>
<td>0.0 - 12.0</td>
<td>6.340</td>
<td>6.412</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 13.0</td>
<td>6.530</td>
<td>6.600</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 14.0</td>
<td>6.722</td>
<td>6.797</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 15.0</td>
<td>6.924</td>
<td>6.972</td>
<td>0.7</td>
</tr>
<tr>
<td>0.0 - 16.0</td>
<td>7.147</td>
<td>7.124</td>
<td>0.3</td>
</tr>
<tr>
<td>0.0 - 17.0</td>
<td>7.380</td>
<td>7.347</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*Reported in Reference [G-3].
### TABLE 2.12

AEP'S COMPARISON OF NFCOST AND GACOST

FOR A WESTINGHOUSE CONTRACT*

Yearly Levelized Annual Fuel Cycle Costs

<table>
<thead>
<tr>
<th>Time (yrs)</th>
<th>GACOST Total (mills/hwhr)</th>
<th>NFCOST Total (mills/hwhr)</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 1.0</td>
<td>4.310</td>
<td>4.431</td>
<td>2.8</td>
</tr>
<tr>
<td>0.0 - 2.0</td>
<td>4.713</td>
<td>4.813</td>
<td>2.1</td>
</tr>
<tr>
<td>0.0 - 3.0</td>
<td>5.054</td>
<td>5.140</td>
<td>1.7</td>
</tr>
<tr>
<td>0.0 - 4.0</td>
<td>5.262</td>
<td>5.337</td>
<td>1.4</td>
</tr>
<tr>
<td>0.0 - 5.0</td>
<td>5.310</td>
<td>5.376</td>
<td>1.2</td>
</tr>
<tr>
<td>0.0 - 6.0</td>
<td>5.355</td>
<td>5.416</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 7.0</td>
<td>5.480</td>
<td>5.538</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 8.0</td>
<td>5.662</td>
<td>5.722</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0 - 9.0</td>
<td>5.355</td>
<td>5.912</td>
<td>0.9</td>
</tr>
<tr>
<td>0.0 - 10.0</td>
<td>6.060</td>
<td>6.107</td>
<td>0.8</td>
</tr>
<tr>
<td>0.0 - 11.0</td>
<td>6.258</td>
<td>6.304</td>
<td>0.7</td>
</tr>
<tr>
<td>0.0 - 12.0</td>
<td>6.497</td>
<td>6.491</td>
<td>0.1</td>
</tr>
<tr>
<td>0.0 - 13.0</td>
<td>6.816</td>
<td>6.830</td>
<td>2.0</td>
</tr>
<tr>
<td>0.0 - 14.0</td>
<td>7.185</td>
<td>6.878</td>
<td>4.3</td>
</tr>
<tr>
<td>0.0 - 15.0</td>
<td>-</td>
<td>7.015</td>
<td>-</td>
</tr>
<tr>
<td>0.0 - 16.0</td>
<td>-</td>
<td>7.034</td>
<td>-</td>
</tr>
<tr>
<td>0.0 - 17.0</td>
<td>-</td>
<td>7.102</td>
<td>-</td>
</tr>
<tr>
<td>0.0 - 18.0</td>
<td>-</td>
<td>7.106</td>
<td>-</td>
</tr>
</tbody>
</table>

*Reported in Reference [G-3].
that the above scheme is equivalent to payment of the full price three months before delivery, hence an EFVP of 3 months would be used. The impact of the EFVP approximation on the difference in working capital charges was checked by constructing a GACOST case using EFVP input instead of the actual progress payment input. Because of the reduction in the difference, it can be concluded that the NFCOST-EFVP method is quite adequate for fuel cycle cost calculations, and although NFCOST does not have progress payment capability, it is not a drawback to the use of the code.

2.5.3 ENUF/SIMMOD and MITCOST II

A comparison between ENUF/SIMMOD and MITCOST II has been done by Abbaspour and Driscoll [A-1] for a typical three batch PWR. The results of their study are shown in Tables 2.13 and 2.14, where base case values are assumed with the exception of the varied parameter specified in the table. It can be observed that the difference between ENUF/SIMMOD and MITCOST II is less than -3% (with the exception of $\tau = 0$, where it is slightly larger), averaging approximately -2%. The results are consistently biased negatively. The sources of the discrepancy are attributed to the following:

1. Only steady state batches are considered by ENUF/SIMMOD, inducing two-thirds of the error.

2. ENUF/SIMMOD compounds discretely, using a single midpoint cash flow, instead of compounding continuously using a continuous cash flow, inducing about one-fifth of the error.

3. ENUF/SIMMOD is a much less detailed code compared to MITCOST II, inducing the remaining two fifteenth
<table>
<thead>
<tr>
<th>Transaction</th>
<th>Lead or Lag Time(^{***}) (yr)</th>
<th>Unit Cost</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pay for U(_3)O(_8)</td>
<td>-1.0467</td>
<td>35 $/lb</td>
<td>5.005 x 10(^5) lb</td>
</tr>
<tr>
<td>Pay for conversion or for UF(_6)</td>
<td>-0.5417</td>
<td>4.0 $/kg</td>
<td>1.9155 x 10(^5) kg</td>
</tr>
<tr>
<td>Pay for separative** work</td>
<td>-0.5417</td>
<td>85 $/SWU</td>
<td>1.5211 x 10(^5) kg</td>
</tr>
<tr>
<td>Pay for fabrication</td>
<td>-0.2083</td>
<td>101.0 $/kg</td>
<td>3.3764 x 10(^4) kg</td>
</tr>
<tr>
<td>Pay for shipping fuel to reprocessing</td>
<td>0.5</td>
<td>15.0 $/kg</td>
<td>3.3764 x 10(^4) kg</td>
</tr>
<tr>
<td>Pay for reprocessing</td>
<td>0.75</td>
<td>150.0 $/kg</td>
<td>3.3764 x 10(^4) kg</td>
</tr>
<tr>
<td>Pay for waste disposal</td>
<td>0.75</td>
<td>100.0 $/kg</td>
<td>3.3764 x 10(^4) kg</td>
</tr>
<tr>
<td>Credit for U(_3)O(_8)</td>
<td>1</td>
<td>-35 $/lb</td>
<td>1.1246 x 10(^5) lb</td>
</tr>
<tr>
<td>Credit for conversion or for UF(_6)</td>
<td>1</td>
<td>-4.0 $/kg</td>
<td>3.3764 x 10(^4) kg</td>
</tr>
<tr>
<td>Credit for separative work</td>
<td>1</td>
<td>-85 $/kg</td>
<td>5.896 x 10(^3) kg</td>
</tr>
<tr>
<td>Credit for Pu</td>
<td>1</td>
<td>-27140 $/kg</td>
<td>230.0 kg</td>
</tr>
</tbody>
</table>

Note: Asterisks explained on next page.
TABLE 2.13 (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>$8.41462 \times 10^4$ kwhre</td>
</tr>
<tr>
<td>H</td>
<td>3800 MWth</td>
</tr>
<tr>
<td>N</td>
<td>30 batches</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.342, MWe/MWTH</td>
</tr>
<tr>
<td>$t_{R,D.}$</td>
<td>0.125 (yr), refueling downtime</td>
</tr>
<tr>
<td>$t_c$</td>
<td>0.9349 yrs.</td>
</tr>
<tr>
<td>$t_R$</td>
<td>2.8297 yrs.</td>
</tr>
<tr>
<td>L</td>
<td>0.75</td>
</tr>
<tr>
<td>L'</td>
<td>0.8599</td>
</tr>
</tbody>
</table>

Economic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>50%</td>
</tr>
<tr>
<td>$f_b$</td>
<td>0.5</td>
</tr>
<tr>
<td>$f_s$</td>
<td>0.5</td>
</tr>
<tr>
<td>$r_b$</td>
<td>8%/yr</td>
</tr>
<tr>
<td>$r_s$</td>
<td>14%/yr</td>
</tr>
<tr>
<td>$x^+$</td>
<td>9%/yr</td>
</tr>
<tr>
<td>$y_i$</td>
<td>$y_e$</td>
</tr>
</tbody>
</table>

Billing periods per year = 12††
Tax periods per year = 4††

* Reported in Ref. [A-1].

** Tails assay enrichment is assumed to be 0.2% (w/o).

*** Lag times are given with respect to the time at which the batch was discharged, i.e. they must be incremented by the irradiation interval ($t_R = 2.9547$ yrs.) in fuel cycle cost calculations.

† $x = (1 - \tau)f_b r_b + f_s r_s$.
†† Only for use in MITCOST II.
### TABLE 2.14

A COMPARISON OF MITCOST II AND ENUF/SIMMOD FOR

**SEVERAL PARAMETRIC VARIATIONS**

<table>
<thead>
<tr>
<th>Parameter Varied From the Case Base</th>
<th>Value Used</th>
<th>$e_f$ MITCOST II</th>
<th>$e_f$ Simple Model</th>
<th>% Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount Rate</td>
<td>0.05</td>
<td>5.002</td>
<td>4.888</td>
<td>-2.28%</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>6.992</td>
<td>6.794</td>
<td>-2.83%</td>
</tr>
<tr>
<td>Unit Price of $U_3O_8$</td>
<td>15 $/lb</td>
<td>4.256</td>
<td>4.132</td>
<td>-2.93%</td>
</tr>
<tr>
<td></td>
<td>55 $/lb</td>
<td>7.471</td>
<td>7.302</td>
<td>-2.29%</td>
</tr>
<tr>
<td></td>
<td>90 $/lb</td>
<td>10.288</td>
<td>10.076</td>
<td>-2.06%</td>
</tr>
<tr>
<td>Lead Time for Purchasing $U_3O_8$</td>
<td>-2 years</td>
<td>6.327</td>
<td>6.157</td>
<td>-2.68%</td>
</tr>
<tr>
<td>Lag Time for Reprocessing</td>
<td>4.0 years</td>
<td>5.921</td>
<td>5.802</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>8.0 years</td>
<td>5.967</td>
<td>5.873</td>
<td>-1.57%</td>
</tr>
<tr>
<td>Availability Based Capacity Factor</td>
<td>0.54</td>
<td>6.531</td>
<td>6.412</td>
<td>-1.83%</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>5.756</td>
<td>5.608</td>
<td>-2.57%</td>
</tr>
<tr>
<td>Tax Rate</td>
<td>0.0</td>
<td>5.186</td>
<td>5.015</td>
<td>-3.3%</td>
</tr>
</tbody>
</table>

*Diff = $[(e_{S.M.} - e_{MITCOST})/e_{MITCOST}]^{100}$

**Reported in Reference [A-1].**
Chapter Summary

In this chapter, a critique of six fuel cycle economic codes was presented. The aspects that were critiqued dealt with discounting theory, programming, simplifying assumptions and errors induced as a result of those assumptions. Comparisons of the codes GEM and MITCOST, NFCOST and GACOST, and ENUF/SIMMOD and MITCOST II were cited. MITCOST II was found to have the most complete treatment of taxes and depreciation. The codes GACOST and LNFCC were found to have several major deficiencies. The less advanced codes, NFCOST and ENUF/SIMMOD gave results which were in good agreement with the more advanced codes GACOST and MITCOST II, respectively.

The success of these simpler codes, and inherent errors and uncertainties in both the methodology and input data which make greater sophistication of questionable value, encourage further inquiry into such approaches. In particular, a methodology which deals in a straightforward manner with the separate categories of "direct" and "carrying" charges will be refined and incorporated into a computer program in the next chapter.
CHAPTER 3
THE DIRECT PLUS CARRYING CHARGE MODEL

3.1 Introduction

The Direct Plus Carrying Charge Model (DCC) will be derived and compared to ENUF/SIMMOD in this chapter. The derivation will consist of repeating Abbaspour's derivation of ENUF/SIMMOD, followed by a derivation of simplifications leading to the DCC model. In particular, the carrying charge and escalation factors will be examined in detail. The results of the DCC model will then be compared to the results of ENUF/SIMMOD. The section before the chapter summary will examine a constant dollar treatment.

3.2 Derivation of DCC

A review of the derivation of ENUF/SIMMOD by Abbaspour [A-1] follows. Abbaspour described the cash flow in ENUF/SIMMOD by use of a figure similar to Fig. 3.1. In this figure:

\[ C_i (i=1,m) = \text{Expenses or credits which occur for batch } n, \text{ such as purchase of } U_3O_8 \text{ and fabrication expenditures.} \]

\[ t_i (i=1,m) = \text{The time at which payment or credit for step } i \text{ will occur for batch } n, \text{ with respect to the start of irradiation of batch } n; \ t_i \text{ is negative if the cash flow is before the start of irradiation of batch } n, \text{ and it is positive if it occurs after this reference time.} \]

\[ t_c = \text{The intra-refueling interval (time between post-refueling startups).} \]
Start of irradiation of first batch

Fig. 3.1  Cash Flow Diagram Considered for Simple Method.
\[ (n-1)t_c = \text{Time elapsed before irradiation of batch n.} \]
\[ t_r = \text{Batch irradiation interval.} \]
\[ \frac{t_r}{2} = \text{Irradiation midpoint.} \]

Revenue and depreciation are assumed to occur at the midpoint of irradiation, as mentioned in Section 2.4. The other important assumption is that only steady state refueling batches are considered.

Starting with a modified cash flow formulation of a present worth balance (see the text by Smith [S-5] for an explanation) and substituting for depreciation, before-tax cash flow in year \( j \), and an end of life salvage value, one arrives at the following equation for \( N \) batches:

\[
\sum_{n=1}^{N} e_f E \left[ (F/P, y, (n-1)t_c + \frac{t_r}{2}) (P/F, x, (n-1)t_c + \frac{t_r}{2}) \right]
= \frac{1}{1-T} \sum_{n=1}^{N} \left[ \sum_{i} M_i C_i (F/P, y_i, (n-1)t_c + t_i) (P/F, x, (n-1)t_c + t_i) \right]
- \frac{T}{1-T} \sum_{n=1}^{N} \left[ \sum_{i} M_i C_i (F/P, y_i, (n-1)t_c + t_i) \right] (P/F, x, (n-1)t_c + \frac{t_r}{2})
\]

where

\[ x = \text{discount rate} = (1-T) f_b r_b + f_s r_s \]
\[ \tau = \text{tax fraction} \]
\[ f_b = \text{debt fraction} \]
\[ f_s = \text{equity fraction} = 1 - f_b \]
\[ r_b = \text{rate of return to bond holders} \]
\[ r_s = \text{rate of return to stock holders} \]
\[ y_i = \text{escalation rate for transaction } i \]
\[ e_f = \text{overall levelized fuel cycle cost} \]
E = the amount of electricity batch n produces during its total residence time in the core, kWhre.

\[ C_i = \text{the unit price of the } i\text{th transaction} \]

\[ M_i = \text{transaction quantity of the } i\text{th step} \]

\[ (P/F, x, t) = (1 + x)^{-t} = 1/(F/P, x, t), \text{ the present worth factor.} \]

The brackets on the left-hand-side of the equal sign contain the product of the escalation of the price charged and the present worth as of time zero. The brackets on the first term on the right-hand-side of the equal sign contain the escalated unit cost. The brackets on the second term contain the depreciable investment, and the terms in parentheses to the right of the brackets treat the depreciable investment as a lump sum at the midpoint of irradiation.

The present worth factor \((P/F, x, (n-1)t_c + t_r/2)\) can be decomposed as follows:

\[
(P/F, x, (n-1)t_c + t_r/2) = (1 + x)^{-((n-1)t_c + t_r/2)}
\]

\[
= (1 + x)^{-((n-1)t_c)} (1 + x)^{-t_r/2} = (P/F, x, (n-1)t_c)(P/F, x, t_r/2)
\]

(3.2)

and similarly

\[
(F/P, x, (n-1)t_c + t_r/2) = (P/F, x, (n-1)t_c + t_r/2)^{-1}
\]

\[
= (F/P, x, (n-1)t_c) (F/P, x, t_r/2)
\]

(3.3)

Terms not containing \(n\) can then be factored out of the sum over \(n\) as follows:
$e_f \left( \frac{F}{P}, y_e, t_{r/2} \right) \left( \frac{P}{F}, x, t_{r/2} \right) \sum_{n=1}^{n-1} \left( \frac{F}{P}, y_e, (n-1)t_c \right) \left( \frac{P}{F}, x, (n-1)t_c \right)

= \frac{1}{1-\tau} \left\{ \sum_{i=1}^{m_i c_i} (F/P, y_{i, t_i}) \left( P/F, x, t_i \right) \sum_{n=1}^{n-1} \left( F/P, y_{i, t_c}, (n-1)t_c \right) \left( P/F, x, (n-1)t_c \right) \right\}

= \frac{\tau}{1-\tau} \left[ \sum_{i=1}^{m_i c_i} (F/P, y_{i, t_i}) \sum_{n=1}^{n-1} \left( F/P, y_{i, t_c}, (n-1)t_c \right) \left( P/F, x, (n-1)t_c \right) \right].

(P/F, x, t_{r/2}) \quad (3.4)

Solving for $e_f$ and rearranging terms:

$$e_f = \frac{1}{\tau} \left\{ \sum_{i=1}^{m_i c_i} (F/P, y_{i, t_i}) \left[ \frac{1}{1-\tau} \right] \left( P/F, x, t_i \right) - \left[ \frac{\tau}{1-\tau} \right] \right\}.$$

Define as $F_i$, a "financial factor"

$$\left( \frac{F}{P}, y_{i, t_i} \right) \sum_{n=1}^{n-1} \left( F/P, y_e, (n-1)t_c \right) \left( P/F, x, (n-1)t_c \right)

\left( \frac{F}{P}, y_e, t_{r/2} \right) \sum_{n=1}^{n-1} \left( F/P, y_e, (n-1)t_c \right) \left( P/F, x, (n-1)t_c \right)

Define as $G_i$, an "escalation factor"

The $G_i$ factor can be simplified as follows. Note that Eq. (3.4) has

sums of the form:

$$\sum_{i=0}^{N-1} \left\{ \left( \frac{1 + y_{i, t_c}}{1 + x} \right)^n \right\}.$$

This summation is a geometric series with an initial value of 1, common

t ratio of $(1+y_{i, t_c})/1+x)^c$, and last term $(1+y_{i, t_c})^{(N-1)t_c}$, which has the
sum:
\[ 1 - \left[ \frac{1 + y}{1 + x} \right]^{tc N} \]
\[ 1 - \left[ \frac{1 + y}{1 + x} \right]^{tc c} \]

Also, note that:
\[ (P/F, x, t_c) = (F/P, x, t_c)^{-1} = \left[ \frac{1}{1 + x} \right]^{t_c c} \] (3.6)

so that:
\[
G_i = \left\{ \frac{(P/F, y_e, t_{r/2}) \left[ 1 - \frac{(P/F, x, Nt_c)}{(P/F, y_e, Nt_c)} \right] \left[ 1 - \frac{(P/F, x, t_c)}{(P/F, y_e, t_c)} \right]}{(P/F, y_i, t_1) \left[ 1 - \frac{(P/F, y_e, Nt_c)}{(P/F, x, Nt_c)} \right] \left[ 1 - \frac{(P/F, y_i, t_c)}{(P/F, x, t_c)} \right]} \right\} (3.7)

Using these definitions, the so-called "simple economics model" can be written in the form:
\[ e_f = \frac{1}{E} \sum_{i} M_i C_i F_i G_i \text{, mills/kWhr} \] (3.8)

This formulation shows quite clearly that \( e_f \) varies linearly with \( M_i \), \( C_i \), \( F_i \), and \( G_i \). It should be noted that on the once-through fuel cycle it may be current practice in some jurisdictions to capitalize and depreciate the front-end, and expense the back end transactions; for expensed transactions we take:
\[ F_i = \frac{(P/F, x, t_1)}{(P/F, x, t_{r/2})} \] (3.9)

If one assumes a continuous flow of revenue and depreciation over the irradiation interval \( t_r \) instead of a lump-sum transaction at \( t_{r/2} \), then the following transformations apply:
(P/F, x, t_r/2) → \frac{1}{t_r} (P/\bar{A}, x, t_r)

(P/F, y, t_r/2) → \frac{1}{t_r} (P/\bar{A}, x, t_r)

Simplifications leading to the Direct Plus Carrying Charge Model which divides costs into "direct costs" plus "carrying charges" follow.

3.2.1 Financial Factor Simplifications

The carrying charge was defined in Section 2.2.2 as the revenue increment needed to support an investment. It is the difference between the future worth of an investment at some time after its occurrence and the direct cost; the direct cost is the cash transaction cost at the time of payment. The Direct Plus Carrying Charge Model can be developed as follows [D-2]. Ignoring the escalation for now, and starting with Eq. (3.8), we have:

\[ e_i = \frac{1}{E} \sum M_i C_i F_i \]  \hspace{1cm} (3.10)

where, as derived previously,

\[ F_i = \left( \frac{1}{1-\tau} \right) \frac{(P/F, x, t_1)}{(P/F, x, t_r/2)} - \frac{\tau}{1-\tau} \]  \hspace{1cm} (3.11)

for capitalized and depreciated treatment. Let

\[ (P/F, x, t) = e^{-xt} \approx 1 - xt + \ldots \]  \hspace{1cm} (3.12)

for continuous compounding, expanded through terms of first order.

Therefore:

\[ F \approx \left( \frac{1}{1-\tau} \right) \left[ 1 + x (t_r/2 - t_1) \right] - \frac{\tau}{1-\tau} \]

\[ \approx \left( \frac{1}{1-\tau} - \frac{\tau}{1-\tau} \right) + \frac{x}{1-\tau} (t_r/2 - t_1) \]
Define a carrying charge rate, \( \phi \), as:

\[
\phi \approx \frac{x}{1-\tau} \quad (3.14)
\]

(As a point of interest it is pointed out that this definition of \( \phi \) is exact only for a very long-lived investment: not the case here, hence its use must be considered an empirical convenience in the present instance.)

With this definition Eq. (3.13) becomes:

\[
F_i \approx 1 + \phi(t_{r/2} - t_i) \quad (3.15)
\]

and Eq. (3.10) becomes:

\[
e_f = \frac{1}{E} \sum_i M_i C_i \left[ 1 + \phi(t_{r/2} - t_i) \right] \quad (3.16)
\]

or

\[
e_f = \frac{1}{E} \sum_i M_i C_i + \phi \sum_i \frac{M_i}{E} C_i (t_{r/2} - t_i) \quad (3.17)
\]

The first term in Eq. (3.17) is the direct cost and the second term is the carrying charges at annual rate \( \phi \) for the time interval from purchase to the midpoint of irradiation. All times are measured from the start of irradiation; and note that front-end \( t_i \) values are negative and back-end values are positive. While Eq. (3.17) is clearly approximate because of the neglect of higher order terms in Eq. (3.12), this discrepancy is easily remedied.

From Eq. (3.16), with \( \Delta T_i = t_{r/2} - t_i \), we have:
Let us define an adjusted $\Delta T^*_i$, and thus:

$$F_i = 1 + \phi \Delta T^*_i$$

(3.18)

With $\phi = x/(1-r)$, and some rearranging,

$$x \Delta T^*_i = \frac{(P/F, x, t)}{(P/F, x, t_{r/2})} - 1$$

(3.20)

Equation (3.20) serves to define the effective time span $\Delta T^*_i$. For continuous compounding $(P/F, x, t) = e^{-xt}$,

$$\Delta T^*_i = \left[ \frac{e^{\Delta T_i}}{x} - 1 \right]$$

(3.21)

For discrete compounding, Eq. (3.21) becomes:

$$\Delta T^*_i = \left[ \frac{(1+x)^{\Delta T_i}}{x} - 1 \right]$$

(3.22)

If Eq. (3.21) is expanded to first order, we find $\Delta T^*_i = \Delta T_i$, as expected. The minor calculation involved to find $\Delta T^*_i$ values is trivial, and it allows us to use the simple, and conceptually clear, direct plus carrying charge approach while retaining the accuracy of Abbaspour's model. The next step is to simplify the treatment of the escalation factor, $G_i$.

### 3.2.2 Escalation Factor Simplification

Assume for the moment that the effect of the discount rate $x$ cancels, or alternately that $x = 0$. Consider the following cash flow diagram, where $D_o$ is the direct cost of the investment at the beginning.
of radiation (MC).

\[
D_o \rightarrow D_o (1+y_1)^t_c \rightarrow D_o (1+y_1)^{2t_c} \rightarrow D_o (1+y_1)^{3t_c} \rightarrow D_o (1+y_1)^{(N-1)t_c}
\]

Then we have:

\[
D_\ell \cdot N = D_o \sum_{j=0}^{N-1} (1+y_1)^{jt_c} \\
= D_o \left\{1 + (1-y_1)^{t_c} + (1-y_1)^{2t_c} + \cdots + (1+y_1)^{(N-1)t_c}\right\}
\]

from which

\[
G_{io} = \left(\frac{D_\ell}{D_o}\right) = \frac{1}{N} \left\{\frac{(1+y_1)^{Nt_c} - 1}{(1+y_1)^{t_c} - 1}\right\}
\]

which can be approximated as:

\[
\approx \frac{(1+y_1)^{Nt_c} - 1}{Ny_1^{t_c}} \approx \frac{(1+y_1)^{Nt_c} - 1}{Ny_1^{t_c}}
\]

\[
\approx 1 + \left(\frac{N-1}{2}\right)y_1^{t_c} + \frac{(N-1)(N-2)}{6}(y_1^{t_c})^2 + \cdots (3.25)
\]

Now assume \(N \gg 2\); then \((N-2) \approx (N-1)\) and

\[
\left(\frac{D_\ell}{D_o}\right) \approx 1 + y_1^{(N-1)t_c} + \frac{[y_1(N-1)t_c]^2}{6} + \cdots (3.26)
\]
\[
\left(\frac{D_{t}}{D_{0}}\right) \approx \left[1 + \frac{(N-1)t_{c}}{1 + y_{1}}\right]^{2} \quad (3.27)
\]

Note that Eq. (3.27) suggests escalation over (roughly) half of the total time interval in question. Also, Eqs. (3.24) and (3.27) reduce to the correct limiting cases:

- only one cycle: \( N = 1 \) \( \frac{D_{t}}{D_{0}} \rightarrow 1 \)
- no escalation: \( y_{1} = 0 \) \( \frac{D_{t}}{D_{0}} \rightarrow 1 \)
- short time span: \( t_{1} = 0 \) \( \frac{D_{t}}{D_{0}} \rightarrow 1 \)

Equation (3.27) applies when there is no revenue escalation \( (y_{e} = 0) \) and no adjustment has been made for the time lag between \( t_{1} \) and time zero in the first cycle.

Now assume that the discount rate, \( x \), does not cancel and let revenue escalate as well:

\[
D_{t} \sum_{j=0}^{N-1} \left(\frac{1+y}{1+x}\right)^{j}t_{c} = D_{0} \sum_{j=0}^{N-1} \left(\frac{1+y_{1}}{1+x}\right)^{j}t_{c} \quad (3.28)
\]

so that

\[
\frac{D_{t}}{D_{0}} = \frac{1}{N} \frac{\left(\frac{1+y_{t}}{1+x}\right)^{Nt_{c}} - 1}{\left(\frac{1+y_{e}}{1+x}\right)^{t_{c}} - 1 - \frac{1}{N}} \quad (3.29)
\]

We can approximate:

\[
\left(\frac{1+y}{1+x}\right) \approx 1 + (y - x) \quad (3.30)
\]
and then both the numerator and denominator resemble the form which
we have previously approximated in going from Eq. (3.24) to (3.27);
hence we can write:

\[
\frac{D_i}{D_o} \approx \frac{[1+(y_i-x)]^{(N-1)t_c/2}}{[1+(y_e-x)]^{(N-1)t_c/2}} \approx \frac{[1+(y_i-y_e)]^{(N-1)t_c/2}}{[1+(y_e-x)]}
\]

(3.31)

Equation (3.31) reduces to Eq. (3.27) when \(y_e = x = 0\). This derivation
shows why \(x\) does cancel to first order. Equation (3.31) also suggests
that our approximation should become more accurate when \(y_i\) and \(x\), and
\(y_i\) and \(y_e\) are close in magnitude, since then the first order series
expansions become more accurate. Note also that Eq. (3.31) goes to
1.0 as \(x\) goes to infinity; i.e. when the discount rate is so high as to
close off any effect of future events.

The adjustment for the time lag between \(t_i\) and time zero in the
first cycle is accounted for by the same factor that Abbaspour derives in
ENUF/SIMMOD: one merely multiplies \(G_{10} = (D_i/D_o)\) by:

\[
\frac{(1 + y_e)^{-t/2}}{(1 + y_i)^{-t_i}}
\]

(3.32)

to obtain \(G_i\): thus, using Eq. (3.27),

\[
G_i = \left[ (1 + y_i)^{(N-1)t_c/2} \right] \frac{(1 + y_e)^{-t/2}}{(1 + y_i)^{-t_i}}
\]

(3.33)
3.3 Results - Comparison with ENUF/SIMMOD

Before proceeding with the comparison, a brief digression is in order to establish what constitutes acceptable agreement. Cavoulacos carried out an uncertainty analysis for the code ENUF/SIMMOD using both linear statistical uncertainty propagation and Monte Carlo simulation. The results of his work are reported in Table 3.1, where the mean and the 1σ (one standard deviation) interval are listed for \( (e_f)_{\text{OT}} \), \( (e_f)_{\text{recycle}} \), and \( e_f \Delta \), the nuclear fuel cycle cost for the once-through PWR, the recycle mode PWR and their difference, respectively. His results suggest that estimation of levelized lifetime fuel cycle costs within approximately ± 10% can be considered acceptable.

The escalation factor, \( G_1 \), used in DCC for the comparison was the first two terms of the expansion in Eq. (3.26); adding the third term significantly increased the overall difference between the levelized fuel cycle costs obtained from the two codes except for when escalation or \( (x-y) \) is negative, where it improved significantly. Similarly, inclusion of even more terms - culminating in Eq. (3.27) - also increased the difference, so that the linear expression was preferred over all others for positive escalation, namely:

\[
G_1 = \left[ 1 + y_i \frac{(N-1)t_c}{2} \right] \frac{(1 + y_e)^{-t_r/2}}{(1 + y_i)^{-t_i}} \quad (3.34)
\]

Use of Eq. (3.27) decreased the difference when escalation or \( (x-y) \) is negative, but not as much as the use of three terms in the expansion; thus it can be concluded that for negative \( y \) or \( (x-y) \), the following equation is preferred:
<table>
<thead>
<tr>
<th>Case</th>
<th>($e_f$) OT (T)</th>
<th>($e_f$) recycle (T)</th>
<th>$e_f\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>11.168 ± 1.2246</td>
<td>10.869 ± 1.1563</td>
<td>0.299 ± 1.6787</td>
</tr>
<tr>
<td>Case 2</td>
<td>11.279 ± 1.2809</td>
<td>11.109 ± 1.2017</td>
<td>0.170 ± 1.7119</td>
</tr>
<tr>
<td>Case 3</td>
<td>11.312 ± 1.0137</td>
<td>10.650 ± 0.9947</td>
<td>0.661 ± 1.4202</td>
</tr>
<tr>
<td>Case 4</td>
<td>10.022 ± 1.1416</td>
<td>9.900 ± 1.0933</td>
<td>0.122 ± 1.5479</td>
</tr>
<tr>
<td>Case 5</td>
<td>10.040 ± 1.1270</td>
<td>9.984 ± 1.0658</td>
<td>0.056 ± 1.5774</td>
</tr>
<tr>
<td>Case 6</td>
<td>10.176 ± 0.9092</td>
<td>9.514 ± 0.8915</td>
<td>0.661 ± 1.2733</td>
</tr>
</tbody>
</table>

Case 1: Then-current mills/kWhe, beta input pdfs.
Case 2: Then-current mills/kWhe, normal input pdfs.
Case 3: Then-current mills/kWhe, linear uncertainty propagation.
Case 4: Perpetual-constant mills/kWhe, beta input pdfs.
Case 5: Perpetual-constant mills/kWhe, normal input pdfs.
Case 6: Perpetual-constant mills/kWhe, linear uncertainty propagation.

*Reported in Reference [C-1].
Only seven transactions were used in the comparison. They are:

Representative Transactions for OT LWR Fuel Cycle

Front-End
- Purchase of $\text{U}_3\text{O}_8$
- Conversion to $\text{UF}_6$
- Enrichment
- Fabrication

Back-End
- Interim Storage
- Shipping of Fuel
- Disposal

The back-end activities are still open to much change and uncertainty. That is, much of what the back-end activities consist of is dependent upon whether or not a once-through or recycle refueling strategy is chosen. As yet, only the once-through mode is used. Even this is incomplete, in that spent fuel is being held in storage pools at reactor sites since no facilities exist for disposal of intact assemblies. The prolonged wait to ship fuel to reprocessing and storage sites is another indeterminable cost. In consideration of the above facts, the case used for the comparison must be considered as an idealized conceptualization of a hoped-for future reality. The quantities, unit costs, and lead or lag times are those used by Abbaspour, as listed in Table 2.13 of the preceding chapter.
The values used for interim storage are the values used by Abbaspour for reprocessing.

In both codes, either the burnup, enrichment, or intra-refueling interval can be input. Here, the intra-refueling interval was always input, and the program calculated the other two parameters from it. The intra-refueling interval was chosen over the other two since the effect of time on fuel costs was considered the most important aspect to be studied. ENUF/SIMMOD has three accounting options to choose from. They are nuclear fuel depreciated, nuclear fuel expensed, and front-end depreciated with back-end expensed. The third choice was always used since it currently appears to be the most appropriate accounting method for nuclear fuel.

In the comparisons which follow, cases are emphasized when escalation ($y_e$ or $y_i$) is present. If not ($y_e = y_i = 0$), the DCC and ENUF/SIMMOD models must be (and were confirmed to be) in exact agreement because we have used an effective time lag to force agreement.

Table 3.2 lists a comparison of the total levelized fuel cost obtained from the two models. See Appendix E for a listing of the DCC computer program used to generate these results. As can be observed, the DCC model generally produces results that are within the uncertainty band (i.e. $\pm 10\%$) estimated by Cavoulacos for ENUF/SIMMOD, except for TIME = 64 years. Table 3.3 lists the results for the same case as Table 3.2 except that the escalation rate of revenue is 6 percent instead of 0.0 percent. From this table we can see that the error decreases when $y_i = 4$ percent and increases when $y_i = 8$ percent. Again, the error

* In the final version of DCC the "exact" (i.e., Abbaspour's) prescription for $G_i$ is used; in the comparisons which follow, various approximations, as indicated, will be used.
### Table 3.2

**Comparison between DCC and ENUF/SIMMOD**

\( (y_e = 0.0 \text{ yr}^{-1}, x = 0.09 \text{ yr}^{-1}) \)

<table>
<thead>
<tr>
<th>Time Span (years)</th>
<th>% Diff* in ( e_f(y_i = 0.04 \text{ yr}^{-1}) )</th>
<th>% Diff* in ( e_f(y_i = 0.06 \text{ yr}^{-1}) )</th>
<th>% Diff* in ( e_f(y_i = 0.08 \text{ yr}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-0.214</td>
<td>-0.152</td>
<td>0.0094</td>
</tr>
<tr>
<td>8</td>
<td>-0.602</td>
<td>-0.096</td>
<td>0.855</td>
</tr>
<tr>
<td>16</td>
<td>-2.095</td>
<td>-0.019</td>
<td>3.589</td>
</tr>
<tr>
<td>32</td>
<td>-8.468</td>
<td>-2.106</td>
<td>8.617</td>
</tr>
<tr>
<td>64</td>
<td>-33.07</td>
<td>-17.616</td>
<td>9.958</td>
</tr>
</tbody>
</table>

\[ \% \text{ Diff} = \frac{e_f(ENUF) - e_f(DCC)}{e_f(ENUF)} \times 100 \]

**Note:** % Diff would be zero at all time spans if \( y_e = y_i = 0.0 \).
### TABLE 3.3

**COMPARISON BETWEEN DCC AND ENUF/SIMMOD**

\( (y_e = 0.06 \text{ yr}^{-1}, x = 0.09 \text{ yr}^{-1}) \)

<table>
<thead>
<tr>
<th>Time Span (years)</th>
<th>% Diff* in ( e_f(y_i = 0.04 \text{ yr}^{-1}) )</th>
<th>% Diff* in ( e_f(y_i = 0.06 \text{ yr}^{-1}) )</th>
<th>% Diff* in ( e_f(y_i = 0.08 \text{ yr}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-0.0615</td>
<td>0.00</td>
<td>0.161</td>
</tr>
<tr>
<td>8</td>
<td>-0.505</td>
<td>0.00</td>
<td>0.951</td>
</tr>
<tr>
<td>16</td>
<td>-2.076</td>
<td>0.00</td>
<td>3.607</td>
</tr>
<tr>
<td>32</td>
<td>-6.231</td>
<td>0.00</td>
<td>10.502</td>
</tr>
<tr>
<td>64</td>
<td>-13.14</td>
<td>0.00</td>
<td>23.444</td>
</tr>
</tbody>
</table>

\* \( \% \text{ Diff} = \frac{e_f(ENUF) - e_f(DCC)}{e_f(ENUF)} \times 100 \)
is unacceptable at \( \text{TIME} = 64 \) years. Note that agreement is exact when \( y_e = y_i = 6\%/\text{yr} \), as required, since the \( G_i \) equations for the two models are then identical.

Table 3.4(a) lists seven escalation rates corresponding to each of the seven transactions. These escalation rates were chosen to represent a situation where there is a wide variation of rates. Note that transaction five has a negative escalation. A more detailed study of negative escalation rates and the respective errors induced in \( e_i \) will be discussed in conjunction with Table 3.6, shortly. Part (b) of Table 3.4 lists the percent differences between the codes when these escalation rates are used. The error is allowable up to \( \text{TIME} = 16 \) years.

In actuality one is not free to vary the escalation and discount rates arbitrarily. Considering only monetary inflation one would have \( x \approx (y + 0.03) \text{yr}^{-1} \). From Table 3.5(a) we can see that as \( (x-y) \) deviates from \( (x-y) = 0.03 \) (roughly), the percent error between the escalation factor \( G_i \) for the two models generally increases. This can also be observed in Table 3.5(b) for a larger range of escalation rates.

Table 3.6 lists a range of negative escalation rates from \(-5\) percent to \(0\) percent per year. Column 4 lists the differences between the codes using Eq. (3.34) and column 7 lists the differences using Eq. (3.35). It can be concluded from the table that the error is unacceptable for escalation rates more negative than \(-1.5\) percent per year.

Figure 3.2 plots all the error data from the comparisons of the two codes, and generally shows that the error in our approximation to \( G_i \) is directly proportional to \((x-y)T\) to the first power. An investigation was made to see if the error for higher values of \((x-y)T\) could be reduced by the insertion of a constant \( \gamma \) in the equation such that
**TABLE 3.4**

**COMPARISON BETWEEN DCC AND ENUF/SIMMOD**

\( y_e = 0.0 \, \text{yr}^{-1}, \, x = 0.09 \, \text{yr}^{-1} \)

(a) Input Data

<table>
<thead>
<tr>
<th>Transaction Number</th>
<th>Rate of Escalation, ( y_i ) (yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>-0.010</td>
</tr>
<tr>
<td>6</td>
<td>0.125</td>
</tr>
<tr>
<td>7</td>
<td>0.200</td>
</tr>
</tbody>
</table>

(b) Results

<table>
<thead>
<tr>
<th>Time Span (years)</th>
<th>% Diff(^*) in ( e_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.264</td>
</tr>
<tr>
<td>8</td>
<td>1.634</td>
</tr>
<tr>
<td>16</td>
<td>5.508</td>
</tr>
<tr>
<td>32</td>
<td>15.158</td>
</tr>
<tr>
<td>64</td>
<td>58.13</td>
</tr>
</tbody>
</table>

\(^*\%\) Diff = \( \frac{e_f(ENUF) - e_f(DCC)}{e_f(ENUF)} \) x 100
TABLE 3.5
STUDY OF \((x-y)\) DEPENDENCE OF ERROR

(a)  
TIME = 15.9990 years  
DISCOUNT RATE = 0.0900 per year  
ESCALATION RATE OF REVENUE = 0.0000 per year  

<table>
<thead>
<tr>
<th>STEP</th>
<th>G(I)</th>
<th>DCC G(I)</th>
<th>% DIFF</th>
<th>Y</th>
<th>Y*T</th>
<th>X-Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2303</td>
<td>1.2567</td>
<td>-2.0952</td>
<td>0.040</td>
<td>0.640</td>
<td>0.050</td>
</tr>
<tr>
<td>2</td>
<td>1.3335</td>
<td>1.3505</td>
<td>-1.2732</td>
<td>0.050</td>
<td>0.800</td>
<td>0.040</td>
</tr>
<tr>
<td>3</td>
<td>1.3750</td>
<td>1.3843</td>
<td>-0.6967</td>
<td>0.055</td>
<td>0.880</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>1.4460</td>
<td>1.4463</td>
<td>-0.0185</td>
<td>0.060</td>
<td>0.960</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>1.7556</td>
<td>1.7423</td>
<td>0.7554</td>
<td>0.065</td>
<td>1.040</td>
<td>0.025</td>
</tr>
<tr>
<td>6</td>
<td>1.8366</td>
<td>1.8069</td>
<td>1.6186</td>
<td>0.070</td>
<td>1.120</td>
<td>0.020</td>
</tr>
<tr>
<td>7</td>
<td>1.9734</td>
<td>1.9025</td>
<td>3.5893</td>
<td>0.080</td>
<td>1.280</td>
<td>0.010</td>
</tr>
</tbody>
</table>

(b)  
TIME = 32.0010 years  
DISCOUNT RATE = 0.0900 per year  
ESCALATION RATE OF REVENUE = 0.0000 per year  

<table>
<thead>
<tr>
<th>STEP</th>
<th>G(I)</th>
<th>DCC G(I)</th>
<th>% DIFF</th>
<th>Y</th>
<th>Y*T</th>
<th>X-Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7165</td>
<td>0.2391</td>
<td>66.6250</td>
<td>-0.050</td>
<td>-1.600</td>
<td>0.140</td>
</tr>
<tr>
<td>2</td>
<td>1.0962</td>
<td>1.1485</td>
<td>-5.3459</td>
<td>0.010</td>
<td>0.320</td>
<td>0.080</td>
</tr>
<tr>
<td>3</td>
<td>1.4609</td>
<td>1.5847</td>
<td>-8.4684</td>
<td>0.040</td>
<td>1.280</td>
<td>0.050</td>
</tr>
<tr>
<td>4</td>
<td>1.8655</td>
<td>1.9048</td>
<td>-2.1060</td>
<td>0.060</td>
<td>1.920</td>
<td>0.030</td>
</tr>
<tr>
<td>5</td>
<td>3.3182</td>
<td>3.0323</td>
<td>8.6167</td>
<td>0.080</td>
<td>2.560</td>
<td>0.010</td>
</tr>
<tr>
<td>6</td>
<td>4.7381</td>
<td>3.7110</td>
<td>21.6785</td>
<td>0.100</td>
<td>3.200</td>
<td>-0.010</td>
</tr>
<tr>
<td>7</td>
<td>6.7184</td>
<td>4.3439</td>
<td>35.3432</td>
<td>0.120</td>
<td>3.840</td>
<td>-0.030</td>
</tr>
<tr>
<td>STEP</td>
<td>GI</td>
<td>DCC GI</td>
<td>% DIFF</td>
<td>Y</td>
<td>M10</td>
<td>%D</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>--------</td>
<td>--------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>0.7165</td>
<td>0.2391</td>
<td>66.6250</td>
<td>-0.050</td>
<td>0.6599</td>
<td>7.9101</td>
</tr>
<tr>
<td>2</td>
<td>0.7437</td>
<td>0.3898</td>
<td>47.5823</td>
<td>-0.040</td>
<td>0.6507</td>
<td>12.5035</td>
</tr>
<tr>
<td>3</td>
<td>0.7954</td>
<td>0.5449</td>
<td>31.4945</td>
<td>-0.030</td>
<td>0.6908</td>
<td>13.1484</td>
</tr>
<tr>
<td>4</td>
<td>0.8487</td>
<td>0.6936</td>
<td>18.2767</td>
<td>-0.020</td>
<td>0.7576</td>
<td>10.7280</td>
</tr>
<tr>
<td>5</td>
<td>0.8288</td>
<td>0.7235</td>
<td>12.7116</td>
<td>-0.015</td>
<td>0.7573</td>
<td>8.6330</td>
</tr>
<tr>
<td>6</td>
<td>0.8814</td>
<td>0.8124</td>
<td>7.8221</td>
<td>-0.010</td>
<td>0.8278</td>
<td>6.0830</td>
</tr>
<tr>
<td>7</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.000</td>
<td>1.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
Fig. 3.2 Percent Error in $G_i$ vs $(x-y)T$. 
\[ G_i = \left[ 1 + y \frac{(N-1)t_c}{2} \right] \frac{\left( \frac{(1 + y_i)^{-t/2}}{(1 + y_e)^{-t_1}} \right)} \]

(3.36)

It was found that for \( \gamma > 1 \), the difference increased (except for escalation rates > 12\%, and then the difference is very small). For \( \gamma < 1 \), the difference decreased, but \( \gamma \) is dependent on what escalation rate is chosen. In other words, no one \( \gamma \) factor can be applied to all escalation rates to obtain better results. Nevertheless there is some systematic behavior which merits future attention.

### 3.4 Constant Dollar Analysis

The preceding section compared the two codes ENUF/SIMMOD and DCC using then current dollars and the market discount rate. Another method is that of using "constant dollars" and a deflated discount rate, which provides results in dollars of known (today's) purchasing power. To change from a then-current cost to a constant dollar basis, one reduces all transaction escalation rates by \( y_i \) and defines a new discount rate \( x^* \) according to the relations in Appendix D.

A comparison between the two methods was made using values in Table 2.13 with \( \text{TIME} = 32 \) years, \( y_e = 0.06 \text{ yr}^{-1} \) and \( y_1 = 0.08 \text{ yr}^{-1} \).

The results of the comparison using both the ENUF/SIMMOD and DCC models and the percent difference between them are as follows:

<table>
<thead>
<tr>
<th>Case</th>
<th>( e_f^*(\text{ENUF/SIMMOD}) )</th>
<th>( e_f(\text{DCC}) )</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Then current.</td>
<td>8.229</td>
<td>7.365</td>
<td>10.501</td>
</tr>
<tr>
<td>Constant dollar:deflate ( r_b, r_s )</td>
<td>8.386</td>
<td>9.071</td>
<td>-8.17</td>
</tr>
<tr>
<td>Constant dollar:deflate ( x )</td>
<td>7.547</td>
<td>7.538</td>
<td>0.12</td>
</tr>
</tbody>
</table>

* \( e_f \) in (mills/kwhre). \( e_f(\text{DCC}) \) uses an approximate \( G_i \).
3.5 Chapter Summary

In this chapter, the Direct Plus Carrying Charge Model (DCC) was derived by first reviewing Abbaspour's Simple Model (ENUF/SIMMOD) and then simplifying the financial and escalation factors. The results of the DCC model for the overall levelized fuel cost were compared to that of ENUF/SIMMOD. The most important conclusion is that the DCC model is in acceptable agreement (i.e., ± 10 percent) with ENUF/SIMMOD for time spans ≤ 32 years, which is likely to include most cases of interest. It is in exact agreement when none of the transactions are escalated or when they escalate at the same rate as the revenue. Furthermore, when realistic values of escalation relative to the discount rate are used (since the latter must include an inflation allowance) the approximation to the escalation factor $G_i$ derived in this chapter is at its best. One must be careful, however, not to use the approximation to deal with negative escalation (i.e. a decreasing price in real terms due to innovation or learning).
CHAPTER 4
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Introduction

Accurate evaluation of the contribution of the nuclear fuel cycle to the cost of electricity has been of interest among the nuclear community for several decades. Various methods have been developed to do such computations but no one approach has gained general acceptance. Motivated by these circumstances, the present work reviews this prior work, compares and critiques some of the available computer programs, and extends some of the prior work done at MIT in a way which could make it more attractive as a generalized way to both teach and carry out engineering economic studies of the nuclear fuel cycle.

In this chapter, a summary of the thesis is provided, along with conclusions and recommendations for further work.

4.2 Summary

Seven computer codes were critiqued and compared in this thesis; they are shown in Table 4.1 together with some of their key features. The major theoretical aspects critiqued for each code were the explicit tax treatment, and the degree of detail with which cash flows are described within each code. Also examined were programming features of the codes, assumptions made, and the errors induced as a result. Four detailed code vs code comparisons were cited or carried out:

- GEM vs MITCOST
- NFCOST vs GACOST
- ENUF/SIMMOD vs MITCOST II
- ENUF/SIMMOD vs DCC
TABLE 4.1
SUMMARY OF KEY FEATURES OF EVALUATED PROGRAMS

<table>
<thead>
<tr>
<th>Code</th>
<th>Key Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>GACOST</td>
<td>There are four options available for calculating the fuel value at the beginning and end of each reload interval.</td>
</tr>
<tr>
<td>GEM</td>
<td>Provides for a combined federal and state tax. Code written in double precision. Three distinct types of economic analysis are used, each yielding identical results.</td>
</tr>
<tr>
<td>MITCOST II</td>
<td>Provides for four types of taxes and four types of depreciation. Payment schedule for taxes need not coincide with the expense or credit payments. The input data is clearly grouped.</td>
</tr>
<tr>
<td>NFCOST</td>
<td>Treats two types of depreciation. There are two different carrying charge rates: one for the period of irradiation, and a different one for non-irradiation periods.</td>
</tr>
<tr>
<td>LNFCC</td>
<td>Requires no input files - a default listing is provided.</td>
</tr>
<tr>
<td>ENUF/SIMMOD</td>
<td>Uses the tax fraction method and treats depreciation implicitly. Requires no input files - a default listing is provided.</td>
</tr>
<tr>
<td>DCC</td>
<td>Uses the tax fraction method and treats depreciation implicitly. Requires no input files - a default listing is provided.</td>
</tr>
</tbody>
</table>
MITCOST II was found to have the most complete treatment of taxes and depreciation. The codes GACOST and LNFCC were found to have several major deficiencies; in particular, the lack of treatment of taxes and depreciation. The less advanced codes, NFCOST and ENUF/SIMMOD gave results which were in good agreement with the more advanced codes GACOST and MITCOST II, respectively.

Finally, the Direct Plus Carrying Charge (DCC) economics model was derived from Abbaspour's ENUF/SIMMOD. Based on a simple transformation of the time span variable, it was shown to be an exact and simple alternative approach to the generation and presentation of nuclear fuel costs. Approximate prescriptions for levelizing over long time spans in the presence of price escalation were also derived and evaluated.

An interactive computer program, DCC, in the BASIC language for microcomputer use, was prepared to implement the model for convenient use in teaching and research applications. Table 4.2 summarizes the DCC algorithm.

The financial factors, $F_i$, ENUF/SIMMOD and DCC yield identical values. In the presence of escalation the two models are also in exact agreement if the same $G_i$ is used in both codes; however, a simpler, approximate prescription for $G_i$ was derived for use in the comparisons detailed in this work.

4.3 Conclusions

The following conclusions may be drawn from the results of this study. In general:

- The success of the simpler codes, and inherent errors and uncertainties in both the methodology and input data,
TABLE 4.2

THE DCC ALGORITHM

1. The financial factor, \( F_i \), is calculated using the formulation of a "direct cost" and a "carrying charge". The equation derived for \( F_i \) in this study is
\[
F_i = [1 + \sigma \Delta T_i^E],
\]
where
\[
\Delta T_i^E = \left[ \frac{(1 + x) \Delta T_i}{x} - 1 \right]
\]
and \( \Delta T_i = t_r/2 - t_i \)
for discrete compounding.

2. The escalation factor, \( G_i \) is determined:
\[
G_i = \left[ 1 + y_i \frac{(N-1)c}{2} \right] \frac{(1 + y_e)^{-t_r/2}}{(1 + y_i)^{-t_i}}
\]

3. The overall levelized fuel cost, \( e_f \), is then determined:
\[
e_f = \sum_{i=1}^{N} M_i C_i F_i G_i
\]

where
\[
M_i = \text{transaction quantity of the } i^{\text{th}} \text{ step.}
\]
\[
C_i = \text{the unit price of the } i^{\text{th}} \text{ step.}\]
encourage use of such approaches.

- MITCOST II is the most complete and easiest to use of three more elaborate codes - MITCOST II, GACOST, and GEM.

Based on the results from the comparison of ENUF/SIMMOD and DCC, and since ENUF/SIMMOD compared well with MITCOST II, the following conclusion may be drawn:

- The DCC model is a competitive alternative to the more advanced economics codes when accuracy on the order of $\pm 2\%$ is acceptable, and is pedagogically preferable because it treats the categories of "direct" and "carrying" charges in a straightforward manner.

4.4 Recommendations for Further Research

The recommendations for further research based on the analysis and results of the present study are the following:

- The code DCC should be run on more test cases, among which are recommended: current vs constant dollar approaches, recycle mode applications, cases constrained by the known correlation between discount rates and the rate of monetary inflation, etc.

- Better approximations to the escalation ($G_i$) factor should be developed, in particular for negative escalation and for time spans exceeding 32 years.

- In the area of theoretical studies, the contention by Correa (see Appendix B) that there are inherent flaws in the methodology used in all of the codes described in this work should be examined in a definitive manner.
REFERENCES


D-2 Driscoll, Michael J., "Class Notes for Course 22.34, Nuclear Power Economics", MIT, Fall 1982.


APPENDIX A
VONDY'S METHOD*

Suppose that in connection with a given power plant a company makes an initial capital investment of $I_i$ in each year $i$ of $n$ years of plant life. Suppose that current expenses in year $i$ are $C_i$ and that tax depreciation charges in year $i$ are $D_i$. Suppose further that all investments are to be fully depreciated for tax purposes at the end of $n$ years, so that

$$\sum_{i=0}^{n} I_i = \sum_{i=1}^{n} D_i$$  \hspace{1cm} (A.1)

and suppose that all money raised from investors is to be written off by the end of $n$ years. Suppose that the company is obligated to pay the bondholders a fixed fraction $b$ of the principal outstanding each year and wants to return to the stockholders $s$ fraction of the principal outstanding $b = f_b r_b$, and $s = f_s r_s$. $f_b$ is the fraction of the investment raised by sale of bonds, and $f_s$ is the fraction raised from sale of stocks. $f_b$ and $f_s$ are assumed kept constant as the investment is written off. Finally, we suppose that the company sells $E_i$ kwhr of electricity in year $i$.

We wish to find the unit price of electricity $\bar{e}$ in mills per kwhr, which, if charged uniformly during the life of the plant, will just pay for all current expenses and income taxes, will give bondholders and stockholders their required return, and will just write off the principal outstanding to zero by the end of $n$ years.

During the first year, revenue is $0.001 \bar{e} E_1$, current expenses are $C_1$, bondholders' return is $I_0 b$, stockholders' return is $I_0 s$, and

*Reported in Reference [D-2].
income taxes paid are \( \tau(0.001 \tilde{e} E_1 - C_1 - I_0 b - D'_1) \). Funds available to write off principal then are:

\[
0.001 \tilde{e} E_1 - C_1 - I_0 (s+b) - \tau(0.001 \tilde{e} E_1 - C_1 - I_0 b - D'_1)
\]

As investment in amount \( I_1 \) is made in year 1, the principal on which return must be paid during year 2 is:

\[
V_2 = I_0 + I_1 - [0.001 \tilde{e} E_1 - C_1 - I_0 (s+b) - \tau(0.001 \tilde{e} E_1 - C_1 - I_0 b - D'_1)]
\]

This expression is valid whether or not deferred income taxes are charged as a current expense and then used to write off the principal. Grouping terms in (A.2) results in:

\[
V_2 = I_0 [1 + b(1-\tau) + s] + I_1 + C_1 (1-\tau) - D'_1 \tau - 0.001 \tilde{e} E_1 (1-\tau)
\]

(A.3)

During the second year, revenue is \( 0.001 \tilde{e} E_2 \), current expenses are \( C_2 \), bondholders' return is \( V_2 b \), stockholders' return is \( V_2 s \), and income taxes paid are \( \tau(0.001 \tilde{e} E_2 - C_2 - V_2 b - D'_2) \). Funds available to write off principal then are:

\[
0.001 \tilde{e} E_2 - C_2 - V_2 (s+b) - \tau(0.001 \tilde{e} E_2 - C_2 - V_2 b - D'_2)
\]

As investment in amount \( I_2 \) is made in year 2, the principal on which return must be paid in year 3 is:

\[
V_3 = V_2 + I_2 - [0.001 \tilde{e} E_1 - C_2 - V_2 (s+b) - \tau(0.001 \tilde{e} E_2 - C_2 - V_2 b - D'_2)]
\]

(A.4)
Grouping terms in (A.4) yields:

\[ V_3 = V_2[1 + b(1-\tau) + s] + I_2 + C_2(1-\tau) - D_2' - 0.001 \bar{e} E_1(1-\tau) \tag{A.5} \]

Substitution for \( V_2 \) from (A.3) yields:

\[ V_3 = I_0(1+x)^2 + I_1(1+x) + I_2 + C_1(1-\tau)(1+x) \]
\[ + C_2(1-\tau) - D_1' - D_2' \]
\[ - 0.001 \bar{e} E_1(1-\tau)(1+x) - 0.001 \bar{e} E_2(1-\tau) \tag{A.6} \]

where

\[ x = b(1-\tau) + s \tag{A.7} \]

the effective cost of money.

By continuing in this way, the principal outstanding at the end of the \( n \)th year is:

\[ V_{n+1} = \sum_{i=0}^{n} I_i(1+x)^{n-i} + \sum_{i=1}^{n} C_i(1+x)^{n-i}(1-\tau) \]
\[ - \sum_{i=1}^{n} \tau D_i'(1+x)^{n-i} - 0.001 \bar{e} \sum_{i=1}^{n} E_i(1+x)^{n-i}(1-\tau) \tag{A.8} \]

\( I_n = 0 \), as no investment is made at the end of the \( n \)th year. \( \bar{e} \) is to be such that all principal is to be written off at the end of the \( n \)th year, so that

\[ V_{n+1} = 0 \tag{A.9} \]

The result of dividing Eq. (A.8) by \((1+x)^n\), using (A.9) and solving for \( \bar{e} \) is:
\[
\hat{e} = \frac{I_0}{1-\tau} + \sum_{i=1}^{n} \frac{I_i}{1-\tau} + \frac{C_i - \frac{\tau D_i}{1-\tau}}{(1+x)^i} \sum_{i=1}^{n} \frac{E_i}{1000 (1+x)^i}
\]

This corresponds to Abbaspour's Eq. (2.13), Smith's Eq. (10.3), Vondy's Eq. (F.9), and Correa's Eq. (9).
APPENDIX B

NON-EQUIVALENCE OF LEVELIZED COSTS

Correa [C-5] makes some interesting points regarding Vondy's method. He shows that while discounting the modified cash flow pattern at the rate $x$ correctly balances the present worth, the levelized revenue is not identically the same as the revenue levelized using the actual cash flow pattern and the discount rate, $r$, where, as will be recalled,

$$r = f_b r_b + (1-f_b)r_s$$  \hspace{1cm} (B.1)

$$x = r - \tau_f r_b$$  \hspace{1cm} (B.2)

Even more interesting, he derives an even simpler modified cash flow pattern which correctly balances when discounted at a rate $w$, where:

$$w = x/(1-\tau);$$  \hspace{1cm} (B.3)

note that we have called this same parameter $\sigma$ in the DCC method.

The true and $x$-modified cash flow patterns have already been discussed in considerable detail in Appendix A, Abbaspour's report, Smith's textbook, etc. Hence we need discuss only Correa's new transformation here. He shows that (in our nomenclature):

$$\sum_{i=1}^{n} R_i(P/F, w, i) = \sum_{i=0}^{n} L_i(P/F, w, i) + \sum_{i=1}^{n} M_i(P/F, w, i)$$

$$- \left( \frac{\tau}{1-\tau} \right) \sum_{i=1}^{n} \delta D_i(P/F, w, i)$$  \hspace{1cm} (B.4)

where:
\[ R_i = \text{annual revenue requirement}; \]
\[ M_i = \text{annual O & M costs}; \]
\[ I_i = \text{capital costs: initial and salvage}; \]
\[ \delta D_i = DT_i - DB_i, \text{annual difference between tax and book depreciation} \]
\[ \text{very often zero.} \]

Hence Eq. (B.4) corresponds to a remarkably simple cash flow diagram. For nuclear fuel, where \( M_i \) and \( \delta D_i \) will generally be zero, only capital cash flow vectors, \( I_i \), will be present.

Table B.1 is a simple numerical example constructed to illustrate Correa's observations. As shown at the bottom of the table, the present worth of the revenue requirement (LHS) balances the present worth of the appropriate cash flows (RHS) in each case, whether discounted at \( r, x \) or \( w \).

The final entries at the bottom of the page are the levelized revenue requirements, i.e.,

\[ R_{LZ} = \left\{ \sum_{i=1}^{R} R_i (P/F, z, i) \right\} (A/P, z, n) \]  \hspace{1cm} (B.5)

Note that the three entries \( R_{Lr}, R_{Lx} \) and \( R_{Lw} \), while close in value, are not identical. For present purposes the differences are so small as to be negligible: \( R_{Lx} \) is 0.3% smaller than the correct \( R_{Lr} \) and \( R_{Lw} \) is 1.1% larger. Hence Correa's new method, which eliminates both tax and depreciation cash flow vectors, is recommended for future use in place of Vondy's method. Since his discount rate \( w \), and our carrying charge rate, \( \omega \), are the same, use of his approach to derive the DCC model should also be more straightforward (after the arduous derivation of the \( w \) model itself).

Although the differences among the three approaches just outlined
**TABLE B.1**

**NUMERICAL EXAMPLE**

Example: Unit of fuel costing $100,000, having zero salvage value and a 4-year lifetime.

<table>
<thead>
<tr>
<th>1. Cash Flow Table</th>
<th>End of Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1. Investment remaining (rate base)</td>
<td>100,000</td>
</tr>
<tr>
<td>( V_{i-1} ) less depreciation ( D_{i-1} )</td>
<td></td>
</tr>
<tr>
<td>2. Interest on debt ( f_b r_b V_{i-1} ) with ( f_b r_b = 0.04 )</td>
<td>4,000</td>
</tr>
<tr>
<td>3. Return on equity ( f_s r_s V_{i-1} ) with ( f_s r_s = 0.08 )</td>
<td>8,000</td>
</tr>
<tr>
<td>4. Income tax, ( T_i ) ( \tau/(1-\tau) \cdot ) equity return; ( \tau = 1/2 )</td>
<td>8,000</td>
</tr>
<tr>
<td>5. Depreciation, ( D_i ); ( \frac{100,000-0}{4} = 25,000 )</td>
<td>25,000</td>
</tr>
<tr>
<td>6. Required revenue, ( R_i ); Sum of items 2 through 6.</td>
<td>45,000</td>
</tr>
</tbody>
</table>

Continued on next page.
TABLE B. 1 (continued)
NUMERICAL EXAMPLE

II. Present Worth Balances
\( r = 0.12 \text{ yr}^{-1}; \ x = 0.10 \text{ yr}^{-1}; \ w = \frac{x}{1 - r} = 0.20 \text{ yr}^{-1}. \)

|   | \( P_W \) | LHS \( \frac{45,000}{1.12} + \frac{40,000}{(1.12)^2} + \frac{35,000}{(1.12)^3} + \frac{30,000}{(1.12)^4} = 116,044. \) | RHS \( \frac{100,000}{1} + \frac{8,000}{(1.12)} + \frac{6,000}{(1.12)^2} + \frac{4,000}{(1.12)^3} + \frac{2,000}{(1.12)^4} = 116,044. \) |
|---|---|---|
| 1. | \( P_W \) | LHS \( \frac{45,000}{1.10} + \frac{40,000}{(1.10)^2} + \frac{35,000}{(1.10)^3} + \frac{30,000}{(1.10)^4} = 120,753. \) | RHS \( \frac{200,000}{1} + \frac{25,000}{(1.10)} + \frac{25,000}{(1.10)^2} + \frac{25,000}{(1.10)^3} + \frac{25,000}{(1.10)^4} = 120,753. \) |
| 2. | \( P_W \) | LHS \( \frac{45,000}{1.20} + \frac{40,000}{(1.20)^2} + \frac{35,000}{(1.20)^3} + \frac{30,000}{(1.20)^4} = 100,000 \) | RHS \( \frac{100,000}{1} = 100,000 \) |

III. Levelized Revenues
\( R_{Lr} = 38,206; \ R_{Lx} = 38,094; \ R_{Lw} = 38,629. \)
are trivial over the life of a single batch, they can be appreciable if we levelize over the life of a reactor.

Let \( PW_z \) be the present worth of revenue requirements as of the start of irradiation using \( z \) as the discount rate.

Now consider escalation at rate \( y \) and compute the lifetime levelized revenue over \( N \) identical annual reload batches,

\[
R_{LLz} = \left\{ \sum_{i=0}^{N-1} PW_z \cdot \frac{F}{P, y, i} \frac{P}{F, z, i} \right\} \frac{(A/P, z, N)}{(A/P, z, N)}
\]

\[
= PW_z \left\{ 1 + \sum_{i=1}^{N-1} \frac{1}{(1+y)^i} \right\} \frac{(A/P, z, N)}{(A/P, z, N)}
\]

where \( \mu = \frac{(1+z)}{(1+y)} - 1 \)

\[
\Rightarrow R_{LLz} = PW_z \left\{ 1 + \frac{1}{\mu} \right\} z
\]  

(B.6)

For large \( N \), \((A/P, z, N) \rightarrow z\). Thus,

\[
\approx R_{LLz} = PW_z \left\{ 1 + \frac{1}{\mu} \right\} z
\]  

(B.7)

and, finally,

\[
\approx R_{LLz} = PW_z \left( \frac{z(1+z)}{z-y} \right).
\]  

(B.8)

For our three examples, with \( y = 0.06 \) yr\(^{-1}\):

\[
r = 0.12 \text{ yr}^{-1} \quad \approx R_{LLr} = 38,206 \left[ \frac{(0.12)(1.12)}{0.06} \right] = 85,581
\]

\[
x = 0.10 \text{ yr}^{-1} \quad \approx R_{LLx} = 38,094 \left[ \frac{(0.10)(1.10)}{0.04} \right] = 104,759
\]

\[
w = 0.20 \text{ yr}^{-1} \quad \approx R_{LLw} = 38,629 \left[ \frac{(0.20)(1.20)}{0.14} \right] = 66,221
\]
And the differences are quite substantial! Hence one should use the rate \( r \) to levelize over long periods even if the \( w \) or \( x \) approximations were used to levelize over a batch.
APPENDIX C

AN IMPORTANT QUALIFICATION REGARDING INFLATION/DEFLATION*

While it is fairly common practice to use constant dollar transactions and a deflated discount rate in lieu of then-current dollars and the actual market discount rate (alternative procedures which are mathematically equivalent under certain circumstances), there is one important exception. When tax deductions related to depreciation are involved, this transformation breaks down and is no longer exact.

For ordinary transactions the same present worth is obtained by either convention. Starting with the inflated versions:

\[ PW = I(t) e^{-xt} \]  
(C. 1)

and writing the transaction in time zero dollars times an inflator, and breaking the discount rate into components

\[ PW = [I(o) e^{yt}] e^{-(x_d+y)t} \]  
(C. 2)

we arrive at

\[ PW = I(o) e^{-x_d t} \]  
(C. 3)

which is the deflated version.

However, yearly depreciation cash flow is, in general, some fraction of initial value less salvage:

\[ D(t) = f(t) \frac{I(o)}{n} [I(o) - I(n)] \]  
(C. 4)

which has a present worth:

*Reported in Ref. [D-2]. See also Ref. [C-7] and Ref. [S-8].
PW = \int [I_o(t) - I(n)] e^{-xt} \\
= \int [I_o(t) - I(n)] e^{yn} e^{-(x_d + y)t} \\
PW = \left[ \int I(o) e^{-x_d t} e^{-yt} \right] - \left[ \int I(n) e^{-x_d t} e^{y(n-t)} \right] \tag{C.5}

Thus the front-end transaction is left with an uncompensated deflator and the back-end transaction with an uncompensated inflator if we try our usual transformation. Neglect of these factors would overestimate the depreciation deduction using deflated cash flows and discount rates, and hence underestimate the unit cost of product (a discrepancy noted in passing by Abbaspour [A-1]).

Thus, while the difference is not large, it is best to retain the use of then-current dollars and market discount rates whenever taxes and depreciation are involved; as in the usual case in engineering economic analyses associated with projects undertaken by investor-owned utilities in particular, and private enterprise in general. When taxes are not assumed (as for government-owned facilities) or excluded from consideration (as transfer payments in cost-benefit studies), the above reservations are not applicable.
APPENDIX D

DEFLATING RATES OF RETURN*

Note that one does not obtain equivalent results by deflating the bond and stock rates of return to find a deflated discount rate (the preferred procedure) as opposed to deflating the discount rate itself.

For example, we have:

\[ x = (1 - \tau) f_b r_b + f_s r_s \]  \hspace{1cm} (D.1)

in which

\[ f_b + f_s = 1.0 \]  \hspace{1cm} (D.2)

Deflating \( r_b \) and \( r_s \):

\[ (1 + r_{bo})(1 + y) = (1 + r_b) \]  \hspace{1cm} (D.3)

\[ (1 + r_{so})(1 + y) = (1 + r_s) \]  \hspace{1cm} (D.4)

If we define:

\[ x_0 = (1 - \tau) f_b r_{bo} + f_s r_{so} \]  \hspace{1cm} (D.5)

then algebraic manipulation of the above relations gives:

\[ x = y - \tau f_b y + (1 + y) x_0 \]  \hspace{1cm} (D.6)

If, on the other hand, we write directly:

\[ (1 + x_0^*) (1 + y) = (1 + x) \]  \hspace{1cm} (D.7)

then we find, by combining the last two equations:

*Reported in Reference [D-2].
and hence $x_0^* = x_0$ only if $\tau$ or $f_b$ are zero.

Thus, if $x_0 = 0.09$ yr$^{-1}$, $\tau = f_b = 1/2$, and $y = 0.06$ yr$^{-1}$, we find that $x_0^* = 0.075$, a quite significant discrepancy. Substitution of $x_0^* = 0.075$ yr$^{-1}$ into Eq. (D.7), or $x_0 = 0.09$ yr$^{-1}$ into Eq. (D.6), yields $x = 0.14$ yr$^{-1}$, the market discount rate.
APPENDIX E

THE DIRECT PLUS CARRYING CHARGE MODEL (DCC)

CODE LISTING AND USER'S MANUAL

This appendix documents the DCC program. It is written in the
BASIC language for the TEKTRONIX Model 4051, 32 K RAM mini-
computer. Conversion to one of the other variations of BASIC is a
relatively simple matter. The code is rather short, just over 400
statements; together with storage reserved for various arrays it can be
accommodated in any computer having on the order of 32 K RAM.
Hence it can be used with most of the popular microcomputer brands now
on the market.

The program is interactive in nature and hence very simple to
use. It has default values built in for all parameters, and prompts the
user for revisions prior to executing a run. All parameters used in a
computation are recorded as input in the printout following each calcula-
tion. Once a parameter has been changed it remains in its altered state
for subsequent computations; the program is restored to its original
state by typing "N" at the end of the program when the user is asked if
he or she wants to run DCC again.

If the program is run using default values, the sample problem
shown in Appendix F is obtained. First time users should execute this
problem to verify the program tape and their mastery of computer
control features.

The program listing contains interspersed REMARK statements
which should facilitate the insertion of modifications by the user. Table
E.1 is an algorithm for the program, which indicates the section of the
TABLE E.1
THE DCC CODE ALGORITHM

1. The number of transaction is inputted (up to 15) and the user specifies one of the following parameters: burnup, enrichment, or intra-refueling interval; the program will then calculate the other two from the user's specification. (Line No. 410)

2. According to user instructions default values of the input parameters are modified. (Line No. 630)

3. Two of the following are calculated based on user input: burnup, enrichment and intra-refueling interval. Transaction quantities are then calculated based on this information. (Line No. 1730)

4. The financial factor, $F_i$, is calculated using the formulation of a "direct cost" and a "carrying charge". The escalation factor, $G_i$, is then determined. The overall levelized fuel cost is determined: $e_f = \sum_{i=1}^{N} M_i C_i F_i G_i$, where $M_i$ = transaction quantity of the ith step and $C_i$ = the unit price of the ith step. (Line No. 2020)

5. The output is printed. (Line No. 2700)
listing corresponding to each block.

Table E.2 lists the program's capabilities in terms of the number and nature of transactions, etc., and Table E.3 lists each input parameter in the order requested by the code, together with the units expected.

Table E.4 summarizes the equations used in DCC to compute the primary quantities of interest.
### TABLE E. 2

**DCC PROGRAM CAPABILITIES**

<table>
<thead>
<tr>
<th>Number of Transaction</th>
<th>Type of Transaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Purchase of U$_3$O$_8$.</td>
</tr>
<tr>
<td>2</td>
<td>Conversion to UF$_6$.</td>
</tr>
<tr>
<td>3</td>
<td>Enrichment.</td>
</tr>
<tr>
<td>4</td>
<td>Fabrication.</td>
</tr>
<tr>
<td>5</td>
<td>Waste Disposal.</td>
</tr>
<tr>
<td>6</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>7</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>8</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>9</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>10</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>11</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>12</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>13</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>14</td>
<td>User Specifies.</td>
</tr>
<tr>
<td>15</td>
<td>User Specifies.</td>
</tr>
</tbody>
</table>
### TABLE E.3
THE ORDER IN WHICH INPUT PARAMETERS ARE REQUESTED 
AND THE UNITS EXPECTED IN DCC

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Parameter Requested</th>
<th>Units Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fuel enrichment</td>
<td>Weight %</td>
</tr>
<tr>
<td>2</td>
<td>Tails composition of U-235</td>
<td>Weight %</td>
</tr>
<tr>
<td>3</td>
<td>Fabrication yield</td>
<td>Wt. fraction</td>
</tr>
<tr>
<td>4</td>
<td>Enrichment yield</td>
<td>Wt. fraction</td>
</tr>
<tr>
<td>5</td>
<td>Conversion yield</td>
<td>Wt. fraction</td>
</tr>
<tr>
<td>6</td>
<td>Rated thermal power</td>
<td>MWT</td>
</tr>
<tr>
<td>7</td>
<td>(Avail. based) capacity factor</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Thermal efficiency</td>
<td>MWe/MWT</td>
</tr>
<tr>
<td>9</td>
<td>Fuel burnup, total cycle</td>
<td>MWD/MTHM</td>
</tr>
<tr>
<td>10</td>
<td>Intra-refueling interval</td>
<td>Years</td>
</tr>
<tr>
<td>11</td>
<td>Refueling downtime</td>
<td>Years</td>
</tr>
<tr>
<td>12</td>
<td>Number of core batches</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Number of S.S. batches</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>Core fuel loading</td>
<td>MTHM</td>
</tr>
<tr>
<td>15</td>
<td>Equity (stock) fraction</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>Debt (bond) fraction</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>Rate of equity return</td>
<td>Per Year</td>
</tr>
<tr>
<td>18</td>
<td>Rate of debt return</td>
<td>Per Year</td>
</tr>
<tr>
<td>19</td>
<td>Tax fraction</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>Escalation rate of revenue</td>
<td>Per Year</td>
</tr>
<tr>
<td>21</td>
<td>Transaction costs</td>
<td>$/kg or $/lb</td>
</tr>
<tr>
<td>22</td>
<td>Transaction delay times</td>
<td>Years</td>
</tr>
<tr>
<td>23</td>
<td>Transaction escalation rates</td>
<td>Per Year</td>
</tr>
</tbody>
</table>
TABLE E.4
SUMMARY OF EQUATIONS USED IN DCC

The equations used in DCC to compute the primary quantities of interest are as follows:

1. The financial factor, $F_i$:

   \[ F_i = 1 + \delta \Delta T_i^* \]

   where, for discrete compounding,

   \[ \Delta T_i^* = \left[ \frac{\Delta T_i}{x} - 1 \right] \]

   \[ \Delta T = \frac{t_r}{2} - t_i \]

   \[ \delta = \frac{x}{1 - r} \]

2. The escalation factor, $G_i$:

   \[ G_i = \left[ \frac{1 + y_e}{1 + y_1} \right]^{t_r/2 - t_i} \left[ \frac{1 - (1 + x)}{(1 + y_1)} \right] \left[ 1 - \left( \frac{1 - \text{total irr. time of all batches}}{(1 + x)} \right) \right] \]

   \[ \left[ 1 - \left( \frac{1 - \text{intra-refueling interval}}{(1 + y_e)} \right) \right] \left[ 1 - \left( \frac{1 - \text{total irr. time of all batches}}{(1 + y_1)} \right) \right] \]

   \[ \left[ 1 - \left( \frac{1 - \text{intra-refueling interval}}{(1 + y_e)} \right) \right] \]
G_i is calculated using reduced forms of the equation whenever 
\((y_e - x) < 0.0001\) or \((y_i - x) < 0.0001\), or both.

3. The overall levelized fuel cost, \(e_f\):

\[
e_f = \sum_{i=1}^{N} M_i C_i F_i G_i
\]

where

- \(M_i\) = transaction quantity of the \(i^{th}\) step.
- \(C_i\) = the unit price of the \(i^{th}\) step.
80 REMARK THE DIRECT PLUS CARRYING CHARGE MODEL (DCC) FOR NUCLEAR FUEL
90 REMARK CYCLE ECONOMICS CALCULATIONS
95 REMARK DEPT OF NUCLEAR ENGINEERING, MIT
98 REMARK AUGUST 1983
100 INIT
110 29=0
120 DIM A(15), C(15), M(15), P(15), T(15), Y(15), A$(240)
130 DIM B$(30), C$(10), J$(10), Q$(240), R$(240), Z(15)
140 DIM U(15), G(15), H(15)
150 DIM P1(15)
160 DIM T8(15), T6(15)
170 C=0
180 T=0
190 Y=0
200 M=0
210 REMARK PROGRAM OPTION SUBROUTINE
220 GOSUB 410
230 REMARK FIRST INPUT BLOCK SUBROUTINE
240 GOSUB 630
250 REMARK BURNUP MODULE
260 GOSUB 1730
270 REMARK SECOND INPUT BLOCK SUBROUTINE
280 GOSUB 1030
290 REMARK DIRECT PLUS CARRYING CHARGE MODEL (DCC)
300 GOSUB 2020
310 REMARK OUTPUT BLOCK SUBRoutines
320 GOSUB 2700
330 PAGE
340 PRINT "DO YOU WANT TO RUN DCC AGAIN (Y OR N)? : ";
350 INPUT J$
360 IF J$="N" THEN 390
370 Z9=1
380 GO TO 220
390 END
400 REMARK PROGRAM OPTION INPUT SUBROUTINE
410 PAGE
420 PRINT "PROGRAM OPTIONS"
430 PRINT
440 PRINT "Enter the number of cycle transactions: (1-15): ";
450 INPUT T0
460 PRINT
470 A$="Either burnup, enrichment, or refueling interval can be input."
480 PRINT A$
490 PRINT "Enter 1 = burnup, 2 = enrichment, or 3 = interval. "
500 PRINT
510 PRINT "You will set one of these parameters. The program will then"
520 PRINT " calculate the other two from your input."
530 PRINT
540 PRINT "Input the fixed parameter (1, 2 or 3): ";
550 INPUT 01
560 PRINT
570 PRINT "Input this parameter when prompted. Let the program "
580 PRINT " calculate the other two. "
590 FOR J=1 TO 100
600 NEXT J
610 RETURN
620 REMARK FIRST INPUT BLOCK SUBROUTINE
630 IF 29<>1 THEN 640
640 FOR I0=2 TO 5
650 IF 29<>1 THEN 670
660 GOSUB I0-1 OF 4020,4090,4140,4220
670 FIND I0
680 READ @33:A0,A$,A
690 CLOSE
700 IF 29<>1 THEN 720
710 H=Z
720 J1=0
730 J2=0
740 PAGE
750 GO TO 780
760 PAGE
770 PRINT "UPDATED VALUES ARE:"
780 FOR J0=1 TO A0
790 B$=SEG(A$, (J0-1)*40+1,30)
800 C$=SEG(A$, (J0-1)*40+31,10)
810 PRINT USING 820:J0,B$,A(J0),C$
820 IMAGE 5d,5x,30a,5x,fd.4d,58t,10a
830 NEXT J0
840 PRINT USING "2/";
850 PRINT "Input an item number to change that item, or 0 to continue: ";
860 INPUT J0
870 IF J0=0 THEN 980
880 PRINT
890 B$=SEG(A$, (J0-1)*40+1,30)
900 PRINT "Input the desired value of ";B$;": ";
910 INPUT J1
920 J2=1
930 A(J0)=J1
940 GO TO 760
950 REMARK ONLY REPRINT DATA IF CHANGES ARE MADE
960 IF J2=0 THEN 990
970 GO TO 760
980 J2=0
990 GOSUB 10-1 OF 3170,3230,3270,3340
1000 NEXT I0
1010 RETURN
1020 REMARK SECOND INPUT BLOCK SUBROUTINE
1030 REMARK CYCLE TRANSACTION LABEL STRING
1040 FIND 6
1050 READ @33:A$
1060 CLOSE
1070 DIM J$(10)
1080 REMARK TRANSACTION PARAMETER INPUT BLOCKS; FILE 8 IS A DUMMY
1090 FOR I0=7 TO 10
1100 IF I0=8 THEN 1700
1110 FIND I0
1120 READ @33:A
1130 IF Z9<>1 THEN 1150
1140 GOSUB 10-6 OF 4300,4320,4340,4360
1150 CLOSE
1160 PAGE
1170 J2=0
1180 GO TO 10-6 OF 1190,1210,1230,1250
1190 PRINT "Transaction costs"
1200 GO TO 1270
1210 PRINT "Transaction quantities"
1220 GO TO 1270
1230 PRINT "Transaction delay times"
1240 GO TO 1270
1250 PRINT "Transaction escalation rates"
1260 REMARK INPUT RESULT OF BURNUP MODEL
1270 REM
1280 REMARK
1290 FOR J0=1 TO 10
1300 C$=SEG(A$, (J0-1)*10+1,10)
1310 PRINT USING 1320:J0,C$,A(J0)
1320 IMAGE 5d,5x,10a,5x,6e,40t,4x,s
1330 GO TO 10-6 OF 1340,1360,1380,1400
1340 PRINT "$/kg or $/lb"
1350 GO TO 1410
1360 PRINT "kg or lb"
1370 GO TO 1410
1380 PRINT "years"
1390 GO TO 1410
1400 PRINT "per year"
1410 NEXT J0
1420 PRINT
1430 PRI "Enter an item number to change that item, or 0 to continue: ";
1440 INPUT J0
1450 IF J0=0 THEN 1680
1460 PRINT
1470 PRINT "Input the label for parameter ";J0;": ";
1480 INPUT J$
1490 PRINT
1500 PRINT "Enter the new value for ";J$;": ";
1510 INPUT J1
1520 J2=1
1530 IF LEN(J$)=10 THEN 1580
1540 FOR K0=1 TO 10-LEN(J$)
1550 J$=J$&" 
1560 NEXT K0
1570 REMARK J$ MUST HAVE LENGTH 10
1580 Q$=SEG(A$,1,10*J0-10)
1590 R$=SEG(A$,10*J0+1,150-10*J0)
1600 A$=Q$&J$
1610 A$=A$&R$
1620 A(J0)=J1
1630 GO TO 1160
1640 IF J2=0 THEN 1690
1650 PAGE
PRINT "Updated values are: "
GO TO 1280
J2=0
GOSUB 10-6 OF 3410,3450,3490,3530
NEXT 10
RETURN
REMARK BURNUP MODULE
REMARK BURNUP INPUT->1240
IF 01=1 THEN 1810
REMARK ENRICHMENT INPUT->1255
IF 01=2 THEN 1840
REMARK IRRAD TIME INPUT->1225
B0=(T3-T5)*N0*365.25*L*H1/M1
X2=B0/9000*(N0+1)/(2*N0)+1
GO TO 1870
T3=B0*M1/(365.25*L*H1*N0)+T5
X2=B0/9000*(N0+1)/(2*N0)+1
GO TO 1870
B0=9000*(X2-1)*2*N0/(N0+1)
T3=B0*M1/(365.25*L*H1*N0)+T5
REMARK CALCULATE CYCLE MASS FLOWS WHICH ARE CONSTRAINED
L0=L*(1-T5/T3)
FOR J0=6 TO 15
M(J0)=M1/N0*1000
NEXT J0
REMARK CONVERT MASS TO KG
M(5)=M1/N0
M(4)=M1/N0/F4
Q1=(X2-0.711)/(0.711-X3)*(X3/50-1)*LOG(X3/100/(1-X3/100))
Q2=(X2/50-1)*LOG(X2/100/(1-X2/100))-4.868883386*(X2-X3)/(0.711-X3)
M(3)=M(4)/F5*(Q1+Q2)
1980 \( M(2) = M(4)/F_6/F_5 \times (x_2-x_3)/\langle 0.711-x_3 \rangle \)
1990 \( M(1) = 2.6 \times M(2) \)
2000 RETURN
2010 REMARK DIRECT PLUS CARRYING CHARGE MODEL
2020 REMARK
2030 T1=NO*T3
2040 E1=H1*L0*N1*T3*8766000
2050 X1=(1-F3)*F1*R1+F2*R2
2060 T2=T1/2
2070 T4=T3*N2
2080 T9=T3*(N2-1)
2090 P5=X1/(1-F3)
2100 REMark actual start of cycle calculation
2110 REMARK DCC MODEL F FACTOR CALCULATION
2120 J0=1.0E-4
2130 REMARK
2140 L2=0
2150 U9=0
2160 FOR IO=1 TO 4
2170 U(IO)=M(IO)*C(IO)/E1*1000/(1-F3)*((1+X1)^T(T1/2-T(IO))-1)
2180 U9=U9+U(IO)
2190 T8(IO)=T2-T(IO)
2200 T6(IO)=((1+X1)^T(T8(IO)-1)/X1
2210 NEXT IO
2220 FOR IO=5 TO T0
2230 U(IO)=M(IO)*C(IO)/E1*1000/(1-F3)*((1+X1)^T(T1/2-(T(IO)+T1))-1)
2240 U9=U9+U(IO)
2250 T8(IO)=T2-(T(IO)+T1)
2260 T6(IO)=((1+X1)^T(T8(IO)-1)/X1
2270 NEXT IO
2280 FOR IO=1 TO T0
2290 L2=L2+U(IO)
2300 NEXT I0
2310 REMARK DCC MODEL G FACTOR CAL; NOTE BRANCH FOR REDUCED FORMS
2320 FOR I0=1 TO T0
2330 Y7=Y(I0)
2340 IF T(I0)<=0 THEN 2370
2350 T7=T(I0)+T1
2360 GO TO 2470
2370 T7=T(I0)
2380 REMARK J0 ASSIGNED OUTSIDE I0 LOOP
2390 IF ABS(Y0-X1)<J0 AND ABS(Y7-X1)<J0 THEN 2500
2400 REMARK Q1=Q2=0/0==>1 (above)
2410 REMARK Q2=0/0==>1 (below)
2420 IF ABS(Y0-X1)<J0 THEN 2520
2430 REMARK Q1=0/0==>1
2440 IF ABS(Y7-X1)<J0 THEN 2550
2450 Q1=1-(1+X1)↓-T4/(1+Y7)↑-T4/(1-(1+X1)↑-T3/(1+Y7)↑-T3)
2460 Q2=1-(1+X1)↑-T3/(1+Y0)↑-T3/(1-(1+X1)↓-T4/(1+Y0)↑-T4)
2470 G(I0)=(1+Y0)↑-T2/(1+Y7)↑-T7*Q1*Q2
2480 GO TO 2570
2490 REMARK note lim(y7,y0-->0) of g = 1 when no escalation
2500 G(I0)=(1+Y0)↑-T2/(1+Y7)↑-T7
2510 GO TO 2570
2520 Q1=1-(1+X1)↑-T4/(1+Y7)↑-T4/(1-(1+X1)↑-T3/(1+Y7)↑-T3)
2530 G(I0)=(1+Y0)↑-T2/(1+Y7)↑-T7*Q1*N2
2540 GO TO 2570
2550 Q2=1-(1+X1)↑-T3/(1+Y0)↑-T3/(1-(1+X1)↓-T4/(1+Y0)↑-T4)
2560 G(I0)=(1+Y0)↑-T2/(1+Y7)↑-T7*Q2*N2
2570 NEXT I0
2580 REMARK DCC MODEL FINAL CALCULATIONS
2590 H9=0
2600 P9=0
2610 FOR I0=1 TO T0
2620 \( P(I0) = M(I0) \times C(I0) / E1 \times 1000 \)
2630 \( P9 = P9 + P(I0) \)
2640 \( P1(I0) = M(I0) \times C(I0) \)
2650 \( H(I0) = G(I0) \times (P(I0) + U(I0)) \)
2660 \( H9 = H9 + H(I0) \)
2670 NEXT I0
2680 RETURN
2690 REMARK OUTPUT BLOCK SUBROUTINE
2700 REMARK
2710 PAGE
2720 REMARK FIRST OUTPUT BLOCKS
2730 FOR I0 = 2 TO 5
2740 FIND I0
2750 READ @33:A0,A$
2760 CLOSE
2770 GOSUB I0 - 1 OF 3570, 3640, 3690, 3780
2780 FOR J0 = 1 TO A0
2790 B$ = SEG(A$, (J0 - I) * 4 + 1, 10)
2800 C$ = SEG(A$, (J0 - I) * 40 + 1, 10)
2810 PRINT USING 2820:B$,A(J0),C$
2820 IMAGE 5X, 30a, 2x, f.d. 4d, 50t, 10a
2830 NEXT J0
2840 NEXT I0
2850 GOSUB 3860
2860 REMARK PAUSE FOR COPYING
2870 GOSUB 3970
2880 PAGE
2890 REMARK TRANSACTION OUTPUT BLOCKS, IN TWO PARTS
2900 PRINT USING 2910: "STEP", "QUANTITY", "UNIT COST", "DIRECT COST", "LAG"
2910 IMAGE 5a, 5x, 8a, 25t, 9a, 40t, 11a, 55t, 3a
2920 FOR J0 = 1 TO T0
2930 PRINT USING 2940: J0, M(J0), C(J0), P1(J0), T(J0)
2940 IMAGE 2d, 10t, 4e, 25t, 6d, 2d, 40t, 4e, 55t, 2d, 4d
2950 NEXT JO
2960 PRINT
2970 PRINT USING 2980: "STEP", "Y(I)", "DELTA T", "DELTA T*
2980 IMAGE 5a, 8x, 4a, 20t, 7a, 43t, 13a
2990 FOR JO = 1 TO T0
3000 PRINT USING 3010: JO, Y(JO), T8(JO), T6(JO)
3010 IMAGE 2d, 10t, 5d, 4d, 25t, 4d, 4d, 40t, 4d, 4d
3020 NEXT JO
3030 PRINT
3040 PRINT USING 3050: "STEP", "DIRECT C", "CC", "G(I)", "COST, MILLS/KWHRE"
3050 IMAGE 5a, 5x, 15a, 5x, 8a, 5x, 8a, 5x, 18a
3060 FOR JO = 1 TO T0
3070 PRINT USING 3080: JO, P(JO), U(JO), G(JO), H(JO)
3080 IMAGE 2d, 10t, 2d, 4d, 30t, 2d, 4d, 40t, 5d, 4d, 54t, 4d, 3d
3090 NEXT JO
3100 PRINT
3110 PRINT USING 3120: "TOTAL", P9, U9, H9
3120 IMAGE 5a, 10t, 2d, 4d, 30t, 2d, 4d, 54t, 4d, 3d
3130 GOSUB 3970
3140 RETURN
3150 REMARK STORAGE BLOCKS
3160 REMARK STORAGE BLOCKS
3170 X2 = A(1)
3180 X3 = A(2)
3190 F4 = A(3)
3200 F5 = A(4)
3210 F6 = A(5)
3220 RETURN
3230 M1 = A(1)
3240 L = A(2)
3250 M1 = A(3)
FOR J0=1 TO T0
C(J0)=A(J0)
NEXT J0
RETURN
FOR J0=1 TO T0
M(J0)=A(J0)
NEXT J0
RETURN
FOR J0=1 TO T0
T(J0)=A(J0)
NEXT J0
RETURN
FOR J0=1 TO T0
Y(J0)=A(J0)
NEXT J0
RETURN
A(1)=X2
3580 A(2)=X3
3590 A(3)=F4
3600 A(4)=F5
3610 A(5)=F6
3620 PRINT USING "fa":"ENRICHMENT PARAMETERS"
3630 RETURN
3640 A(1)=H1
3650 A(2)=L
3660 A(3)=N1
3670 PRINT USING "fa":"SYSTEM PARAMETERS"
3680 RETURN
3690 A(1)=B0
3700 A(2)=T3
3710 A(3)=T5
3720 A(4)=N0
3730 A(5)=N2
3740 M1=M1/1000
3750 A(6)=M1
3760 PRINT USING "fa":"CYCLE PARAMETERS"
3770 RETURN
3780 A(1)=F2
3790 A(2)=F1
3800 A(3)=R2
3810 A(4)=R1
3820 A(5)=F3
3830 A(6)=Y0
3840 PRINT USING "fa":"FINANCIAL PARAMETERS"
3850 RETURN
3860 PRINT USING "fa":"CALCULATED PARAMETERS"
3870 PRINT USING 3910:"IRRADIATION TIME",T1," YEARS"
3880 PRINT USING 3900:"ENERGY PRODUCED BY BATCH",E1, "KWHRE"
3890 PRINT USING 3910:"DISCOUNT RATE,X",X1," PER YEAR"
PRINT USING 3930: "CAPACITY FACTOR", L0
PRINT USING 3950: "CARRYING CHARGE RATE", P5, "PER YEAR"
RETURN
MOVE 80, ?
PRINT "TYPE RUN TO CONTINUE."
MOVE 80, 4
INPUT J$
RETURN
A(1)=X2
A(2)=X3
A(3)=F4
A(4)=F5
A(5)=F6
Z=A
RETURN
A(1)=H1
A(2)=L
A(3)=N1
Z=A
RETURN
A(1)=B0
A(2)=T3
A(3)=T5
A(4)=N0
A(5)=N2
A(6)=M1
Z=A
RETURN
A(1) = F2
A(2) = F1
A(3) = R2
A(4) = R1
A(5) = F3
A(6) = Y0
Z = A
RETURN

A = C
RETURN

A = M
RETURN

A = T
RETURN

A = Y
RETURN
APPENDIX F
SAMPLE OUTPUT OF DCC

The next several pages contain a sample problem output corresponding to the default problem built into DCC. Note that the program automatically lists all input prior to recording the results of the computation. Also note that all of the parameters are not independent: when enrichment is specified, burnup is computed, as is cycle length.
ENRICHMENT PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL ENRICHMENT</td>
<td>3.2514</td>
</tr>
<tr>
<td>TAILS COMPOSITION OF U-235</td>
<td>0.2000</td>
</tr>
<tr>
<td>FABRICATION YIELD</td>
<td>0.9950</td>
</tr>
<tr>
<td>ENRICHMENT YIELD</td>
<td>0.9950</td>
</tr>
<tr>
<td>CONVERSION YIELD</td>
<td>0.9950</td>
</tr>
</tbody>
</table>

SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATED THERMAL POWER</td>
<td>3800.0000 MWT</td>
</tr>
<tr>
<td>(AVAIL BASED) CAPACITY FACTOR</td>
<td>0.8599</td>
</tr>
<tr>
<td>THERMAL EFFICIENCY</td>
<td>0.3420 MWE/MWT</td>
</tr>
</tbody>
</table>

CYCLE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL BURNUP, TOTAL CYCLE</td>
<td>30393.5570 MWD/MTHM</td>
</tr>
<tr>
<td>INTRA-REFUELING INTERVAL</td>
<td>0.9849 YEARS</td>
</tr>
<tr>
<td>REFUELING DOWNTIME</td>
<td>0.1250 YEARS</td>
</tr>
<tr>
<td>NUMBER OF CORE BATCHES</td>
<td>3.0000</td>
</tr>
<tr>
<td>NUMBER OF STEADY STATE Batches</td>
<td>30.0000</td>
</tr>
<tr>
<td>CORE FUEL LOADING</td>
<td>101.3000 MTHM</td>
</tr>
</tbody>
</table>

FINANCIAL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQUITY (STOCK) FRACTION</td>
<td>0.5000</td>
</tr>
<tr>
<td>DEBT (BOND) FRACTION</td>
<td>0.5000</td>
</tr>
<tr>
<td>RATE OF EQUITY RETURN</td>
<td>0.1400 PER YEAR</td>
</tr>
<tr>
<td>RATE OF DEBT RETURN</td>
<td>0.0800 PER YEAR</td>
</tr>
<tr>
<td>TAX FRACTION</td>
<td>0.5000</td>
</tr>
<tr>
<td>ESCALATION RATE OF REVENUE</td>
<td>0.0600 PER YEAR</td>
</tr>
</tbody>
</table>

CALCULATED PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRRADIATION TIME</td>
<td>2.9547 YEARS</td>
</tr>
<tr>
<td>ENERGY PRODUCED BY BATCH</td>
<td>8.4238E+009 KWHRE</td>
</tr>
<tr>
<td>DISCOUNT RATE, X</td>
<td>0.0900 PER YEAR</td>
</tr>
<tr>
<td>CAPACITY FACTOR</td>
<td>0.7500</td>
</tr>
<tr>
<td>CARRYING CHARGE RATE</td>
<td>0.1800 PER YEAR</td>
</tr>
</tbody>
</table>

TYPE RUN TO CONTINUE.
<table>
<thead>
<tr>
<th>STEP</th>
<th>QUANTITY</th>
<th>UNIT COST</th>
<th>DIRECT COST</th>
<th>LAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.3219E+005</td>
<td>35.00</td>
<td>1.8627E+007</td>
<td>-1.0467</td>
</tr>
<tr>
<td>2</td>
<td>2.0469E+005</td>
<td>4.00</td>
<td>8.1875E+005</td>
<td>-0.5417</td>
</tr>
<tr>
<td>3</td>
<td>1.6576E+005</td>
<td>85.00</td>
<td>1.4090E+007</td>
<td>-0.5417</td>
</tr>
<tr>
<td>4</td>
<td>3.3936E+004</td>
<td>101.00</td>
<td>3.4276E+006</td>
<td>-0.2083</td>
</tr>
<tr>
<td>5</td>
<td>3.3767E+004</td>
<td>100.00</td>
<td>3.3767E+006</td>
<td>0.7500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STEP</th>
<th>Y(I)</th>
<th>DELTA T</th>
<th>DELTA T*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000</td>
<td>2.5241</td>
<td>2.6998</td>
</tr>
<tr>
<td>2</td>
<td>0.0000</td>
<td>2.0191</td>
<td>2.1117</td>
</tr>
<tr>
<td>3</td>
<td>0.0000</td>
<td>2.0191</td>
<td>2.1117</td>
</tr>
<tr>
<td>4</td>
<td>0.0000</td>
<td>1.6857</td>
<td>1.7372</td>
</tr>
<tr>
<td>5</td>
<td>0.0000</td>
<td>-2.2274</td>
<td>-1.9406</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STEP</th>
<th>DIRECT C</th>
<th>CC</th>
<th>G(I)</th>
<th>COST, MILLS/KWHRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.2112</td>
<td>1.0746</td>
<td>1.0000</td>
<td>3.286</td>
</tr>
<tr>
<td>2</td>
<td>0.0972</td>
<td>0.0369</td>
<td>1.0000</td>
<td>0.134</td>
</tr>
<tr>
<td>3</td>
<td>1.6726</td>
<td>0.6358</td>
<td>1.0000</td>
<td>2.388</td>
</tr>
<tr>
<td>4</td>
<td>0.4069</td>
<td>0.1272</td>
<td>1.0000</td>
<td>0.534</td>
</tr>
<tr>
<td>5</td>
<td>0.4008</td>
<td>-0.1400</td>
<td>1.0000</td>
<td>0.261</td>
</tr>
</tbody>
</table>

**TOTAL** 4.7888 1.7345 6.523

TYPE RUN TO CONTINUE.