# TECHNIQUES FOR CALCULATION OF NUCLEAR FUEL COSTS

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## 1.0 INTRODUCTION

The contribution of the nuclear fuel cost to the total cost of producing electricity represents the advantage that nuclear-fueled electrical generating stations have over fossil-fueled stations. Since nuclear fuel provides a means by which utilities can reduce energy production costs over the life of a generating station, there is a continuing need for reliable nuclear fuel cost calculations. However, calculations for the nuclear fuel cost are complicated because there are many processes involved and the cost of maintaining a substantial capital investment over a long period of time must be considered.

Processes which are involved in the preparation, use, and disposal of the fuel are: 1) Low grade uranium ore must be mined, milled, refined, enriched, and fabricated into elements which are mechanically and neutronically acceptable to a particular nuclear reactor. 2) Once placed into a reactor, the fuel elements produce energy but also a substantial number of isotopes which range in value from highly detrimental and dangerous to very valuable and useful. 3) Upon removal from the reactor, the fuel element still contains a valuable material, but requires special handling during movement and reprocessing. The costs of the various nuclear fuel cycle (NFC) processes are difficult to predict with confidence over the lifetime of a nuclear reactor (30-40 years), indeed, even over the lifetime of a single fuel element (3-5 years).

The cost of a single element seems simple to calculate when compared to the cost calculation of an entire reactor core. Complication in NFC cost calculations occur for a variety of reasons: 1) Generally a reactor core is composed of elements of varying initial isotopic composition. 2) As electrical energy is produced, variations in neutron flux shapes combine with the variation in compositions to produce different rates of neutronic transmutation

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within each element. 3) Fuel elements are designed to remain in the core for various time periods; in some cases fuel elements will be placed into the reactor more than once.

The calculations are complicated by the necessity of accounting for the cost (carrying charges) of the capital investment required to finance nuclear fuel. In a fossil fuel generating station, fuel costs are characterized by an outlay of funds essentially simultaneously with consumption. Therefore, even with a substantial stockpile, carrying charges on fuel investment are negligible. With nuclear fuel, however, it is necessary to provide nearly the entire cost of the initial fuel many months before any energy is produced. Even after removal from the reactor, the spent fuel has a substantial value, which must be accounted for until the spent fuel can be sold or reprocessed. To calculate the carrying charges, it is necessary to determine the utility capital structure (percentage in bonds, stocks, etc.), bond interest rate, equity return, income tax rate (federal, state, and local), and other factors which contribute to the cost of a capital investment. These charges must then be combined with the value of the nuclear fuel and the depreciation of each fuel element over the entire life of a reactor core to determine the total cost of the nuclear fuel.

Hence it is apparent that the number of computations associated with the calculation of the nuclear fuel cost for a twenty or thirty year operating period is very large. Hence large computer codes have been developed to cope with the large number of calculations which must be performed. More complicated fuel loading schemes and the integration of several nuclear generating stations into a utility grid have caused the computations to become even more numerous and complex. However, the question arises: do the results obtained by using these computer codes justify the effort exerted? If input parameters (costs) are not reliably known, operating strategies or capabilities not well established, or calculational (accounting) procedures not uniform, it is questionable whether these involved computer codes have an advantage over "hand-calculated" estimates with respect to accuracy, consistancy, or application.

To answer this question, it is necessary to explore first the calculational procedures used to determine if there is a method by which nuclear fuel costs can be reasonably calculated by hand or by a simpler computer code. Comparison with existing computer codes would determine the accuracy and consistancy of these simpler methods. The final comparison, applicability, will concern subjective appraisals of convenience and user needs. Therefore, an evaluation of the methods of nuclear fuel cost calculations (with an emphasis on the comparison between machine versus hand calculations) is the object of the this work.

## 2.0 FUEL CYCLE COST CALCULATIONS AND UTILITY ECONOMICS

The most striking aspect of even the most elementary study of the nuclear fuel cycle is the large number of diverse operations which must be performed and perfectly meshed. Attempts to estimate the economic impact of each of these operations on the cost of the extended use of uranium has led to very involved calculational procedures. So involved are these calculations that it is often difficult to understand the implications of the results. It is much too naive to say that the cheaper the fuel costs, the cheaper the cost of electricity, even though in the long run this may prove true. Moreover, the complexity of the nuclear fuel cycle seems straight-forward when compared to the procedures for establishing utility rates. The impact of the nuclear fuel cost is understood through an understanding of the economics of the operating electrical utility.

It is the economics of generating electricity which motivates detailed cost calculations of the nuclear fuel cycle. These calculations are applied in two major areas: reactor design evaluation and fuel management. Both require standardized application of economic principles to provide reliable results. The identification of appropriate economic principles leads to the development of calculational procedures which provide standardized results for nuclear fuel cost estimates.

### 2.1 Electric Utility Economics

The generation and distribution of electricity requires large capital investments in plant and equipment. This large investment is warranted only if there is a high use factor, which can result only when geographical franchising is permitted. It would not be in the best interest of the public if utilities were required to compete for customers. For instance, if two companies had customers on the same street, it would require duplication of transmission poles and lines, and of services such as meter readings. Hence, one company could serve all the customers with very little increase in costs. In recognition of the advantages to the utility's customers, a single utility is usually granted by the public (the utility's customers) exclusive rights to provide electrical service to a given geographical area. Since there is no competition, prices for electricity cannot be established in the usual manner. Therefore, in exchange for the monopoly on electrical supply, the utility must accept regulation by a government body (the public). In the final analysis, in utility economics there exists the unique situation where the customer dictates the price a supplier may charge for his services.

Regulatory bodies which establish utility rate schedules must allow utilities an adequate return on capital. The utility must make sufficient profit from its rates to attract the capital needed to provide the assets and working capital to render service to the public. Consequently, regulatory bodies are in the ticklish position of weighing public desires, the situation of current money markets, and the plans and operations of the utility. The procedure generally followed is to detail costs associated with installed capacity, cost of production, and cost of consumer services. These costs are applied to two categories of customers, industrial and general, to obtain adequate rate schedules [1].

As the above discussion illustrates, there is very little direct relationship between the cost of electricity (rate schedule) and the cost of nuclear fuel. The relationship is lost in the compromise between utility costs and consumer requirements. It is possible, however, to illustrate the impact of the cost of nuclear fuel from the utilities standpoint. Table 1 shows the

Table 1. Electric Utility Cost Functions

| Function | Percent |
| --- | --- |
| Production System | 55 |
| Bulk Transmission System | 7 |
| Secondary Distribution System | 25 |
| Customer Activities and Sales | 6 |
| General Administration | 7 |
| TOTAL | 100 |

approximate breakdown of generation costs to the electrical utility. Note that the production of electricity accounts for only half of the utility's costs, while the remainder comes from electrical distribution and customer services. Nuclear fuel accounts for approximately 20% of the total generating costs (see Table 2). The actual contribution of the nuclear fuel is dependent on the fraction of electricity generated by nuclear power. If this fraction is 10%, for example, nuclear fuel will account for only 1% of the total cost of electricity to the utility [2].

Is this fraction (1%) large enough to warrant very detailed calculations? The answer is yes. First, inspection of Tables 1 and 2 indicates that all the utility's costs are directly related to either the number of customers or fixed investments, except for nuclear fuel. There may be some room for improvement in operations, but the primary means by which a utility using nuclear power can decrease its costs is by more efficient management of its fuel. Second, calculations [3] show that the cost of nuclear fuel over the life of a nuclear power plant will amount to more than the capital investment in the plant itself. Since we are talking about an investment on the order of a billion dollars, decreasing the cost of nuclear fuel by a small fraction can result in a savings of millions of dollars. This in itself is adequate motivation to pursue those calculations which demonstrate the most economical fuel schemes available.

## 2.2 Fuel Management

The capability of a utility to decrease operation costs by optimization of the nuclear fuel cycle provides a continuing incentive for accurate accounting and projections of fuel costs. The recognition of the interaction between utility operations and planning and the cost of nuclear fuel have led to development of

Table 2. Sample Yearly Costs of Electric Energy Generation

| Cost Component | Annual Cost $10^3$ $ | Unit-energy Cost mills/kw-hr |
|---|---|---|
| Plant Investment | | |
| Depreciating Assets | 45,864 | |
| Nondepreciating Assets | 138 | |
| Subtotal | 46,002 | 6.08 |
| Fuel | | |
| Total Fuel Cost | 12,890 | 1.70 |
| Operation and Maintenance | | |
| Direct Cost | 2,300 | |
| Working Capital | 69 | |
| Subtotal | 2,369 | .34 |
| Total electric energy generation cost | | 8.12 |

nuclear fuel management procedures, which are primarily concerned with minimization of unit energy costs due to fuel but encompass the entire nuclear fuel cycle. The economic calculations are identical to those performed by the design engineer; the difference arises from the fact that nuclear fuel management continues throughout the life of the reactor. A body of information is developed through experience which enables the manager to more accurately predict parameters in the nuclear fuel cost calculations. Additionally, the projections of the fuel manager are usually for shorter time periods, making them less susceptible to unexpected changes in prices. The nuclear fuel manager uses the same procedures as the design engineer, but the greater accuracy of input parameters generally makes his calculations more reliable.

## 2.3 Nuclear Fuel Design Calculations

In a normal business situation, the decision to invest new capital is dictated by the expected rate of return. The expected return on the newly invested capital should be sufficient to cover all costs and insure an attractive profit. In electric utilities, however, the situation is considerably different. The electrical utility is charged with providing all the electricity required. Therefore the utility must expand if there is a growing demand. The decision to invest capital does not exist, and really is not relevant since an adequate return to capital is allowed by the regulatory bodies. The decision is how to invest the capital. Design calculations for a utility are therefore directed toward determination of the most advantageous choice of available alternatives.

From an engineering viewpoint, this process would seem to be straight forward. Simply estimate the cost of all factors involved, sum, and select the alternative with the smallest total cost. From a business viewpoint, however, this is a very superficial treatment. The business executive recognizes that the large amount of capital required (almost $1 billion for a nuclear power plant) is not available to the utility from its own resources. Most will have to be borrowed and then repaid after the plant is in operation. An analysis which fails to consider the cost of borrowing this money, i.e., the interest paid by the utility, can result in large errors in the total cost. The recognition of this cost certainly does not lead to simple calculations, especially if the money market is constantly changing. These two facts, the importance and instability of capital costs, was illustrated in a study by the now disbanded Atomic Energy Commission. The costs of capital, which amounted to 17% of the total cost of a nuclear power plant in 1967, had increased to 40% of the total cost by 1973 [4]. This demonstration of the importance of the cost of using capital has led to the recognition of a definite relationship between time and money, similar to the physical relationship between mass and energy. In order to compare adequately two designs which call for different time schedules for investment, it is necessary to remove the time dependence from the money-time relationship. Methods have been devised to do this, e.g., the internal rate of return and present worth methods, but before explaining these methods, it is necessary to understand the relationship between time and money.

Early in the twentieth century, Albert Einstein proposed a scientific theory which is now a cornerstone in man's understanding of the physical world,

$$E = mc^2 \quad (2.1)$$

There are two variables, energy and mass, and one constant, the speed of light. this relationship was then expanded into the special theory of relativity to relate changes in the energy of a particle to changes in its mass.

Unlike the theory of relativity, the concept of interest (cost of borrowing money) has existed since the earliest written record, as early as 2000 BC. In its simplest concept, interest is given by

$$I = P\ N\ i \tag{2.2}$$

In this case there are two constants: P, the amount invested (principal), and i, the interest (a fraction of P per time interval). The variables are the interest due, I, and the number of time intervals, N. This formula represents the direct relationship between time (N) and money (I). In a manner similar to the theory of relativity, this simple relationship can be expanded into more flexible forms. Assume that the interest will not be paid until some future date and that you must pay interest on the interest due. Therefore, the future value, N times periods hence, of a present value, P, invested at an interest rate, i, is given:

$$F = P(1+i)^N \tag{2.3}$$

The most common term which pervades engineering economic analysis is "present worth". If a certain amount of money is invested, its value a fixed time in the future, "its future worth", is given by the compound interest formula shown above. If the value of an amount of money in the future is known, its "present worth" can be determined by solving for the amount of money you would have to invest today in order to have that known amount in the future, or

$$P = (1+i)^{-N}\ F \tag{2.4}$$

From a practical standpoint, it is the present worth form of the compound interest formula which is most often applied to eliminate time dependence from economic analysis.

In a large corporation, such as an electric utility, a project can be financed by two types of capital: equity and debt capital. Equity capital is that which is owned by the corporation. The most common source of this capital is the sale of stocks, i.e., partial ownership of the company. Debt or borrowed capital is that capital which belongs to companies or individuals other than the corporation. The most common way to obtain this capital is to sell bonds or borrow directly from the money market.

The amount of equity and debt capital (often called capital structure) becomes important when considering the term "interest". Interest is strictly applicable only in conjunction with debt capital. Debt capital has a predetermined payment schedule and rate of return which goes to individuals outside the corporation. It is a cost to the corporation. The "interest" on equity capital is actually profit for the corporation since it represents an income on its own capital. In many cases, the size of this return on equity capital, normally paid out as dividends, is not predetermined and usually is about one-half of the interest on debt capital. This distinction between interest on debt capital and profit on equity capital is very important when considering taxes. Taxes take many forms (local, state and federal: property, sales and income) with federal income tax usually the largest. Since return on equity capital is considered a profit, it is subject to income tax, whereas the interest on debt capital is a cost and therefore not subject to income tax. This is a substantial consideration since corporate income taxes are usually greater than 50% of the profit.

In addition to these concepts there are many refinements of economic theory, such as computation of depreciation and price escalation, which become important as the detail of the analysis is increased. It is difficult for an engineer, however, to feel comfortable with a method of analysis which stems from a direct application of these unfamiliar economic concepts. The engineer is more comfortable with rigorous mathematical derivations. It is possible, however, to arrive at the same method of analysis from both an economic and a mathematical approach.

## 2.4 Comparison of Alternatives: An Economic Approach

An investment is considered economically advisable if the expected rate of return is high enough. Alternately, an investment is considered advisable if it yields sufficient profit. Although the profit motive is not strictly applicable in electric utility, these two concepts can be applied to determine whether one alternative is more economically attractive than another. First consider the nature of the investment involved. A nuclear power plant is a project which involves a complicated series of investments and receipts over a long (perhaps 40 year) period of time. Two projects can differ in the length of the project and the schedule of investments and receipts. To adequately compare these two projects it is necessary to analyze each investment and receipt. The detailing of the movement of money into and out of the project is called a "cash flow" analysis. A cash flow analysis is the basis for comparing investment projects.

The most common method of evaluating the advisability of a single investment is known as the internal rate of return (IRR) method. The basic principle of this method is to compute the interest or profit rate which will cause the present worth of all revenues (investments, disbursements, and receipts) to be zero. Consider the present worth form of the compound interest formula:

$$P = (1+i)^{-N} F \; . \qquad (2.5)$$

This represents the present worth of a single investment. Let $F(n)$ represent the net revenue (which may be positive or negative) during accounting period $n$. The total present worth of a series of payments and receipts is the sum of the present worths of the net revenue of each period, or

$$P_{total} = (1+i)^{-1} F(1) + (1+i)^{-2} F(2) + \ldots + (1+i)^{-N} F(N) \; . \qquad (2.6)$$

i.e.,

$$P_{total} = \sum_{n=1}^{N} (1+i)^{-n} F(n) . \qquad (2.7)$$

If $P_{total}$ is zero and i is positive, i represents the rate at which the invested capital grows in value, or the internal rate of return. This concept can be applied to the comparison of two projects: the project with the highest rate of return is the most attractive economically. There are complications, however. First, the nature of the equation makes it impossible to solve explicitly for i, requiring an iterative procedure which can become time consuming for large projects. The largest drawback, however, is that in this method there is no way to relate the internal rate of return to the expected selling price of electrical energy.

These drawbacks are not encountered in the present worth (PW) method. This method is based on the calculation of the equivalent worth of all revenues at some point in time called the "present". This time does not have to be the current day or year, but can be any time convenient for the analyst. This yields an expression identical to the IRR method,

$$P_{total} = \sum_{n=1}^{N} (1+i)^{-n} F(n) . \qquad (2.8)$$

The difference is that in the PW method the value of i is assumed. To compare alternatives, it is necessary to compute and compare the present worths. In this form, it is easy to separate and solve for the price of energy which causes the present worth of a project to be zero. If this price (c) is a constant multiple of the energy produced, E(n), then

$$P_{total} = \sum_{n=1}^{N} (1+i)^{-n} (cE(n) - F'(n)) = 0 . \qquad (2.9)$$

Therefore,

$$c = \frac{\sum_{n=1}^{N} (1+i)^{-n} F'(n)}{\sum_{n=1}^{N} (1+i)^{-n} E(n)} . \tag{2.10}$$

This indicates the unit price of energy can be interpreted as the ratio of the present worth of all revenues, except income from the sale of energy, to the present worth of all the energy produced. This value is usually called the "levelized" cost since it covers the entire life of the project. It is the most common method of comparing alternate nuclear fuel costs. In this case, i was predetermined and is known as the minimum acceptable rate of return or the discount rate.

## 2.5 Comparison of Alternatives: A Mathematical Approach

Application of the IRR or PW method for comparing alternatives provides little problem for those familiar with the value of money with time. These methods can present problems to the design engineer, however, as expressed by an economics text discussing the PW method:

> "One disadvantage is that it appears to assume that the present worth of all future expenses is to be paid at one time. This, of course is not the case, but the assumption frequently seems to cause some difficulty in the minds of engineers who attempt to use the present worth method."

To clarify and illustrate a procedure applicable in all cash flow situations, consider the following derivation for the unit price of energy.

Assume that a project which spans N consecutive accounting periods consists of a series of disbursements, investments, and receipts. Let F(n) represent the net revenue for each accounting period and

$$F(n) = c\, E(n) - F'(n) . \tag{2.11}$$

where

c = unit price of energy,

E(n) = energy produced during accounting period n,

F'(n) = payments other than sale of energy.

Let Y(n) be the indebtedness at the beginning of period n, and let x be the interest charged on this indebtedness per accounting period. Then

$$Y(n+1) = Y(n) + F(n) + x\ Y(n) \qquad (2.12)$$

This equation states that the indebtedness in any period is the sum of the indebtedness of the previous period, the interest on that indebtedness, and the net revenues of the previous period. If it is required that all indebtedness be retired, i.e., Y(N+1) = 0, the following results:

$$Y(n+1) = (1+x)\ Y(n) + F(n)\ , \qquad (2.13)$$

$$Y(a) = (1+x)\ Y(a-1) + F(a-1)\ , \qquad (2.14)$$

$$Y(a) = (1+x)\ [(1+x)\ Y(a-2) + F(a-2)] + F(a-1)\ , \qquad (2.15)$$

$$Y(a) = \sum_{n=1}^{n=a-1} (1+x)^{a-n-1}\ F(n)\ . \qquad (2.16)$$

Therefore

$$Y(N+1) = \sum_{n=1}^{N} (1+x)^{N-n}\ F(n) = 0\ , \qquad (2.17)$$

which is equivalent to

$$\sum_{n=1}^{N} (1+x)^{-n}\ [c\ E(n) - F'(n)] = 0\ . \qquad (2.18)$$

Therefore, the unit price of energy is

$$c = \frac{\sum_{n=1}^{N} (1+x)^{-n} F'(n)}{\sum_{n-1}^{N} (1+x)^{-n}\ E(n)}\ . \qquad (2.19)$$

This derivation illustrates that the "present worth" concept is not peculiar to economists, but is an economic interpretation of a mathematical problem.

The derivation above did not enumerate the various revenues which are associated with actual fuel cycles, but the technique can be applied to any cash flow scheme and is considered the basis for economic evaluation by the Nuclear Regulatory Commission (NRC) [5]. This technique was expanded by Vondy [6] to account for such items as taxes, investment in both stocks and bonds, depreciation, operating expenses, and income other than from the sale of energy. The result is shown below.

$$P = \frac{\sum_{n=0}^{N} (1+x)^{-n} \left[\frac{Z(n)}{(1-r)} - V(n) + O(n) - \frac{r}{1-r} D(n)\right]}{\sum_{n=1}^{N} (1+x)^{-n} Q(n)} . \qquad (2.20)$$

where

$$D(0) = O(0) = Q(0) = 0,$$

$$x = j(1-r)\, b + i(1-b) .$$

The terms are defined as:

$Q(n)$ = amount of energy sold during the period,

$Z(n)$ = investment,

$V(n)$ = income other than sale of energy,

$D(n)$ = depreciation,

$O(n)$ = deductible operating costs,

$P$ = unit selling price of energy to return all investment costs,

$x$ = discount factor,

$N$ = history life,

$r$ = tax rate on taxible income

$i$ = required return on stock,

j = required return on bonds,

b = fractional indebtedness in bonds.

## 2.6 Conclusion

Electrical utilities present the nuclear engineer with a challenging problem in design evaluation. Their unique economic situation requires cost estimates to be made for a comparative analysis. In particular, calculation of nuclear fuel cycle costs provides the utility with an indication of how different nuclear fuel schemes can affect their energy production costs. Proper application of this knowledge can indirectly influence the cost of electrical energy to the consumer. This is the motivation for an engineer to combine his technical knowledge with economic priciples to obtain reliable comparative analyses. Design of a nuclear reactor system determines the schedule of investments necessary to provide fuel for the reactor. The establishment of this "cash flow" provides the basis for the application of the present worth or discount technique. The final calculations, properly interpreted provide a valuable tool for utility managers.

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## 3.0 FUEL CYCLE COSTS: EXTENDED SEVEN-PAGE METHOD

The analysis of nuclear fuel costs is of continuing importance since proper management of nuclear fuel represents a means of decreasing electrical generation costs throughout the lifetime of the generating station [1]. This analysis is more complex than with fossil fuels because of three major characteristics of nuclear fuel [2]:

1. Large investments prior to use of the fuel are required.
2. Preparation and use of the fuel requires a long time period.
3. The spent fuel has a high residual value.

In addition, these characteristics make the cost of capital, or carrying charges, a significant portion of the total fuel cost, and require a detailed knowledge of the time-varying value of the nuclear fuel.

Since a reactor is generally composed of fuel with different processing costs, exposure histories and energy production capabilities, calculation of nuclear fuel costs is usually performed using large and complex computer codes. Additionally, the economic analyses performed through the use of these codes include the application of discounted worth of money [3], present worth methodology [4], or allocated costs [5] and have features or options such as fuel reinsertion, plutonium recycle and cost escalation. These features result in codes which are so involved that the user can easily lose sight of the physical significance of the calculations performed and the results obtained. A different approach was offered by Bader, Kitzke, and Norman in the form of a hand calculational method originally called "the seven-page method" [6]. Not only can the calculations be done by hand, but the significant steps of the nuclear fuel cycle are presented in chronological order. The user becomes familiar with the economic importance of each step, and the physical significance of each cycle step is always retained.

Unfortunately, this calculational method in its present form has several limitations:

1. It is applicable only to a single batch of fuel and not a reactor core consisting of several batches.
2. It calculates only the total cost (or unit cost of energy) over the entire history of the fuel and does not calculate costs associated with a particular period of time.
3. It does not take into account the economic reality of inflation (or cost escalation).
4. It does not provide for comparative analysis by use of present worth, discounted cash flow or other methods.

The last two of these limitations constitute a substantial departure from the calculation of "fuel cost." The objective is not the calculation of an absolute cost, but the generation of a number which reflects the impact of time-varying investment when compared with other numbers calculated in the same manner.

This chapter is concerned with the calculation of actual fuel cycle costs. For this reason, different methods of comparative analysis are not discussed. Instead the seven-page method is extended to encompass the entire history of a reactor. This extension of the seven-page method provides an accurate fuel cost calculational method while retaining the advantages of simplicity of calculation.

## 3.1 Extension of the seven-page method.

In the seven-page method an investment distribution as a function of time is generated for a single batch of nuclear fuel (Fig. 1). From this distribution the total cost of the batch can be obtained directly. The total cost is the sum of the direct and indirect costs where these costs are defined:

Direct Costs = depreciation of the fuel, i.e., the difference in the value of the fuel at insertion and removal.

Indirect Costs = the sum of the carrying charges during each accounting period (generally assumed to be one month), where the carrying charge is the product of the average investment and carrying charge rate.

In the seven-page method "depreciation" includes the change in value of the fissile material (uranium depletion and plutonium accumulation) and the accrual of funds necessary to cover shipping and reprocessing of spent fuel. In effect, a zero salvage value for the batch is assumed.

These costs are offset by the sale of energy (steam and/or electricity). In the seven-page method, the production of energy is assumed to be constant over the time period that the fuel batch resides in the core (Fig. 2). It is recognized that the actual energy production will be a much more involved function of time; but, the average production value will simplify calculations. To find the necessary minimum selling price for energy (or the cost of energy) income must balance costs:

Energy Sale = Depreciation + Carrying Charges .

This equality can be represented mathematically as (note from Figs. 1 and 2)

$$\int p\, E(t)\, dt = I(A) - I(B) + \int i\, I(t)\, dt, \qquad (3.1)$$

where

$E(t)$, $I(t)$ = energy output and investment as functions of time, respectively,

$p$ = unit price of energy,

$i$ = carrying charge rate,

$I(A)$, $I(B)$ = investment at times A and B, respectively.

The presence of continuous functions in Eq. (3.1) presents problems in calculation. Since accounting is usually done on an "end of period" basis,

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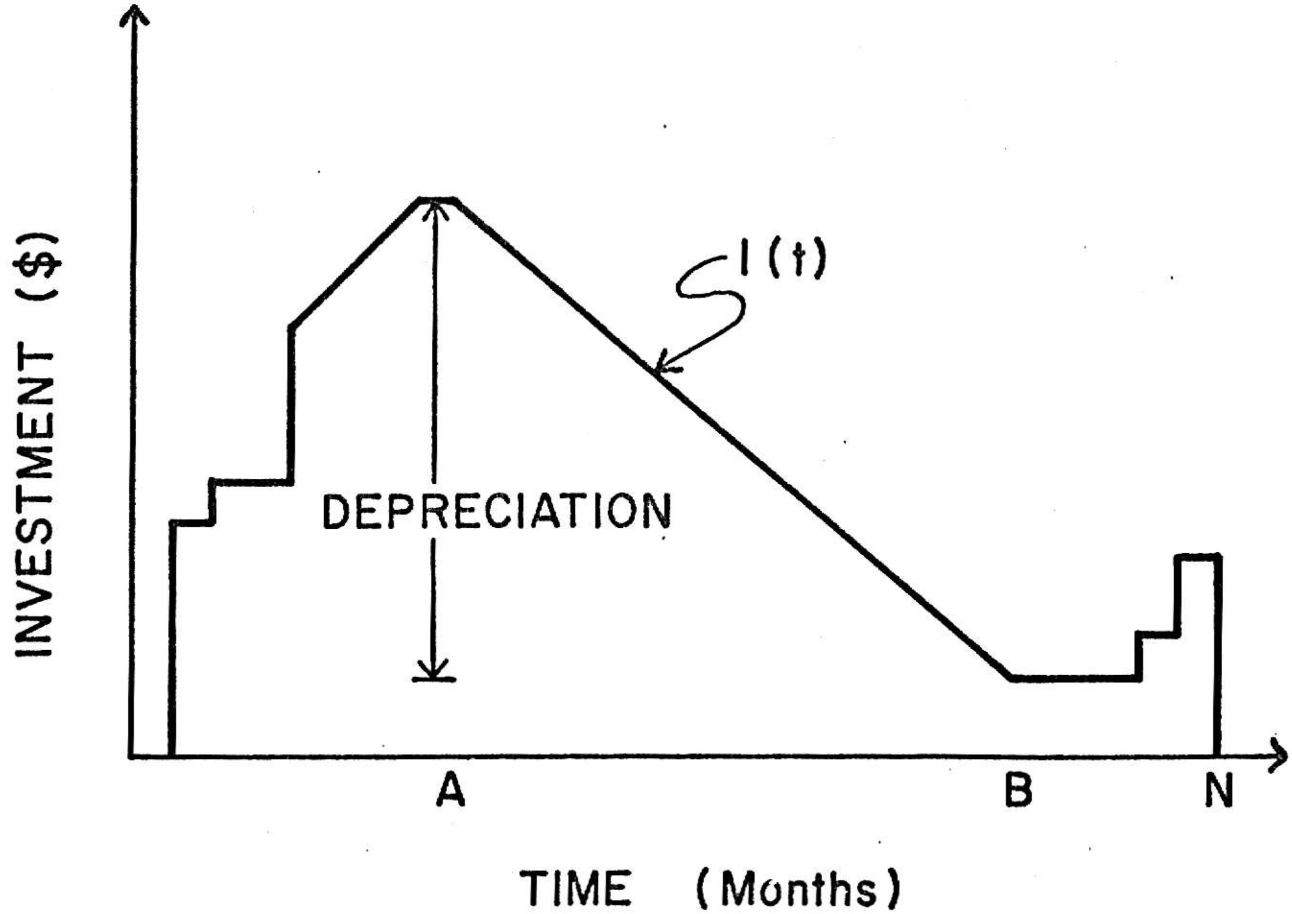


Figure 1. Investment-Time Diagram for a single batch of nuclear fuel

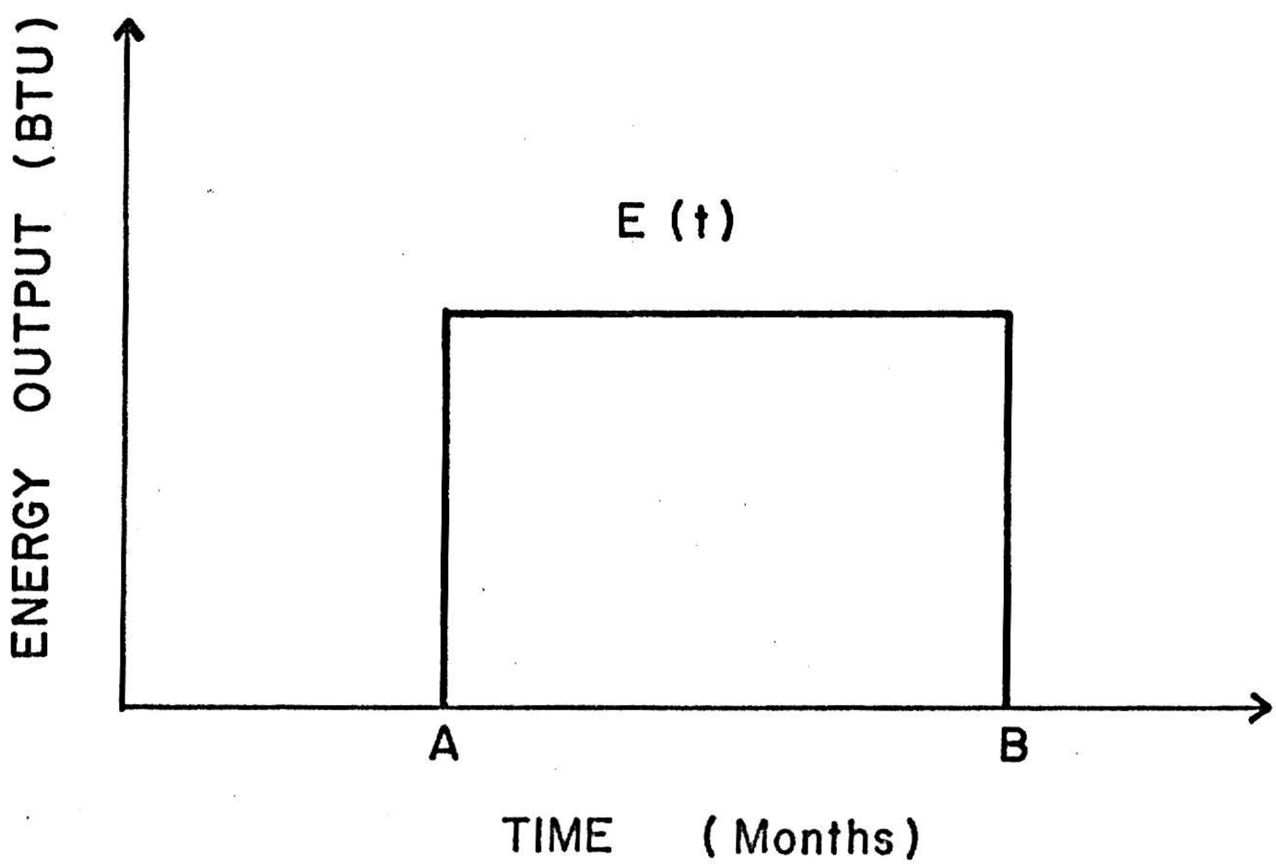


Figure 2. Energy-Time Distribution for a Fuel Batch

let I(n) be a discrete function representing the value of I(t) at the end of each accounting period (Fig. 3). If energy production is also considered as a discrete function of accounting period, n, Eq. (3.1) is equivalent to

$$\sum_{n=1}^{N} p\ E(n) = I(A) - I(B) + \sum_{n=1}^{N} i\ I(n), \tag{3.2}$$

where

n = A is the month of insertion in the core,

n = B is the month of removal from the core,

n = N is the total number of months of the fuel batch history, i.e., the month when all debt is retired.

There will be a slight difference in the calculation of carrying charges between Eqs. (3.1) and (3.2). The difference is small, depending on the size of the continuous depreciation and carrying charge rate. Equation (3.2) represents a more realistic representation.

The investment during any accounting period is

$$I(c) = I(c-1) + Z(c) - V(c) - D(c), \tag{3.3}$$

where

Z(c) = investment during period c,

V(c) = income from sources other than the sale of energy during period c,

D(c) = depreciation during period c.

Equation (3.3) is a recursion formula in I. Since I(0) = 0,

$$I(c) = \sum_{n=1}^{c} [Z(n) - V(n) - D(n)]. \tag{3.4}$$

If all debt is retired at the end of life, i.e., no salvage value,

$$I(N) = 0 = \sum_{n=1}^{N} [Z(n) - V(n) - D(n)]. \tag{3.5}$$

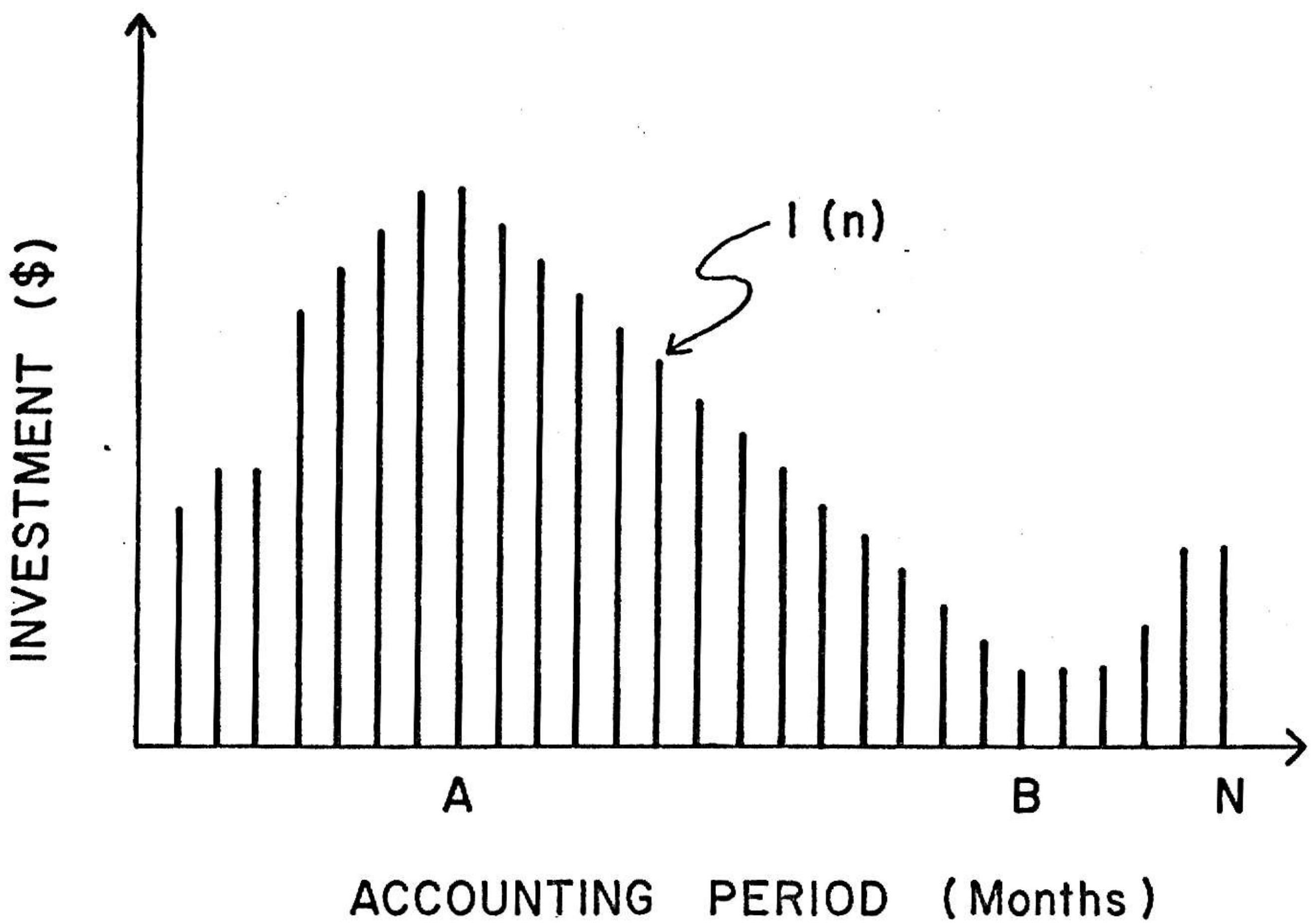


Figure 3. Investment-Time distribution as a discrete function

From Eq. (3.5) the total depreciation is given by

$$I(A) - I(B) = \sum_{n=1}^{N} D(n) = \sum_{n=1}^{N} [Z(n) - V(n)] \qquad (3.6)$$

Equation (3.6) states that the total depreciation during the life of a fuel batch which has no salvage value is the sum of all investments minus all receipts.

The carrying charges associated with the fuel batch are represented by

$$C(N) = \sum_{n=1}^{N} i\ I(n) \qquad (3.7)$$

From Eq. (3.3) it follows that the carrying charges associated with an arbitrary accounting period are

$$C(c) = i[I(c-1) + Z(c) - V(c) - D(c)]. \qquad (3.8)$$

Since I is recursive

$$C(c) = i \sum_{n=1}^{c} [Z(n) - V(n) - D(n)] \qquad (3.9)$$

Therefore, the total carrying charges associated with a fuel batch is the sum of the carrying charges in each accounting period,

$$C(N) = \sum_{m=1}^{N} \left\{ i \sum_{n=1}^{m} [Z(n) - V(n) - D(n)] \right\}, \qquad (3.10)$$

which is identical to

$$C(N) = \sum_{n=1}^{N} i(N - n + 1)\ [Z(n) - V(n) - D(n)] \qquad (3.11)$$

Use of Eqs. (3.3), (3.6), (3.7), and (3.11) allow the balance between income and costs to be written as

$$\sum_{n=1}^{N} p\ E(n) = \sum_{n=1}^{N} [Z(n) - V(n)] + \sum_{n=1}^{N} i(N - n + 1)\ [Z(n) - V(n)]$$

$$- \sum_{n=1}^{N} i(N - n + 1)\ D(n) \qquad (3.12)$$

The argument used to derive Eq. (3.12) was based on the history of a single fuel batch. This argument indicates that calculations must be performed in each accounting period, which can be a large task since a fuel batch may cover one hundred accounting periods and a reactor may use a maximum of fifty different fuel batches. Before extending the calculation to an entire core, consider Eq. (3.12) as:

$$p = \frac{\sum_{n=1}^{N} [i(N - n + 1) + 1][Z(n) - V(n)] - i \sum_{n=1}^{N} (N - n + 1) D(n)}{\sum_{n=1}^{N} E(n)} \qquad (3.13)$$

where p, the energy price, is considered constant with respect to time. The denominator is the amount of energy produced by the fuel batch. This is a design characteristic and can be computed directly from plant capacity, capacity factor, and fuel batch residence time. The term [Z(n) - V(n)] is zero except in those periods where actual disbursements are made or receipts collected. Since the items to be financed are finite, e.g., $U_3O_8$ purchased, fuel elements fabricated, etc., and even with progress payments, the number of periods during which transactions are conducted will be finite.

The most difficult term is the second term of the numerator, which involves a separate calculation for each period that the fuel batch is in the reactor. The calculations can be simplified considerably, however, if the assumption of straight line depreciation is applied:

$$\overline{D} = \sum_{n=1}^{N} [Z(n) - V(n)]/(B-A+1) = D(n) \qquad (3.14)$$

$\overline{D}$ is zero except when n is between times A and B. Therefore, the second term of the numerator in Eq. (3.13) becomes

$$i \sum_{n=1}^{N} (N - n + 1)\ D(n) = \overline{D} \sum_{n=A}^{B} [i(N-1) - i\ n] \tag{3.15}$$

The summation on the right side of Eq. (3.15) is the sum of an arithmetic series of (B-A+1) terms. The first term of the series is i(N+1-A) and the common difference is -i. The term is then given directly as [7]

$$i \sum_{n=1}^{N} (N - n + 1)\ D(n) = \overline{D} \left\{ \frac{(B-A+1)}{2} [2i(N-A+1) - i(B-A)] \right\} \tag{3.16}$$

With the use of Eqs. (3.14) and (3.16), it is only necessary to make two calculations for depreciation and one calculation for each investment or receipt (excluding sale of energy) in order to determine the unit price of energy produced by the fuel batch.

To extend this procedure to an entire core, consider the core as a single fuel batch with a complicated payment and receipt schedule. While this is the general practice, it is not an easy procedure to follow since a core history is normally composed of a complicated arrangement of fuel batches. It would be much more convenient if calculations could be done on a fuel batch basis and these calculations transposed directly to calculate the cost of the entire core. Since Z(n), V(n), and D(n) are zero after the end of the fuel batch history, the value of p (Eq. 3.13) is independent of the value of N, the limit of the summation index, as long as N is greater than or equal to the final accounting period of the batch. Therefore, N can be set equal to the life of the reactor, and the calculations used to determine the cost of each fuel batch can be used directly to calculate the cost of the entire core.

## 3.2 Calculational Procedure

To illustrate this generalized method, it is necessary to establish a calculational procedure. The following items as a function of accounting period must be known about each fuel batch:

1. Investments.
2. Receipts other than sale of energy.
3. Energy production.

To illustrate items 1 and 2, use a cash flow diagram such as Fig. 4. A similar diagram can be constructed for the production of energy (Fig. 5). Hence, the following procedure results:

1. Calculate and tabulate Z(n), V(n), E(n), and i(N-n+1) using the seven-page method for a single fuel batch.
2. Calculate the unit cost of energy, p, for the fuel batch, using Eqs. (3.13), (3.14), and (3.16).
3. Repeat 1 and 2 for each fuel batch.
4. Tabulate and sum $\sum$ [Z(n) - V(n)], E(n), and $\sum$ [i(N-n+1) + 1] [Z(n) - V(n)] for all fuel batches.
5. Calculate p for the entire core, using Eq. (3.13), (3.14), and (3.16).

## 3.3 Application

To illustrate this procedure, a sample problem using a ten fuel batch, ten year core history was used. The first two steps of the calculational procedure are shown in Table 3 for a single fuel batch. A similar table was developed for each fuel batch and together they were used to generate Table 4, which is the results of steps 4 and 5 of the calculational procedure. The calculations in these tables illustrate the simplicity of the procedure but

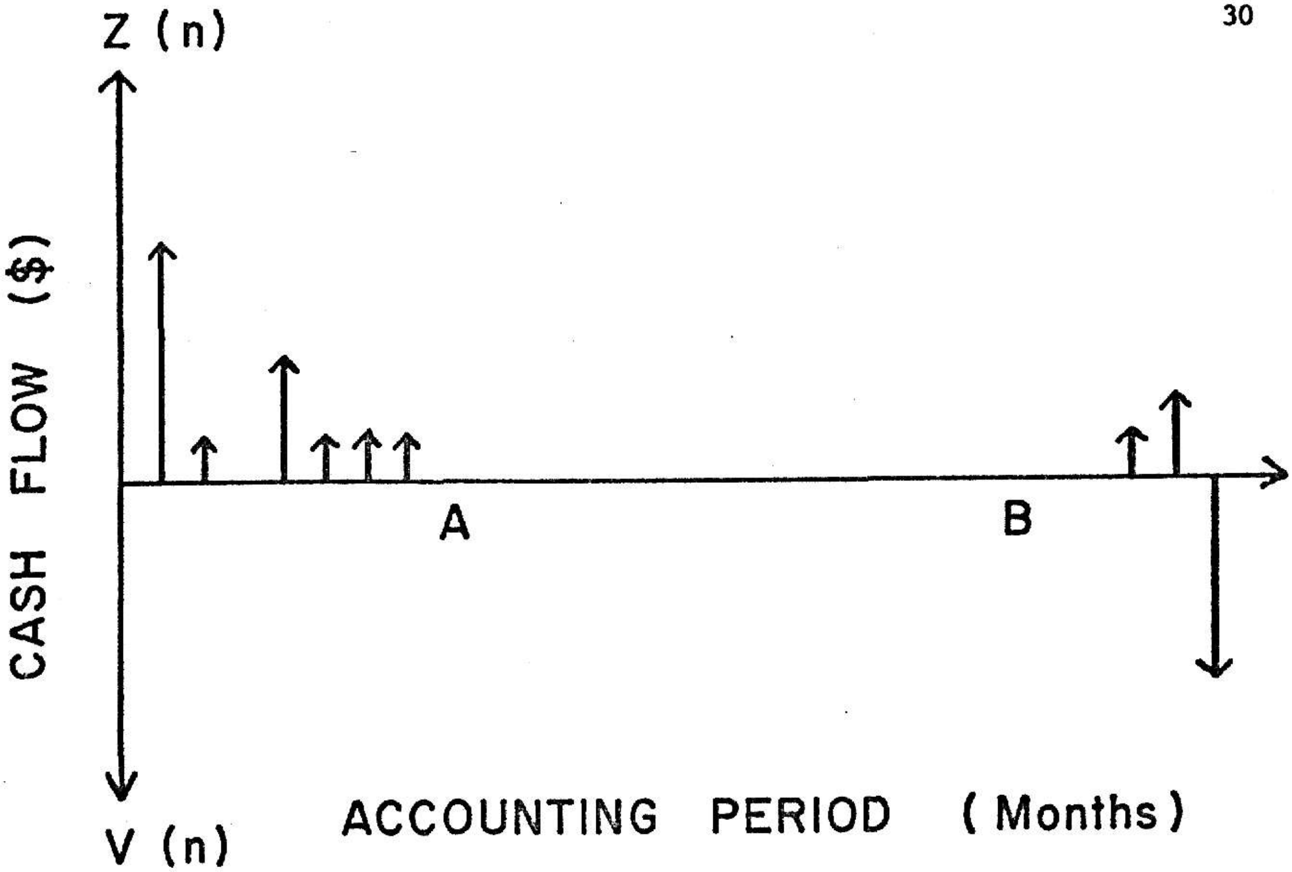


Figure 4. Cash flow diagram for a single nuclear fuel batch

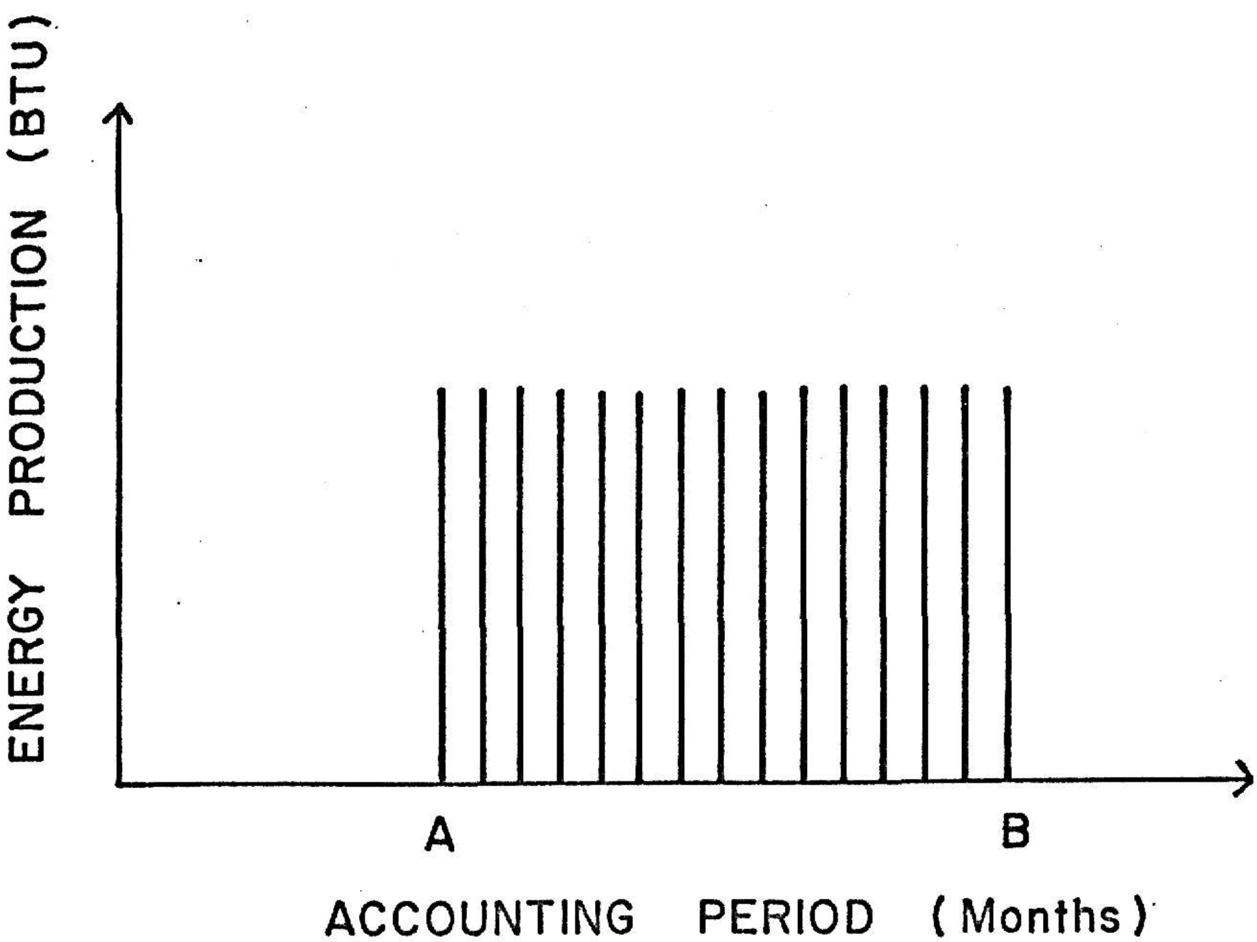


Figure 5. Energy-Time distribution as a discrete function

Table 3. Calculation of Unit Fuel Costs for a Single Batch Extended Seven-Page Method.

N = 118
A = 13
B = 24
i = .01

| Date | n | Payment | i(N-n+1) + 1 | Z(n)[i(N-n+1) + 1] | E(n) |
|---|---|---|---|---|---|
| 1/1977 | 1 | 2856000 | 2.18 | 6226080 | |
| 3/77 | 3 | 364000 | 2.16 | 786240 | |
| 6/77 | 6 | 3063000 | 2.13 | 6524190 | |
| 6/77 | 6 | 397100 | 2.13 | 845823 | |
| 7/77 | 7 | 397100 | 2.12 | 841852 | |
| 8/77 | 8 | 397100 | 2.11 | 837881 | |
| 9/77 | 9 | 397100 | 2.10 | 833910 | |
| 10/77 | 10 | 397100 | 2.09 | 829939 | |
| 1/78 | 13 | Insertion | | | |
| 12/78 | 24 | Removal | | | $2.0331 \times 10^{13}$ |
| 7/79 | 31 | 149000 | 1.88 | 280120 | |
| 10/79 | 34 | 870000 | 1.85 | 1609500 | |
| 10/79 | 34 | -4736000 | 1.85 | -8761600 | |
| | | $\sum Z_n - V_n = 4551500$ | | $\sum = 10853935$ | |

Eq. (3.16) $$i \sum_{n=n}^{B} (N-n+1) = \frac{(24-13+1)}{2} [2(1.06) - .01\ (24-13)] = 12.06$$

Eq. (3.14) $$D(n) = 1451500/(24-13+1) = 379291.67$$

Unit Fuel Cost

Eq. (3.13) $$p = \frac{10853935 - (12.06)(379391.67)}{2.033 \times 10^{13}} = \underline{30.89}\ ¢/\text{MBTU}$$

Table 4. Calculation of Unit Fuel Cost for Entire Core Extended Seven-Page Method.

$N = 118$
$A = 13$
$B = 108$
$i = .01$

| Batch # | $\sum (Z_{(n)}-V_{(n)})$ | $Z[i(N-n+1) + 1](Z_n-V_n)$ | E(n) |
|---|---|---|---|
| 1 | 4551500 | 10853935 | $2.0331 \times 10^{13}$ |
| 2 | 5912500 | 13654505 | $4.0662 \times 10^{13}$ |
| 3 | 7086500 | 15827365 | $6.0992 \times 10^{13}$ |
| 4 | 7086500 | 14976985 | $6.0992 \times 10^{13}$ |
| 5 | 7086500 | 14126605 | $6.0992 \times 10^{13}$ |
| 6 | 7086500 | 13276225 | $6.0992 \times 10^{13}$ |
| 7 | 7086500 | 12425845 | $6.0992 \times 10^{13}$ |
| 8 | 7086500 | 11575465 | $6.0992 \times 10^{13}$ |
| 9 | 5912500 | 9397505 | $4.0662 \times 10^{13}$ |
| 10 | 4551500 | 7030675 | $2.0331 \times 10^{13}$ |
| | $\sum$ 63447000 | $\sum = 123145110$ | $\sum = 4.879 \times 10^{14}$ |

Eq. (3.14) $$D(n) = 63447000/(108-13+1) = 660906.25$$

Eq. (3.16) $$i \sum_{n=A}^{B} (N-n+1) = \frac{108-13+1}{2} [.02(118-13+1) - .01\ (108-13)] = 56.16$$

Unit Fuel Cost

Eq. (3.13) $$p = \frac{123145110 - (56.16)(660906.25)}{4.879 \times 10^{14}} = \underline{17.63} \text{ ¢/MBTU}$$

contain significant round-off errors. To further demonstrate the applicability and accuracy of this procedure, a desk calculator (Tektronix Model 31) was programmed to calculate fuel cycle costs using this extended seven-page calculational method. The results obtained from this calculator are compared with the original seven-page method and three fuel cycle cost codes (GEM, CINCAS and GACOST) in Table 5.

The purpose of this discussion has been to develop a calculational procedure which compares favorably with existing calculational methods as far as accuracy is concerned, but is simple and easy to use. Table 5 illustrates the accuracy of the method by presenting three main points

1. The extended seven-page changes the original seven-page calculations only very slightly.
2. The calculational methods used by the three codes GEM, CINCAS and GACOST, do not produce identical answers.
3. The results of the extended seven-page method correspond very well with the results of the computer codes.

The simplicity of the extended seven-page is demonstrated by the fact that it can be done by hand or programmed on a desk calculator to yield the same results which required, in the case of GEM, an IBM 360, 470k of memory and more than a minute of execution time.

This procedure provides a straight-forward method for extending the seven-page method from the calculation of the cost of a single fuel batch to the levelized cost over the entire life of a core. The generalization to a series of investments and receipts allows the user complete freedom in establishing payment schedules. The procedure is limited, however, primarily by the assumption of uniform energy production and the fact that it requires a complete core history to provide meaningful levelized core costs. However, this procedure

Table 5. Comparison of Extended Seven-Page Method with Existing Calculational Methods.

Levelized Fuel Costs (¢/MBTU)

| Code<br>Batch | 7-Page | Extended<br>7-Page | CINCAS | GEM | GACOST |
|---|---|---|---|---|---|
| #1 | 31.17 | 31.14 | 31.04 | 30.72 | 30.68 |
| #2 | 19.94 | 19.98 | 19.98 | 19.85 | 19.70 |
| #3 | 15.73 | 15.78 | 15.89 | 15.81 | 15.58 |
| Case<br>Levelized | | 17.76 | 16.50 | 17.80 | 17.52 |

provides a basis for both calculating fuel cycle costs and developing more sophisticated and useful calculations.

## 3.4 References


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## 4.0 FUEL CYCLE COSTS: PERIOD CALCULATIONS

Economic analyses of costs associated with the nuclear fuel cycle have two distinct applications. In the design phase of a nuclear generating station the interaction between the economic impact of fuel composition and the corresponding efficiency of power generation must be recognized and considered. The levelized cost of fuel, for a batch and the entire core, is the appropriate parameter for evaluation of different concepts and studying effects of different processes. Once the reactor is in operation, however, the utility must have cost information that is compatible with its accounting techniques and provides the appropriate information for operational decisions concerning core replacement [1]. To accomplish these functions for a utility, a cost calculational method should have the ability to report the costs associated with a single time period (e.g., a month) even though these costs are generated by several batches in varying stages of preparation, irradiation and reprocessing. Additionally, the knowledge of how the cost of fuel changes with energy production is important in decisions relating to distribution of load changes in an electrical grid containing more than one station.

This discussion indicates that simple fuel cost calculational methods, such as the seven page method, have only a limited application in the field of utility planning and operation. Simple calculational procedures have the advantage of not requiring substantial calculational time while retaining the physical significance of the calculations and the accuracy of machine calculations. The object of this chapter is to discuss the application of the seven page method to period cost calculations and compare the results with currently available machine calculations.

## 4.1 Calculation of Period Costs

As illustrated in the extended seven page method, if the assumptions of straight line depreciation and uniform energy production are made, the levelized cost of energy for a fuel batch is given by

$$p = \frac{\sum_{n=1}^{N} [i(N-n+1) + 1][Z(n) - V(n)] - i \sum_{n=1}^{N} (N-n+1)\ D(n)}{\sum_{n=1}^{N} E(n)} , \quad (4.1)$$

where

$$i \sum_{n=1}^{N} (N-n+1)\ D(n) = D(n) \left\{ \frac{(B-A+1)}{2} [2i(N-A+1) - i(B-A)] \right\} , \quad (4.2)$$

and

$$D(n) = \sum_{n=1}^{N} [Z(n) - V(n)]/(B-A+1) , \quad (4.3)$$

and the individual terms are defined as follows:

p = unit price of energy,

n = accounting period (e.g., month),

N = number of accounting periods in batch life,

A = period batch is inserted in core,

B = period batch is removed from core,

i = period carrying charge rate,

Z(n) = investment during period n,

V(n) = receipt, other than sale of energy, during period n,

D(n) = depreciation during period n,

E(n) = energy produced during period n.

Since the number N is independent of batch lifetime, the batch calculations can be used to calculate the levelized cost for an entire reactor core.

To develop a procedure to calculate the cost during a specific period of reactor operation, it is first necessary to divide the lifetime of the core into regular periods of time (e.g., calendar years) and then calculate the total cost during each of these periods. The cost of producing energy (p) during any period of time (Z) which begins in accounting period D and ends in accounting period c is given by

$$p_Z = \frac{\sum_{n=D}^{c} i\ I(n) + \sum_{n=D}^{c} D(n)}{\sum_{n=D}^{c} E(n)} , \qquad (4.3)$$

where

$\sum_{n=D}^{c} i\ I(n)$ = indirect costs,

$\sum_{n=D}^{c} D(n)$ = direct costs,

$\sum_{n=D}^{c} E(n)$ = energy produced.

The only restriction on the time period is that all periods be of the same length (or the same number of accounting periods) except for the first and last time periods, which may be shorter. This in effect superimposes on the reactor history a sequence of uniform time periods, but does not restrict the start or end of the history to the start or end of a time period.

Consider first a single batch of fuel. Again the assumption of straight line depreciation is applied and the depreciation during each accounting period the reactor produces energy is given by Eq. (4.3) where

$$\overline{D} = D(n) . \qquad (4.4)$$

If E is designated as the first accounting period in the time period Z during which the fuel produces energy (requiring that $D \leq E \leq c$) and F is the last, the total direct costs are

$$\sum_{n=D}^{c} D(n) = (F-E+1)\,\overline{D}\,. \tag{4.5}$$

Since

$$I(c) = I(c-1) + V(c) + Z(c) - D(c)\,, \tag{4.6}$$

$$\sum_{n=D}^{c} i\,I(n) = i(c-D+1)\,I\,(D-1) + \sum_{n=D}^{c} [c-n+1][Z(n) - V(n) - D(n)]. \tag{4.7}$$

From Eqs. (4.4), (4.5) and (4.7),

$$P_Z = \frac{\overline{D}\left\{[F-E+1] - i\sum_{n=E}^{c}[c-n+1]\right\} + i(c-D+1)\,I\,(D-1) + i\sum_{n=D}^{c}(c-n+1)[Z(n)-V(n)]}{\sum_{n=D}^{c} E(n)} \tag{4.8}$$

where

$$I(D-1) = \sum_{n=1}^{D-1} (Z(n) - V(n)) - (D-1-A)\,\overline{D}. \tag{4.9}$$

Equation (4.8) is very similar to Eq. (4.1) in that it requires a single calculation for 1) each investment or receipt during the time period, 2) depreciation, and 3) energy production. There is, in addition, a calculation associated with the investment at the beginning of the time period, I(D-1). The procedure used to calculate a period cost is similar to that used to calculate a levelized cost. First, from the definition of the sum of an arithmetic series,

$$i\sum_{n=E}^{F}(c-n+1) = \frac{(F-E+1)}{2}\,[2i(c-E+1) - i(F-E)]\,. \tag{4.10}$$

Therefore, the total unit cost is calculated in the manner:

1. Tabulate Z(n), V(n), E(n), and divide this table into the desired time periods.

2. Calculate $\sum$ (Z(n) - V(n)) [i(c-n+1)], $\sum$ E(n), and I (D-1) for each time period.

3. Use $\overline{D}$ calculated from Eq. (4.3), Eq. (4.10), and with Eq. (4.9) calculate p for each period.

## 4.2 Application

The most immediate consequence of calculating period costs is the substantial increase in the amount of calculational effort involved. In addition to performing the calculations associated with total costs, it is necessary to perform additional calculations in each time period. This becomes very substantial if, for instance, the period is a month and the batch history extends over several years. There is also a corresponding increase in the amount of storage space required if the calculations are to be done by machine. These increases negate a primary advantage of the simple calculational procedures.

However, by limiting the length of the reactor history to 30 years, it was possible to program a desk calculator, the Tektronix Model 31, to perform these calculations. Two types of calculations were performed. In the first, yearly costs for three single batches of varying lengths were calculated and then compared with identical calculations performed with an existing fuel cycle cost code, GEM [2]. The results of these calculations are shown in Table 6. These results show a very good correlation, as expected, since GEM also uses straight line depreciation in single batch calculations. The slight differences are accounted for by the use of continuous discounting in GEM as opposed to the discrete method developed by the seven page method.

In the second calculation, period costs were calculated for a three region core with a ten year, ten batch history and compared with identical calculations done with computer codes GEM, CINCAS [3] and GACOST [4]. The results are shown in Table 7 and Fig. 6. These results illustrate that there is reasonable correlation among the computer codes, but the seven-page calculations follow

Table 6. Yearly Levelized Costs (¢/MBTU) for Single Fuel Batches of Different In-Core Time Periods.

| | | GEM | 7-Page |
|---|---|---|---|
| Batch #1 (1 yr.) | 1978 | 25.74 | 25.84 |
| Batch #2 (2 yr.) | 1978 | 18.33 | 18.47 |
| | 1979 | 16.67 | 16.73 |
| Batch #3 (3 yrs.) | 1978 | 15.58 | 15.78 |
| | 1979 | 14.26 | 14.38 |
| | 1980 | 12.94 | 12.98 |

Table 7. Yearly Levelized Fuel Costs (¢/MBTU) for a Ten Year Core History

| | Extended 7-Page | GACOST | GEM | CINCAS |
|---|---|---|---|---|
| 1977 | 0 | 0 | 0 | 0 |
| 1978 | 18.17 | 22.67 | 20.95 | 23.45 |
| 1979 | 18.06 | 17.11 | 17.10 | 17.60 |
| 1980 | 17.47 | 15.58 | 15.66 | 16.00 |
| 1981 | 17.13 | 15.58 | 15.49 | 16.00 |
| 1982 | 16.96 | 15.58 | 15.49 | 16.00 |
| 1983 | 16.79 | 15.56 | 15.49 | 16.00 |
| 1984 | 16.63 | 16.80 | 16.40 | 17.23 |
| 1985 | 15.33 | 21.30 | 18.61 | 21.78 |
| 1986 | 0 | 0 | 0 | 0 |
| Case | 17.76 | 17.52 | 17.80 | 17.91 |

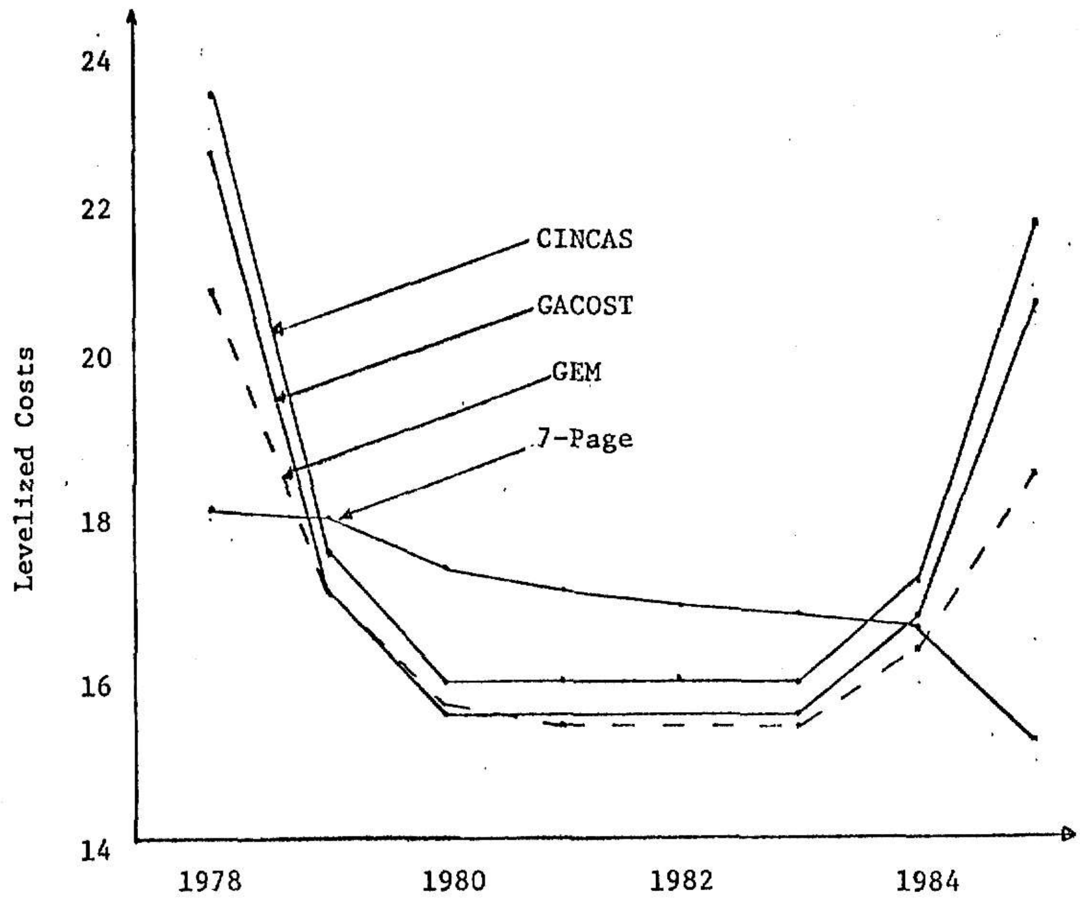


Figure 6. Yearly Levelized Fuel Costs (¢/MBTU) for a Ten Year Core History.

a completely different trend. This aberration is a direct consequence of the assumption of straight line depreciation. This can be illustrated by considering the three batches given in Table 6. These are the same batches which comprise the initial core of the sample reactor. The primary reason for the large difference in costs for the first year is that a substantial cost (primarily fabrication) must be depreciated over a shorter period of time, leading to a higher cost for shorter batches. Therefore, the computer codes, which calculate the core period costs directly from the batch period costs, exhibit behavior determined primarily by batch depreciation. Seven-page, however, which uses a constant depreciation, exhibits a behavior determined by the carrying charges on a declining capital investment.

## 4.3 Discussion

Calculation of period costs for nuclear fuel has about it an amorphous aura which is unusual even in a field characterized by assumptions and lack of standardization. This is caused by the arbitrary nature of two major aspects of these calculations: choice of accounting period and treatment of out-of-core costs. The first of these, choice of accounting period, involves primarily selection of the length and start time of the period. The selection is generally dictated by the needs of the user, but variations in the accounting period can cause drastic differences in the behavior of period costs. This is especially true of individual batches, which are relatively short lived. Figure 7 shows this difference by plotting period cost for the same batch using in the one case the calendar year and in the other the fiscal year as the accounting period.

Since nuclear fuel costs are generally reported per unit energy produced, a special procedure must be developed to treat those costs incurred when no

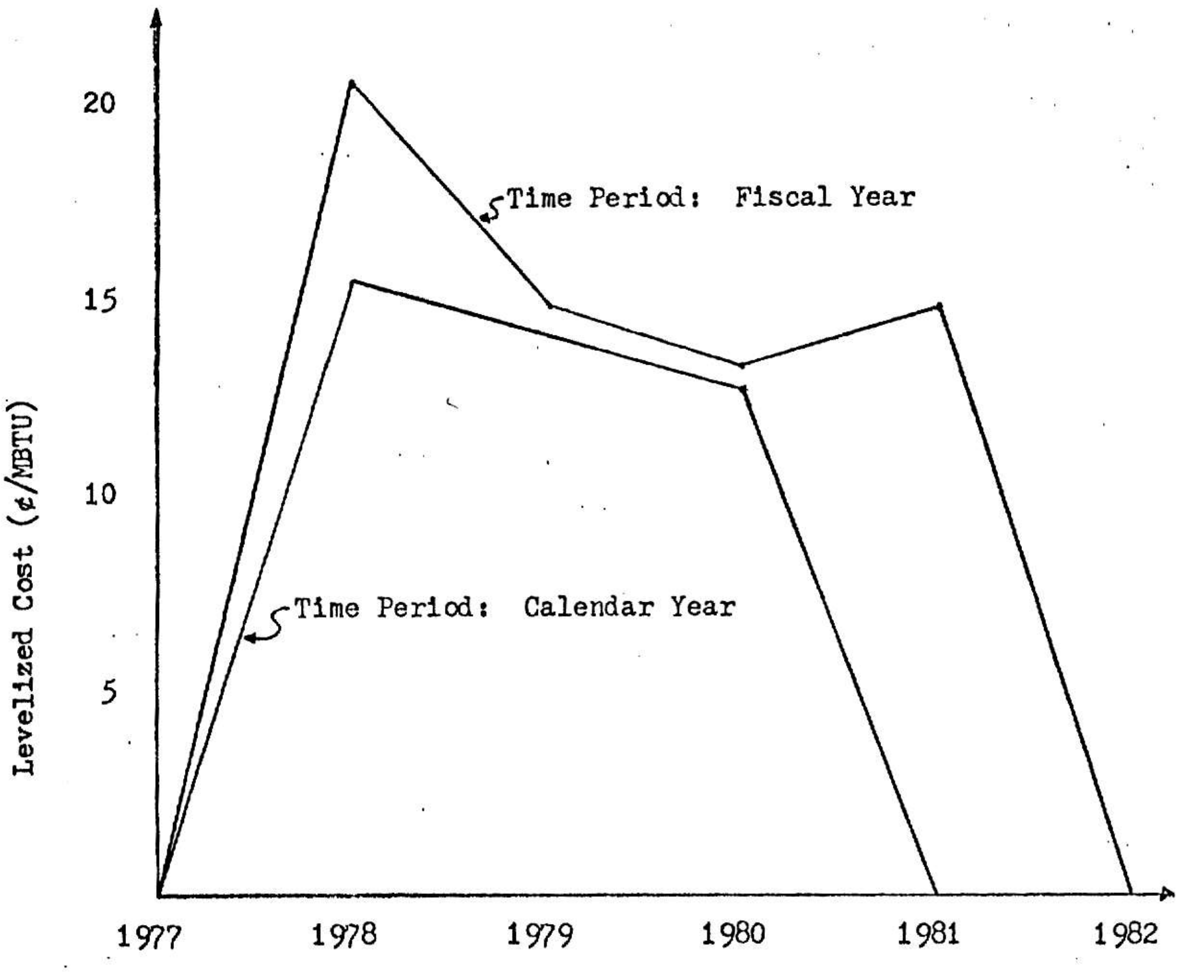


Figure 7. Comparison of Levelized Period Costs for Different Accounting Periods.

energy is produced. There are several ways of doing this. Since most calculations are performed on a batch basis, it is logical to distribute out-of-core costs over those periods when the batch is producing energy. Unfortunately, this will provide an inaccurate distribution of period costs, especially if payments are irregular and occur several accounting periods before or after in-core residence. The other approach to the problem is to look at the reactor as a whole and consider separately energy production and costs. This will produce a realistic picture of the period costs, with the exception of those costs incurred before startup and after shutdown. These can be calculated and then amortized over the life of the reactor. This quickly becomes an insignificant figure, however, so it is usually ignored. The final product is a procedure which is most accurate only after the reactor has been operational for some time and until an unspecified time prior to decommissioning.

In spite of the very arbitrary nature of period calculations, they serve a necessary purpose in utility operational planning. It is obvious that simplified calculational procedure lose their effectiveness when applied to these calculations because of the substantial increase in calculational and storage requirements and because of the unrealistic results produced by the assumption of straight-line depreciation. Therefore, levelized period costs are more efficiently calculated using standard calculational procedures and computer codes.

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## 5.0 FUEL CYCLE COSTS: COMPUTERIZED CALCULATIONS

Computation of the cost of nuclear fuel presents a series of problems which are ideally suited for solution on a digital computer. Computers are especially helpful when computations are numerous and repetitive. A brief overview of the fuel cycle for a reactor will point out those areas particularly suited for computerization.

Nuclear fuel must be mined, milled, enriched, and fabricated into a form suitable for insertion into the reactor. This process may take years and involve several different companies. Once inserted in the reactor, the fuel produces energy by changing its isotopic composition. This production process is generally not uniform and usually covers a period of 3 to 5 years. Once removed from the reactor, the fuel still contains a significant amount of fissile (and valuable) material. This material is recovered through a process which includes storage, shipping, reprocessing, and reconversion. The requirement of procuring the fuel a significant time prior to energy production and sale introduces a substantial cost associated with the capital being used during this time. It must also be recognized that not all of the fuel will be of the same isotopic composition or will remain in the reactor for the same length of time. Finally, inflation has made the cost of goods, services, and money time dependent; therefore, in order to be of use in planning, an economic analysis must be independent of time.

Just how can this maze of calculations be handled adequately by a computer? One way is to isolate those types of calculations which are related in such a way that they can be made into a repetitive procedure. The calculations associated with the nuclear fuel cycle have been broken into the four categories:

1. Cash Flow. Each gram of fuel has associated with it certain costs which must be paid. These include items such as the cost of ore, enriching, fabrication, shipping, and reprocessing. Additionally, there is a return received from the sale of the reprocessed uranium and plutonium. Each of these items which contributes to the value of the fuel is called a cost component. Each component will have associated with it a separate computational procedure to be used to calculate the actual value of the cash flow. The fact that the procedure differs for each component does not lend these calculations easily to computerization. However, if the same procedures are applicable to a large amount of fuel, computerization becomes attractive. Additionally, inflation can be handled easily by a computer if inflation is assumed to follow a regular pattern. Finally, and most importantly, these calculations provide a required basis for the remaining calculations.

2. Direct Costs. When fuel is inserted in the reactor, it is worth a definite amount of money. When it is removed, it still has some monetary worth. The difference between the initial and final value of the fuel is the actual or direct cost of the fuel. The problem is when, during the fuel's residence in the core, is this cost incurred. This question is very important when considering the indirect costs discussed below. By applying an appropriate depreciation procedure, a computer can be used to inventory the time dependent direct costs for a great number of different fuel elements and maintain a time dependent direct costs for the entire reactor core.

3. Indirect Costs. The money invested in nuclear fuel must be obtained from some source (e.g., sale of stocks and bonds, borrowing, or internal funds) and then tied-up for a period which may be as long as 10 years. The use of this money has a price, whether it is in dividends, interest, or a lost opportunity cost, and it is too substantial to be ignored. To calculate these costs, it

is necessary to use the details of both the cash flows and direct costs to maintain a current investment total.

4. Levelized Costs. When working with alternate courses of action, as in most fuel cycle economic analyses, it is convenient to have a single figure of merit for comparison. It does not matter if you are comparing one year with another or with the entire history: one fuel type with another or the entire core. In fuel cycle analysis this figure of merit is generally the unit price of energy, or the levelized cost, of the fuel in mills/kwhe (or ¢/MBTU). To calculate this levelized cost, it is necessary to apply present worth methodology to the direct and indirect costs and the energy production.

Isolation of the calculations associated with nuclear fuel indicates two important aspects of computerization of these calculations. First, a large amount of input is required to detail the economic and energy production history of each gram of fuel. This input can be reduced significantly by treating fuel in batches which have identical histories. But still, it is necessary to generate a detailed accounting of cash flows, mass flows, and energy production over the entire life of the reactor. The second aspect is that once the computer has this information, it can perform an enormous number of calculations to provide a very detailed economic analysis, which is necessary for sound decision making.

In the task of comparing computer codes designed to calculate nuclear fuel costs, we must address the manner in which each code performs the calculations indicated above. From this comparison, a judgment as to the most acceptable code can be made. But a comparison of this type must also address the question of convenience, e.g., which code is the easiest to use, which is the most flexible, or which code provides the most pertinent data. In the following, the computer codes CINCAS, GEM, and GACOST will be evaluated.

5.1 Calculational Procedures

The introductory discussion leaves the impression that there are four consecutive steps in the calculation of nuclear fuel costs. This is not true. There are four types of calculations, but generally they are not done discretely. The levelized cost calculation is actually the most important from a practical point of view, since the results are used in economic decisions. In fact, the method used for levelized costs is the primary theoretical difference between codes. For this reason, the computational procedures used for the first three types of calculations are usually geared toward facilitating the calculation of levelized costs. Present worth methodology is often applied to cash flows prior to computation of direct or indirect costs, and the method of computing indirect costs is dependent on the method of levelizing costs. Therefore a discussion o a particular calculation must include its interrelation with the other types of calculations.

When considering the life history of nuclear fuel, it is apparent that it is divided into three distinct phases: 1) the period of preparation prior to insertion into the reactor core, 2) the period during which the fuel is in the reactor and produces energy, and 3) the period after the fuel is removed from the reactor and during which it undergoes reprocessing. For convenience, these three phases are denoted the preburn, burn and postburn periods. A typical investment-time diagram is shown in Fig. 8. The primary requirement in the levelized cost calculation is the determination of the cost per unit energy as a function of time. Since there is no energy produced during the pre- and postburn periods, this calculation is possible only during the burn period. Therefore a method must be devised to account for those indirect costs incurred during the out-of-core history of the fuel. The method of handling these costs introduces another major difference in the codes.

Before proceeding with actual comparison of codes a note about terminology: the handling of nuclear fuel is much more efficient if it can be assumed that a large amount of fuel undergoes exactly the same preparation, burnup, and reprocessing. This is a reasonable assumption since fuel is normally fabricated into fuel elements which are treated as integral units throughout the fuel cycle. The isotopic change even within a single fuel element will not be uniform. However, use of appropriate average values can make the calculations as accurate as required. For the purpose of this work, any specified amount of fuel, whether it is a single pellet or a number of fuel elements, which has a specified history, is called a batch. Batch is used in this context in GEM and CINCAS, and is identical to the segment defined by GACOST. All these codes use the batch concept as the basis for computations. In the following I will discuss specifically how each code handles each type of calculation. Options are discussed only where they highlight the differences in procedures. Details of options are discussed in the section on code utility. Results, where presented, refer to the sample problem in Appendix A.

## 5.2 Cash Flow

The purpose of this type of calculation is to convert contractual and design data into a time schedule of investments and receipts. Contractual data are usually in the form of prices and payment schedules while the design data include feed requirements and burnup data. The initial step is to identify those specific processes which contribute to these cash flows. This is not a difficult problem since the industry for the front end of the fuel cycle is well established. In Table 8 the cost components calculated by each code are shown. Since the GACOST depletion includes the change in value of uranium and plutonium, the front end components are identical. In the back of the cycle, however, GACOST does not

Table 8. Fuel Cycle Cost Components

| CINCAS | GEM | GACOST |
|---|---|---|
| Uranium | Uranium | Fabrication |
| Plutonium | Plutonium | Depletion |
| Fabrication | Fabrication | Shipping |
| Shipping | Shipping | Storage |
| Reprocessing | Reprocessing | Reprocessing |
| Reconversion | Reconversion | |

perform a separate calculation for reconversion of uraynal nitrate to uranium hexafloride, but does include an additional calculation for the storage of spent fuel prior to reprocessing.

The calculation of these values is fairly simple, since prices are inputed in \$/kg. The only problem arises in working from the weight of fabricated uranium back to the amount of $U_3O_8$ or $UF_6$ needed to obtain this weight. A comparison of the major components is shown in Table 9. There is not an exact agreement because of basic differences in input-output procedures. But even with these differences the actual values are very close.

## 5.3 Direct Costs

Computation of the direct costs of nuclear fuel involves two distinct problems: determination of the total direct cost and determination of its distribution in time. At this point, the concept of cost components can greatly simplify the maze of calculations required if it is recognized that for any particular accounting period (N) the total direct cost is the sum of the direct costs for each cost component, or

$$(\text{direct cost})_N = \sum_i (\text{component}_i \text{ direct cost}_N) \quad . \qquad (5.1)$$

The value of this approach becomes obvious when it is realized that over the burn period the following costs must be accounted for:

1. decrease in uranium value,
2. decrease in fabrication value,
3. increase in plutonium value,
4. postburn expenses.

Now the problem is to determine the direct cost associated with each cost component and allocate it to the proper accounting period.

Table 9. Calculated Values of Cost Components, Batch 83C of Sample Problem. ($)

| | CINCAS | GEM | GACOST |
|---|---|---|---|
| Uranium | 12509055 | 12510178 | 12526000 |
| Plutonium | 1860007 | 1859961 | 1860000 |
| Fabrication | 2482000 | 2482000 | 2482000 |
| Shipping | 595501 | 595500 | 599135 |
| Reprocessing | 3334806 | 3334800 | 3476282 |
| Reconversion | 119100 | 113825 | |

Direct costs are defined as the difference between initial and final value, i.e., the difference in value from the beginning to end of the burn period. This is true of each cost component, also. As illustrated in Table 9, there is little difference among the codes in calculation of the magnitude of cost components. The most difficult problem is the distribution of these direct costs over the burn period of the reactor.

Since the primary result of this calculation will be the cost per unit energy, it is most logical to distribute the cost in the same manner in which energy production is distributed over the burn period. To do this exactly would be nearly impossible because a reactor undergoes daily load changes. However, it is often possible to approximate the reactor output by a constant power level for some period of time. The batch burn period can then be decomposed into a series of "burnup" periods during which the rate of burnup is constant. It is possible from these data to calculate the energy produced during each time period, and to allocate costs to each time period according to the fraction of total energy produced. In other words,

$$C_k = \frac{C\, q_k}{Q} \quad , \qquad (5.2)$$

where:

C = total direct cost of a cost component,

$C_k$ = amount of direct cost allocated to time period k,

$q_k$ = energy produced during time period k,

Q = total energy produced by the batch.

When determining the number and length of burnup periods, the unit of time which the code uses for its calculations, or the accounting period length, is the primary limitation. Each burn period must be a multiple of this accounting period. Each of the codes handles this situation differently. In CINCAS the period is set at one month. In GEM, all accounting is done on a continuous basis, so a burnup period can be of any length. In GACOST, the accounting period is taken as the reload interval, or the time between the insertion of fresh fuel batches into the reactor. The difference in selection of accounting period is due to the method used for calculating levelized costs. The method used by GEM is sensitive to the time distribution of money, while in GACOST the emphasis is on the distribution of energy. These concepts will be discussed below.

## 5.4 Indirect Costs

One of the primary differences between the nuclear and fossil fuel cycles is the very long economic history of nuclear fuel. Fossil fuel is used essentially as soon as it is procurred. Nuclear fuel of appreciable value may remain in the possession of a utility for several years. Therefore there is a substantial cost associated with the monies used to procure this fuel. In fact, it is assumed that the entire investment value of the fuel is borrowed capital and has associated with it an indirect cost, either in the form of bond interest, dividends, or lost opportunity costs. Methods of dealing with these costs form major differences in computer codes for economic analysis.

The first step in determining indirect costs (often called inventory costs) is to determine the rate (per dollar invested per unit time) at which this cost will be assessed. There are two basic approaches to this. The first is to review historical data and from this obtain a representative rate. This is not a difficult task in an operating utility. The accounting department of the utility will be able, from its constant dealing with financial matters, to produce a fairly accurate "cost of money". The other approach is espoused by the NRC [1]. A detailed cash flow analysis which takes into account the capital structure of the utility, differences in bond interest and dividend rates, and applicable taxes, will produce a discount rate. This discount rate is often interpreted as the cost of money adjusted for taxes (e.g., the discounted cash flow method of Vondy [2]). It also should be noted that the discount rate is strictly applicable only in the cash flow analysis for which it was derived.

Since the final characterization of fuel costs is on a per unit energy basis, some method has to be established for dealing with those costs incurred when no energy is produced, i.e., during the pre- and postburn periods. Since direct costs are distributed over the burn period, only indirect costs are incurred during the rest of the cycle. The basic philosophy of all the codes in dealing with this problem is that the out-of-core indirect costs incurred during pre- and postburn periods should be distributed over the burn period in the same manner as direct costs, in proportion to the energy production. However, the method for determining these indirect costs differ, at least theoretically. CINCAS takes the simplest approach. It offers the option of simple interest or compound interest. GEM, however, uses the discount technique of Vondy adapted to accept non-zero salvage value [3]. GACOST, on the other hand, computes the preburn indirect costs of a payment as the difference between the actual value of the payment and its present worth at reactor startup. The three equations are shown in Table 10 as they are presented in the code manuals. (NOTE: Definitions of symbols are in the appendix which pertains to the appropriate code). The interesting thing about these formulas is that, in the end, they are identical, (NOTE: The only exception is that the cash flow analysis of GEM corrects an investment for income taxes with the factor $(1-R)^{-1}$.), to the general form indicated in Table 10. Thus the theory behind these codes is different, but the final calculations are often identical.

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Table 10. Formulas for Calculation of Preburn Period Indirect Costs

| | |
|---|---|
| CINCAS (Interest on Progress Payments) | $\Delta = \sum_{I=1}^{NPP} \left[ (1+RP)^{M(I)} - 1 \right] * P(I)$ |
| GEM (Inventory Charges) | $CP_k = P_\infty \, AI_k \sum_{i=1}^{n_k} \left[ f1_{i,k} * ((1+X)^{d_i} - 1)/X \right]$ |
| GACOST (Preirradiation Working Capital Expense) | $PRW = EXPMX * \left[ \sum_{j=1}^{J} X_j * PWF(I_{pre.} - TPAY_j) - \sum_{j=1}^{J} X_j \right]$ |
| GENERAL FORM (Preburn Indirect Costs) | $Cost = \sum_{n=1}^{N} Payment_n \left( (1+i)^{t_n} - 1 \right)$ |

where: N = total number of progress payments
i = interest rate
$t_n$ = time prior to start up that payment is made

The postburn period represents a different problem because it involves more than a simple series of payments and receipts. In particular, during reprocessing money is invested in the fuel, increasing its value. It is necessary to model this investment process to compute indirect costs properly. In CINCAS and GACOST, a linear increase in value over the reprocessing period is assumed. This is equivalent to assuming that the entire investment occurs at the midpoint of the period. CINCAS differs substantially from the other codes at this point, however, by computing a simple interest as the indirect cost. GACOST calculates the indirect cost as the difference between the actual payment and its present worth at shutdown (equivalent to compound interest). GEM avoids the problem of reprocessing altogether by considering only the postburn payment schedule discounted to shutdown. The formulas used by the codes for this calculation are shown in Table 11. Note that GEM immediately discounts the indirect costs to startup.

There is, in addition to preburn and postburn indirect costs, a charge associated with the value of the fuel during the burn period. A basic approach to this problem is direct and simple. It is necessary only to determine the average value of the fuel during any accounting period, multiply it by the cost of money and then charge the indirect cost to that accounting period. This, in fact, is the procedure followed by CINCAS. GACOST, however, uses a different method which in effect charges compound interest. This method considers the value of the fuel at the beginning and end of the reload interval. It takes the difference between these two values present worthed to the midpoint of the interval. This difference is the sum of the direct costs and the indirect costs. GEM calculates the direct plus indirect costs by discounting the final value of the investment to startup. Both the distribution of the investment and the discounting are continuous. The difference between the discounted

Table 11. Formulas for Calculation of Postburn Period Indirect Costs

| | |
|---|---|
| CINCAS (Post Irradiation Inventory) | $POST(J) = ROFF * \Delta\theta_J^F \left(YF^3 * W_N^U * V_N^U + YF4 * W_N^{Pu} * V^{Pu} - W_N^U * (CSHIP + CREP + YF3*CREC)\right) * (NMSTO + NMREP + NMSA) + CSHIP*W_N^U*(NMREP + NMSA) + CREP*W_N^U*(NMREP/2 + NMSA)$ |
| GEM (Postburn Inventory Charges) | $CPO_k = P_\infty AF_k \sum_{i=1}^{m_k} \left\{ f2_{i,k} \left( \frac{1 - (1+X)^{-(S_{i,k}-t_n)}}{X(1+X)^{t_n-t_o}} \right) \right\}$ |
| GACOST (Post Irradiation Working Capital Expense) | $POSTWC = VTOT * \left(1.0 - PWF(I_{post},TCOOL) * PWF(I',TBYB)\right)$ |

investment and actual investment constitutes the sum of direct and indirect costs. Table 12 shows the equations used by each of the codes for calculations during the burn period. As discussed above, GEM and GACOST calculate the direct and indirect costs simultaneously while CINCAS uses two separate calculations.

5.5 Levelized Costs

The above discussion has alluded to the calculation of levelized cost as an overiding consideration in the development of calculational methods. Consequently the discussion in this section is very limited, since it constitutes only one calculation. Table 13 shows the formulas used for levelized cost calculations. The major variables in these equations involve costs ($/month, C(t), FCR). They are calculated directly from equations of the form illustrated in Tables 10, 11, and 12. The other factors are concerned with present worth (or discounting) and energy production, both of which are determined from code input. The calculation, then follows directly.

It is appropriate here to delineate the basic theoretical differences in the codes. There are two basic philosophies. The first applies to the discounted worth of money. This method is the ratio of the present worth of all cash flows over the levelizing period to the present worth of all energy produced over the levelizing period. This technique is used by both CINCAS and GEM. The major differences between these codes is the method of accounting for indirect costs. CINCAS uses discrete discounting, with the accounting period set at one month, while GEM uses continuous discounting.

The other method, used in GACOST, is called the "discounted energy cost" method. The difference between this method and discounted cash flow is that it initially calculates the cost in each accounting period per unit energy rather

Table 12. Formulas Used for Burn Period Cost Calculations

| | |
|---|---|
| CINCAS: | |
| Indirect Costs | $URIN(J) = RON * W - \theta_J^{MF} * \left(G * W_N^U * (CSHIP + CREP) + YF3*CREC*W_N^U\right)$ |
| | where: $W = W_O^U * V_O^U + \Delta_U + \theta_J^{MF} * \left(W_O^F*V_O^F - YF3*W_N^F*V_N^F\right)$ |
| | $G = W_O^U * V_N^U/(W_N^U*V_N^U + W_N^{Pu}*V^{Pu})$ |
| Direct Costs | $UEX(J) = (W_O^U + V_O^U - YF3*W_N^U*V_N^U + \Delta_U) * \theta_J^F$ |
| GEM | $CB_k = \frac{AF_k}{1-R}(1 - \exp(-rt_{n,o})) + (AI_k - AF_k)$ |
| | $* \left(1 - \frac{R}{1-R} * \sum_{i=1}^{n} \left\{\frac{Q_i}{Q_t}\left(\frac{\exp(rt_{i,i-1}) - 1}{rt_{i,i-1}}\right)\exp(rt_{o,i})\right\}\right)$ |
| GACOST | $FC(s,n) = \sum_{j=1}^{J}\left(\frac{P_i * PWF(I_{ic},\ell_n/2) - P_f * PWF(I_{ic},\ell_n/2)}{E(s,n)}\right)$ |

Table 13. Formulas for Calculation of Levelized Fuel Costs

| | |
|---|---|
| CINCAS | $P = \dfrac{\sum_{j=1}^{N} (\$/\text{month})_j * P(MD_j)}{\sum_{j=1}^{N} KWHE_j * P(MD_j)}$ |
| GEM | $C'(T_n) = \dfrac{\int_{T_n} dt\ C(t)\ e^{r(\eta-t)}}{\int_{T_n} dt\ P(t)\ e^{r(\eta-t)}}$ |
| GACOST | $FCC = \dfrac{\sum_{n=1}^{L} FCR(n) * E(n) * PWF(I_p,T_n)}{\sum_{n=1}^{L} E(n) * PWF(I_p,T_n)}$ |

than calculating initially a cash flow sequence. This unit energy is then discounted to obtain a levelized cost. This method superficially does not seem to differ from the discounted cash flow method except in the order in which the calculations are performed.

5.6 Code Utility

In the final analysis, the quality of a code must be judged not only on its theoretical basis and its calculational procedures, but also on its ability to communicate with the user. A code which does not generate understandable and useful results has little practical value. But the concept of communication involves more than the printed output. It includes the preparation by the user of the input which accurately specifies the problem and identification by the code of obvious inconsistancies in the input. Comparison of codes should then be based on two functions, input and output. The many options provided by each code usually affect the type of input and output rather than the calculations done by the code. In fact, most options are provided to allow the user simpler methods to model his particular problem. The following discussion then, will address the input and output procedures directly and include in this discussion the options provided by each code.

When the batch concept is used in fuel cycle cost calculations, each cost component calculated by a computer code is calculated initially for each batch. This idea may be approached from a different point of view. In each batch analyzed, the code initially performs calculations for each cost component. In other words, the distinction between batch costs as a function of cost components and component costs as a function of fuel batches depends primarily on which one you are interested in. Since both are calculated by the codes, this distinction is of little consequence to the user. It forms, however, a basic difference in the input/output procedures in different codes. Should input data be organized such that you input all component data for each batch, or should you input all batch data for each component? Generally, CINCAS and GEM input data on a batch basis, whereas GACOST uses the component concept. Each has its advantages, as discussed below.

5.7 Input

Specification of a fuel cycle problem by a code user involves the inputing as a function of time of three groups of parameters: economic data, mass flow data, and cash flow data. Economic data involves the price of each activity which contributes to nuclear fuel costs (yellowcake, fabrication, reprocessing, etc.) and the data necessary to calculate the magnitude of these activities (losses and penalties associated with each activity) and the capital charges (carrying charge rate, income tax rate, etc.). The mass flow data delineates the change in the isotopic composition of the fuel while it resides in the core. Cash flow data specifies the particular time when payment is to be made for cost components (ore, enriching, reprocessing, etc.). A summary of the major parameters which must be inputed as a function of time is shown in Table 14. Since there are more than thirty parameters listed in this table and considering that each is a function of time, it is obvious that the preparation of input data is a formidable job.

To simplify this preparation, it is necessary to find a common denominator among the parameters other than time. There are two obvious ones, the fuel batch and the fuel cost component. The batch concept is attractive because the number of batches is limited (usually less than 50). If you can standardizethe the mass flow data for several batches (equilibrium batch), the only variables

Table 14. Major Computer Code Input Parameters

| | |
|---|---|
| **Economic Data** | |
| $U_3O_8$ | Carrying charge |
| Conversion | Income tax |
| Enriching | Dividend rate |
| Fabrication | Bond interest rate |
| Plutonium | Bond to total debt ratio |
| Reprocessing | Losses |
| Reconversion | Penalties for $U^{236}$ and $U^{232}$ |
| Storage | Escalation rates |
| Shipping | |
| **Mass Flow Data** | |
| Initial isotopic composition | |
| Final isotopic composition | |
| Capacity factor | |
| Power level | |
| Efficiency | |
| **Cash Flow Data** | |
| Insertion and removal date of fuel | |
| $U_3O_8$ payments | |
| Conversion payments | |
| Enriching payments | |
| Fabrication payments | |
| Storage payments | |
| Reprocessing payments | |
| Reconversion payments | |
| Shipping payments | |
| Spent U and Pu receipts | |

remaining are those associated with costs. And, if these costs are assumed constant, the input data simply consists of the initiation of all the parameters and then a schedule of batch residence times. This, indeed, is the procedure used by both CINCAS and GEM. Table 15 shows a list of the cards used by GEM. After initiation of a case, the code reads a set of cards for each batch. Only the first batch must contain all types of cards. Subsequent batches need only have an ID card to designate in-core residence time. The code automatically uses all other data from the previous batch. It should be noted, however, that any data can be changed with each batch.

The selection of cost components as the common denominator does not seem to have the simplifying advantage of the batch concept. But, as illustrated in Table 14, the number of cost components, and even the number of necessary input parameters, is limited to a specific number, regardless of the size of the reactor history (and number of batches) involved in a particular problem. If the actual operating procedure of a utility is considered, the cost component basis for input is more logical than the batch basis. This is because most input parameters are determined independently. For example, design considerations determine what the isotopic composition of all batches must be. The parameters associated with fabrication, however, are determined through negotiations with private corporations which are independent of design procedures. The same applies to each major cost component. The grouping of input into the cost component categories then more nearly models utility operating procedures.

The operation of the batch basis input was direct and simple: designate the number of batches and read a set of input data for each batch. In the component basis, however, the situation is not so simple. Table 16 lists the cards which must be inputed into GACOST. There are many more kinds of cards than are needed in GEM. This would tend to leave the impression that prepara-

Table 15. Carde Type Description, GEM

| | |
|---|---|
| | Control Cards |
| a | BWR |
| b | INPT |
| c | END |
| | Case Data Cards |
| A | Case Identification |
| B | Case Dates |
| C | Case Description |
| D | Case Output Options |
| | Batch Data Cards |
| ID | Batch Identification |
| 1 | Uranium Prices |
| 2 | Fabrication and Service Costs |
| 3 | Feed Losses |
| 4 | Plutonium Prices |
| 5 | Fuel Weights |
| 6 | Number of Enrichment Types and Energy Time Steps |
| 7 | Uranium Enrichment Data |
| 8 | Energy Production |
| 9 | Economic Parameters |
| 10 | Batch Output Option |
| 11 (Optional) | Prepayment Schedule |
| 12 (Optional) | Frontend Package Prepayment Schedule |
| 13 (Optional) | Plutonium Storage Information |
| 14 (Optional) | Postburn Sale/Transfer/Charge Schedule |
| 15 (Optional) | "Rear-end Package" Sale/Charge Schedule |
| 16 (Optional) | Escalation Information |

Table 16. Card Type Description, GACOST

| Type | Description |
|---|---|
| Title 1 | Title |
| Title 2 | Title |
| 1 | Option Selection |
| 2 | Option Selection |
| 3 | Energy Production |
| 4 | Interest Rates |
| 5 | Output Options |
| 6 | Region Volume Fractions |
| 7 | Reload Sequence |
| 8 | Preworking Capital add on |
| 9A | Number Progress Payments, Ore |
| 9B | Time of Progress Payments |
| 9C | Fraction of Total Purchase/Payment |
| 10A | Conversion |
| 10B | |
| 10C | |
| 11A | Enriching |
| 11B | |
| 11C | |
| 12A | Fabrication |
| 12B | |
| 12C | |
| 13A | Recycle U and Pu |
| 13B | |
| 13C | |
| 14A | Post Irradiation Time Intervals |
| 14B | |
| 15A | Capacity Factor/reload Interval |
| 15B | Capacity Factor/year |
| 15C | |
| 16 | Full Power Days/reload Interval |

Table 16. (Continued)

| | |
|---|---|
| 17A | Fabrication Costs/Year |
| 17B | |
| 17C | |
| 18A | Shipping Costs/Year |
| 18B | |
| 18C | |
| 19A | Enrichment, Ore, Conversion Costs/year |
| 19B | |
| 20A | Segments With Recycled Fuel |
| 20B | |
| 21A | Losses/Segment |
| 21B | |
| 22A | Optional Penalty Application/Fuel Type |
| 22B | |
| 23A | $U^{232}$ Penalty Table |
| 23B | |
| 24A | $U^{236}$ Penalty Table |
| 24B | |
| 24C | Fuel Dilution Factors |
| 24D | |
| E-1 | Escalation Options |
| E-2 | Escalation Time Period |
| E-3 | Method of Escalation |
| E-3A | Rate of Price Increase (Labor & Materials) |
| E-3B | |
| E-3C | Base Price |
| E-4 | Escalation Factor |
| E-5 | Base Year |
| E-6 | End Year |
| 25A | Initial Region Weights |
| 25B | |
| 25C | |
| 25D | |
| 25E | Final Region Weights |
| 26A | Fuel Value/segment |
| 26B | |
| 27A | Energy Produced/segment |
| 27B | |
| T-1 - T-10B | Fabrication Learning Curve Input |

tion of input for GACOST is correspondingly more difficult. This is true, but this increase in difficulty is not substantial if a general procedure is recognized. Additionally, the use of this type of input allows GACOST to offer a large number of options without undue proliferation of input data.

A general procedure used by GACOST applies to all input parameters. As an illustrative example, the input of cash flow data pertaining to fuel fabrication will be used. The steps are four in number:

1. Card 1. Designate parameter which invokes the option (NPROP) and indicate limiting number (in this case number of batches),
2. Card 12A. Indicate applicable batch numbers and the number of prepayments,
3. Card 12B and 12C. Designate for each prepayment the fraction of total paid and the time prior to batch insertion,
4. Repeat 2 and 3 until the limiting number has been reached.

The necessity to designate an option parameter for each input parameter (there are 36 separate ones in GACOST) seems to be rather cumbersome. It is, but the benefits as far as code capabilities are greatly increased. For example, the input of fabrication prices (for both uranium and thorium fuel cycles) can be performed in four separate ways:

1. Designate different prices for each batch,
2. Designate different prices for each year,
3. Designate base prices which are then escalated by variable percentages according to material and labor costs,
4. Designate base prices which are changed according to analytical learning curves.

The more significant options offered by GACOST are mentioned in Appendix D.

To compare the effectiveness of the two input procedures requires an understanding of the user for which the code was designed. GACOST was designed for flexible, high volume use in a continuing nuclear industry. As such, its input procedures are complicated and require a significant amount of study and use for an individual to take advantage of the wide range of options it offers. GEM and CINCAS are capable of supporting the professional in the nuclear industry, but they are also designed for use by novices in the field. University students, for example, with little background in fuel cycle mechanics or economics would be able to prepare accurately proper input for these codes after a cursory reading of the applicable manual. The major advantage of the batch input is its simplicity, while the component input offers the user greater flexibility.

## 5.8 Output

The usefulness of a code is limited by the ability of a user to interpret its calculations. In these codes, the primary calculation is the levelized cost of fuel over the history of the reactor. But to be able to utilize correctly this cost a user must be able to determine the impact of different cost components, the cost of different fuel batches, and the distribution of these costs in time. Again the choice must be made whether to output batch costs as a function of cost components, or to output component costs as a function of fuel batches. It is logical that output should follow the same procedure as input, and CINCAS and GEM organize output on a batch basis while GACOST is organized on a cost component basis.

The batch basis input/output greatly simplifies computer workflow since data associated with a particular batch can be outputed prior to accepting input for the next batch. This can greatly reduce the size of the code (Note that GACOST requires almost twice the storage space of GEM, four times the space of CINCAS). However, it necessitates the division of output into two separate blocks, batch output and case output. It is possible to retain the calculated costs and display an overall case summary, but the variation of input parameters cannot be displayed in the same manner since they are destroyed after each batch costs are calculated. Input/output on a cost component basis allows the output of a distribution of an input parameter over the entire core history. This output can be useful in analyzing a problem which uses, for example, computer aided price escalation.

The selection and organization of output data must, to a certain extent, be predetermined by the code. A user should have the option, however, of suppressing certain data which are of no interest to him. A user concerned only with the final levelized cost should not be presented with a detailed summary of batch mass flow data, for example. Each of the codes has attempted to allow the user to exert a certain amount of control over the output. CINCAS allows the least control. Table 17 summarizes the major output sections (samples are in Appendix B). Note that it is not possible to suppress batch output completely. This led to the production of 96 pages of unnecessary and repetitive output for the sample problem in Appendix A. The fact that batch data are always outputed is probably the reason that case data are not summarized on a batch basis. In GEM, both these drawbacks are eliminated (Table 18). The batch output is neatly summarized on two pages, both of which may be suppressed. Case summary is much more extensive than in CINCAS, and breaks down the calculated costs by batches, years, and cost components. In fact, the only items not summarized for the case are the input parameters. GACOST is able to handle this by organizing the output on a component basis. The user selects one or all of the thirty-two tables to be printed (Table 19). Of these thirty-two tables, twenty-one summarize input data and the remaining eleven are calculated data. When a table is printed, it covers the entire

Table 17. Summary of Output, CINCAS

| |
|---|
| Batch Output (vs. Time) |
| Batch Description |
| Batch Mass Inventory |
| Batch Fuel Costs, $ |
| Batch Fuel Costs, Present Worth $ |
| Batch Summary, mills/kwhe or ¢/MBTU (optional) |
| Case Output (vs. Time) (optional) |
| Case Mass Inventory |
| Case Fuel Costs, $ |
| Case Fuel Costs, Present Worth $ |
| Case Summary, mills/kwhe or ¢/MBTU |

Table 18. Summary of Output, GEM

| |
|---|
| Case Input |
| Batch Output |
| Batch Description Page |
| Batch Economic Analysis Page |
| Case Output |
| Case Description Page |
| Batch Summary Page |
| Yearly Batch Costs Page |
| Yearly Case Costs Page |
| Yearly and Cumulative Fuel Cycle Costs Page |
| Batch and Cumulative Fuel Cycle Costs Page |
| Case Evaluation Page |

Table 19. Output Tables, GACOST

| | |
|---|---|
| 1 | GCA Company Heading |
| 2 | Plant Characteristics |
| 3 | Indication of Whether or Not the Cycle is a Buyback Cycle Indication About How Preirradiation Working Capital is Treated |
| 4 | Progress Payments |
| 5 | Time Characteristics |
| 6 | Reload Characteristics |
| 7 | Fabrication Cost Parameters |
| 8 | Fuel Handling Cost Parameters |
| 9 | Ore Cost Parameters |
| 10 | Source and Disposition of Fuel |
| 11 | Fuel Losses |
| 12 | Application of a U-232 Penalty |
| 13 | Application of a U-236 Penalty |
| 14 | U-232 and U-236 Deduction Tables |
| 15 | Core Loadings vs. Time |
| 16 | Fuel Mass Flows |
| 17 | Fuel Values at Insertion and Discharge for Each Segment |
| 18 | Energy and Capacity Factors |
| 19 | Yearly Cash Flow |
| 20 | Values and Costs Per Reload-Interval and Segment |
| 21 | Value of Fuel in the Core vs. Time |
| 22 | Expenditures, Values and Costs per Segment |
| 23 | Reload-Interval Fuel Cycle Cost vs. Time |
| 24 | Reload-Interval Fuel Costs vs. Time |
| 25 | Yearly Levelized Fuel Cycle Costs vs. Time |
| 26 | Yearly Levelized Fuel Costs vs. Time |
| 27 | Levelized Fuel Cycle Costs vs. Time |
| 28 | Levelized Fuel Costs vs. Time |
| 29 | Burnup per Reload-Interval |
| 30 | Escalation Table, Escalation Factors |
| 31 | Escalation Table, Escalated Costs |
| 32 | Fissile Loading Factors |

reactor history, eliminating the necessity of artificially breaking output into batch and case sections. Again, as in the input, use of the batch basis simplifies output, while the use of the component basis increases flexibility.

## 5.9 Code Evaluation

Determination of which code is "best" is a very subjective process. It involves the two major topics already discussed, calculational procedures and code utility. Since code utility is primarily a function of the code user, it cannot be applied directly in an objective evaluation of the codes. The calculational procedures, however, should provide all users with consistent and accurate results. For this reason the primary means of comparison among the codes will be the calculational output.

The medium for this comparison is a sample problem formulated specifically for the purpose of code comparison. Details of this problem are presented in Appendix A. The selection of a one year interval between reloadings, with all reload intervals starting on the first of the year, is intended to insure correspondence between accounting periods. This is necessary since the output of GEM and CINCAS are based on a calendar year whereas GACOST outputs on a reload interval basis. Similarly a simplified 12% carrying charge rate with no income tax was used since each code treats the input for capital charges differently. Even with these modifications, it is difficult to compare directly, since the procedures used by each code vary considerably. For example, each code calculates a figure titled "uranium" cost for each year for each batch. Unfortunately it is impossible to compare these numbers since they actually are different costs. The GEM calculation includes uranium depletion and the contribution of carrying charges in the preburn, burn and postburn periods. CINCAS does not include in its calculation the carrying charges associated with the postburn period, and GACOST calculates only uranium depletion.

Similar differences are found in practically all the calculations done by the codes. In fact, the only numbers which can be lifted directly from the code outputs and compared are the levelized costs on a yearly and batch basis (Tables 20 and 21). Inspection of these results shows that there are no substantial deviations in the calculational results of the codes.

Which code, then, is the best? This can only be answered by the user. Below is a summarized evaluation of each code.

CINCAS. The simplest and smallest of the codes. Its capabilities are limited primarily in the evaluation of indirect costs (fixed accounting period and average carrying charge rate) and escalation of price data. User has little control over output, but the code is easy to use.

GEM. This code gives the impression of being an advanced version of CINCAS. The theoretical procedure is much more advanced and allows the user greater flexibility in the use of price escalation, thorium fuel cycles, etc. The user has more control over output, and the output is very well organized with much more emphasis on case evaluation.

GACOST. The code with the greatest flexibility, it is also the most difficult to use. Input procedures are organized differently than GEM and CINCAS because of the greater number of options available. For high volume use, however, it offers the greatest modeling flexibility.

## 5.10 References


1. NUS-531, Guide for Economic Evaluation of Nuclear Reactor Plant Designs, NUS Corp., Rockville, Md., Jan. 1969.

2. D. R. VONDY, "Basis and Certain Features of the Discount Technique," ORNL 3686, Appendix F, Oak Ridge National Laboratory, 1965.

3. DANIEL F. HANG, "Fuel Cycle Economics," Education and Research in the Nuclear Fuel Cycle, D. M. Elliot and L. E. Weaver, ed., University of Oklahoma Press, Norman, Oklahoma, 1972, 67-83.

Table 20. Sample Problem Yearly Levelized Costs (mills/kwhe)

| | CINCAS | GEM | GACOST |
|---|---|---|---|
| 1983 | 4.8501 | 4.4921 | 4.823 |
| 1984 | 3.6197 | 3.5859 | 3.623 |
| 1985 | 3.2816 | 3.2646 | 3.294 |
| 1986 | 3.2816 | 3.2271 | 3.294 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| 2005 | 3.2186 | 3.2275 | 3.294 |
| 2006 | 3.5418 | 3.4336 | 3.553 |
| 2007 | 4.5009 | 3.9655 | 4.503 |

Table 21. Sample Problem Case Levelized Costs (mills/kwhe)

| | CINCAS | GEM | GACOST |
|---|---|---|---|
| Batch 83A | 6.5717 | 6.5053 | 6.5179 |
| 83B | 4.1944 | 4.1724 | 4.1877 |
| 83C | 3.3087 | 3.3016 | 3.3158 |
| Case | 3.5090 | 3.4983 | 3.513 |

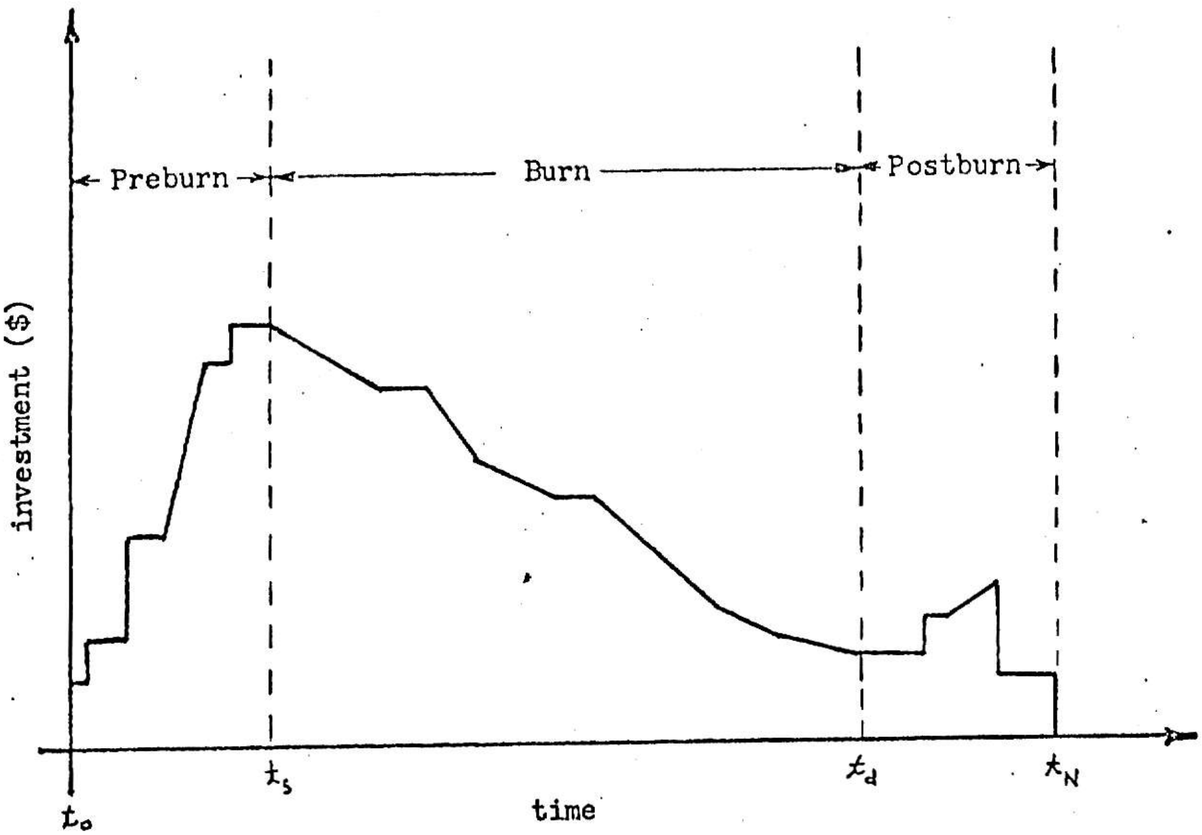


Figure 8. Typical Batch Fuel Cycle Investment History

# APPENDIX A: SAMPLE PROBLEM

In order to provide comparative results from each code to aid in evaluation, each was used to perform an economic analysis of a simplified reactor fuel loading scheme. This sample problem is based on data which was gleened from current market information. The reloading scheme is not typical of actual reactors, since it is geared towards simplifying the comparison of calculations rather than optimization of fuel usage and power distribution. The core was divided into three equal regions which all have the same initial isotopic composition. Each region experiences the same constant power level. Batches are assumed removed and inserted on the first day of each year and one third of the core is removed each year. This scheme is very inefficient, especially for the first and last core, however, it is useful for comparing computer codes.

The data used are shown in Tables A-1 through A-4. To aid in identification, each batch is numbered with the last two digits of the year that fuel is inserted into the reactor. The initial core has the batches labeled 83A, 83B, and 83C, with 83A remaining in the core one year, 83B two years and 83C three years. The computer outputs for each of the codes are shown in the appendix which describes the code.

Table A-1. General Data, Sample Problem

| | |
|---|---|
| Type | PWR |
| Capacity | 1000 MW(T) |
| Number of Regions | 3 |
| Startup | 1/1/1983 |
| Shutdown | 31/2/2008 |
| Operating History | 25 years |
| Batch History (Equilibrium) | 3 years |
| Total Batches | 27 |
| Capacity Factor | .85 |
| Plant Efficiency | .33 |

Table A-2. Mass Flow Data, Sample Problem

| Batch Number | | 83A,07 | 83B,06 | 83C,05 |
|---|---|---|---|---|
| Uranium (kg) | Initial | 24820 | 24820 | 24820 |
| | Final | 24487 | 24154 | 23820 |
| Enrichment (wt%) | Initial | 3.20 | 3.20 | 3.20 |
| | Final | 2.45 | 1.70 | .95 |
| Separative Work Units | Initial | 4.746 | 4.746 | 4.746 |
| | Final | 3.123 | 1.603 | .308 |
| Plutonium Discharged (kg) | | 52 | 104 | 155 |
| Energy Produced (BTU) (x $10^{-13}$) | | 2.033 | 4.066 | 6.099 |

Table A-3. Cash Flow Data, Sample Problem

| Cost Component | | Number of Months |
|---|---|---|
| Prior to Insertion | | |
| Procure $U_3O_8$ | | 12 |
| Complete Conversion | | 10 |
| Complete Enriching | | 7 |
| Fabrication - | 20% | 7 |
| | 40% | 6 |
| | 60% | 5 |
| | 80% | 4 |
| | 100% | 3 |
| After Removal | | |
| Spent Fuel Cooling | | 4 |
| Shipping | | 7 |
| Reprocessing | | 10 |

Table A-4. Economic Cost Data, Sample Problem

| | |
|---|---|
| $U_3O_8$ | 15.00 \$/lb<br>(33.07 \$/kg) |
| Conversion to $UF_6$ | 1.50 \$/lb<br>(3.31 \$/kg) |
| Enrichment | 54.00 \$/kg<br>(tails = .2%) |
| Fabrication | 100.00 \$/kg |
| Spent Fuel Shipping | 25.00 \$/kg |
| Recovery | 140.00 \$/kg U |
| Reconversion | 5.00 \$/kg U |
| Plutonium | 12.00 \$/gm Pu |
| Annual Carrying Charge Rate | 12% |

# APPENDIX B: COMPUTER CODE CINCAS

## General

CINCAS is a nuclear fuel cycle cost code designed to be used for either engineering economy predictions of fuel cycle costs or for accounting forecasting of such costs. It was developed as a joint effort among several midwest utilities, architect firms and universities. Code listing, sample problem and manual were obtained from the Argonne Code Center, Argonne National Laboratory.

## Theoretical Procedure

CINCAS deals exclusively with a one month time interval. The objective of the code is to properly determine all costs associated with the nuclear fuel and then allocate them to each month of the fuel history in accordance with the amount of energy produced. Since there is no energy produced prior to insertion into the core, capital charges associated with prepayments are treated in a manner similar to interest during construction and added to the inventory value of the fuel as it is inserted into the reactor. The capital charges for the post-irradiation period are very similar, but they are treated as a separate cost item and calculated from the date the batch is removed from the core.

There are, including the post irradiation charges already discussed, ten cost categories directly addressed by CINCAS (Table B-1). Tha magnitude of each of the direct cost categories is determined by the difference between its inventory value at startup and shutdown. The inventory costs (except post irradiation) for each month are based on the midmonth inventory value of the cost component. The primary problem, then, involves determination of the monthly inventory distribution. This is done by determining the monthly fractional burnup for the batch. An example set of equations is shown in

Table B-1. Cost Categories, CINCAS

| Direct Costs | Indirect Costs |
|---|---|
| Uranium Expense | Uranium Inventory |
| Plutonium Credit | Plutonium Inventory |
| Fabrication Expense | Fabrication Inventory |
| Reprocessing Expense | Post Irradiation Inventory |
| Reconversion Expense | |

Table B-2. In these equations the uranium expense and inventory values are calculated for each month utilizing the straight line method of burnup. There are similar calculations conducted for each of the cost components. After calculating the inventory and expense costs associated with each month, CINCAS then calculates total costs in each month simply by summing the monthly contribution of each cost component. Once this is done, CINCAS performs two calculations on the total costs. It first calculates the burnup average which is a non-present worthed ratio of costs to energy production. Then it calculates levelized average, which is the ratio of present worthed costs to present worthed energy production. The equations for these calculations are shown in Table B-3, and the nomenclature used in these equations is shown in Table B-4.

## Code Capabilities

CINCAS is designed particularly for light water reactors utilizing uranium as a fuel. As such, it is not capable of handling thorium fuel cycles or breeder reactors. The code can handle any number of batches but limits the length of a particular case to 40 years. The accounting period of one month allows the user to output costs up to twelve times each year. CINCAS provides a unique output of the absolute value of cash flows versus the present worthed values of both cash flows and unit costs. The major options available in CINCAS are in Table B-5.

Input in CINCAS is organized on a batch basis and cost parameters and payment lead times are retained by succeeding batches. In this type of organization it is necessary only to identify the batch with a card and designate appropriate burnup data if cost data is unchanged. It is possible, however, to change all data, except case present worth factor, for each batch. The only

Table B-2. Formulas for Uranium Monthly Cost Calculations CINCAS

Incremental Monthly Batch Burnup Fraction

$$\Delta\theta_J^F = \Delta\theta_J / \theta_N$$

Uranium Expense

$$UEX(J) = (W_O^U * V_O^U - YF3 * W_N^U * V_N^U + \Delta_U) * \Delta\theta_J^F$$

Uranium Inventory

$$URIN(J) = RON * \ W - \theta_J^{MF} * \Big(G * W_N^U * (CSHIP + CREP) + YF3 * CREC * W_N^U\Big)$$

where:

$$G = W_N^U * V_O^U \ / \ (W_N^U * V_N^U + W_N^{Pu} * V^{Pu})$$

$$W = W_O^U * V_O^U + \Delta_U + \theta_J^{MF} * \Big(W_O^U * V_O^U + \Delta_U - YF3 * W_N^U * V_N^U\Big)$$

Table B-3. Formulas for Total Cost Calculations, CINCAS

$$\text{Burnup Averages} = \frac{\sum_{j=1}^{N} (\$/\text{month})_j}{W_O^U * \theta_N}$$

$$\text{Levelized Averages} = \frac{\sum_{j=1}^{N} (\$/\text{month})_j * P(MD_j)}{\sum_{j=1}^{N} \Delta\theta_j * P(MD_j)}$$

Table B-4. Symbols Used in CINCAS

| | | |
|---|---|---|
| CFAB | = | unescalated unit cost of fabrication, including taxes \$/kg fabricated uranium |
| CREC | = | unit spent fuel reconversion cost, \$/kg reprocessed U |
| CREP | = | unit spent fuel reprocessing cost, \$/lb discharged U |
| CSHIP | = | unit spent fuel storage and shipping cost, \$/kg discharged U |
| KWHE(J) | = | electrical kilowatt-hours produced by batch in Jth month of in-core time |
| $MD_J$ | = | month date number associated with in-core month J |
| N | = | number of months between startup and discharge |
| NFPP | = | number of fabrication progress payments |
| NMREP | = | number of months batch is in reprocessing |
| NMSA | = | number of months batch is between end of reprocessing and combined reconversion and sale |
| NMSTO | = | number of months batch is in spent fuel storage and shipping |
| P(MD) | = | present-worth factor to end on month date MD |
| RON | = | on-site monthly carrying charge rate for fuel (fraction) |
| $V_0^U$ | = | unit value of uranium in batch at startup, \$/kg U |
| $V_J^U$ | = | unit value of uranium in batch at end of month J, \$/kg U |
| $V_N^U$ | = | unit value of uranium in batch at discharge, \$/kg U |
| $V^{Pu}$ | = | unit value of plutonium in batch at recovery, \$/kg fissile Pu |
| $W_0^{Pu}$ | = | kg fissile Pu in batch at startup |
| $W_J^{Pu}$ | = | kg fissile Pu in batch at end of month J |
| $W_N^{Pu}$ | = | kg fissile Pu in batch at discharge |
| $W_0^U$ | = | kg uranium in batch at startup (same as BMU) |
| $W_J^U$ | = | kg uranium in batch at end of month J |
| $W_N^U$ | = | kg uranium in batch at discharge |
| YF3 | = | yield fraction of uranium reprocessing |
| $\Delta_U$ | = | capitalized interest on uranium progress payments occurring before batch startup |
| $\Delta\theta_J$ | = | monthly incremental batch burnup of in-core month J, MWD/kg initial U |
| $\Delta\theta_J^F$ | = | incremental monthly batch burnup fraction of in-core month J |

Table B-4 (Continued)

---

$\theta_J$ = end-of-month cumulative batch burnup for in-core month J, MWD/kg initial U

$\theta_N$ = batch burnup at discharge, MWD/kg initial U

$\theta_J^{MF}$ = mid-month cumulative batch burnup fraction for in-core month J

Table B-5. Major User Options, CINCAS

| |
|---|
| **Economic Data** |
| Escalation of fabrication payments |
| Simple or compound interest on prepayments |
| Optional present worth calculations |
| Income tax calculation |
| Separate interest rates for prepayments, off-site and on-site residence, and present worth |
| **Mass Flow Data** |
| Straight line or actual-value burnup |
| Reinserted batch |
| **Input/Output** |
| Input for one batch applies to all subsequent batches until changed |
| Variable case analysis dates |
| Always outputs $ with option of mills/kwhe and/or ¢/MBTU |
| Output up to twelve times yearly |

restriction on this change is that the first batch in the input stream must also be the first batch inserted into the reactor.

The output of CINCAS is also organized on a batch basis. The major drawback of the output is that the user does not have the option of suppressing the summary of each batch. This is probably the reason why the case summary output is not done on a batch basis.

## Code Results

The output for the sample problem in Appendix A is shown in the following figures:

Figure B-1. Batch Description,

Figure B-2. Batch Mass Inventory,

Fibure B-3. Batch Fuel Costs, $,

Figure B-4. Batch Fuel Costs, Present Worthed $,

Figure B-5. Batch Summary, Batch 83A,

Figure B-6. Batch Summary, Batch 83B,

Figure B-7. Batch Summary, Batch 83C,

Figure B-8. Case Mass Inventory,

Figure B-9. Case Fuel Costs, $,

Figure B-10. Case Fuel Costs, Present Worthed $,

Figure B-11. Case Summary.

THE FOLLOWING PAGES ARE BADLY SPECKLED DUE TO BEING POOR QUALITY PHOTOCOPIES.

THIS IS AS RECEIVED FROM CUSTOMER.

*CINCAS*
BASE PROBLEM - CODE COMPARISON
BATCH 83C

FIRST IRRADIATION PERIOD 1/83 TO 1/86 - 36 MONTHS

| TIMES (MONTHS) | |
|---|---|
| IRRADIATION | 36 |
| STORAGE AND SHIPPING | 7 |
| REPROCESSING | 3 |
| FROM REPROCESSING TO SALE | 0 |

FEED UF6 ENRICHMENT 0.7110 WT. P.C. U-235
TAIL UF6 ENRICHMENT 0.2000 ''

| COST COMPONENTS | | |
|---|---|---|
| NATURAL URANIUM NET TO CONVERSION | 15.00 | $/LB U3O8 |
| CONVERSION FROM U3O8 TO UF6 | 1.50 | $/LB U AS UF6 |
| SEPARATIVE WORK | 54.00 | $/KG SEPARATIVE WORK |
| FABRICATION (NET + DELIVERED) | 100.00 | $/KG CONTAINED U |
| SPENT FUEL SHIPPING | 25.00 | $/KG DISCHARGED U |
| REPROCESSING | 140.00 | $/KG DISCHARGED U |
| RECONVERSION | 5.00 | $/KG REPROCESSED U |
| PU RECOVERY PRICE | 12.00 | $/GRAM FISSILE PU |

| INTEREST RATES (PER CENT PER ANNUM) | |
|---|---|
| INVENTORY PRIOR TO IRRADIATION | 12.00 |
| OFF-SITE CARRYING CHARGE RATE | 12.00 |
| ON-SITE CARRYING CHARGE RATE | 12.00 |
| FEDERAL INCOME TAX RATE | 0.0 |

| LOSSES (PER CENT OF FEED) | |
|---|---|
| U3O8 TO UF6 | 0.0 |
| URANIUM FABRICATION | 0.0 |
| URANIUM REPROCESSING | 0.0 |
| PLUTONIUM REPROCESSING | 0.0 |
| UNRECOVERABLE FABRICATION LOSSES | 0.0 |

EXPOSURE TABLE

| | MWD/KG INIT U | KG U | KG NF U | KG U235 | KG PU | P.C. U OF INIT U | WT P.C. U235 | P.C. PU OF INIT U | PLANT EFF DURING IRR'N | UNIFORM MONTHLY KWHE |
|---|---|---|---|---|---|---|---|---|---|---|
| AT INSERTION | 0.0 | 24820. | 24026. | 794.24 | 0.0 | 100.000 | 3.200 | 0.0 | | |
| 1ST WITHDRAWAL | 30.000 | 23820. | 23594. | 226.29 | 155.001 | 95.971 | 0.950 | 0.624 | 0.330 | 0.1636E 09 |

URANIUM UNIT VALUE TABLE

| | | | | |
|---|---|---|---|---|
| FEED REQUIRED | 15.226 LB U3O8/KG ENRICHED U | | | |
| TOTAL FEED | 377921. LB U3O8 INCLUDING FABRICATION OVERAGE | | | |
| FEED COST | 228.40 | $/KG ENRICHED U | 45.318 | PER CENT OF TOTAL |
| CONVERSION COST | 19.37 | '' | 3.843 | '' |
| ENRICHMENT COST | 256.23 | '' | 50.839 | '' |
| TOTAL COST | 503.99 | '' | 100.000 | '' |

URANIUM PROGRESS PAYMENT SCHEDULE

TYPE — MONTHS BEFORE POWER/PER CENT OF TYPE COST

ORE
12/100.00

CONVERSION
10/100.00

ENRICHMENT
7/100.00

Figure B-1. Batch Description

*CINCAS*

3 URANIUM PROGPESS PAYMENTS ($)

| MCNTH BEFORE PCWER | U308 | CCNVERSICN | ENRICHMENT | MONTHLY TOTAL | P.C. CF GRAND TOTAL |
|---|---|---|---|---|---|
| 12 | 5668815. | C. | C. | 5668E15. | 45.32 |
| 1C | 0. | 4807C4. | 0. | 48C704. | 3.E4 |
| 7 | 0. | C. | 6359536. | 6359536. | 5C.E4 |
| TCTALS | 5668E17. | 48C7C4. | 6359537. | 125C5C55. | 1C0.C0 |

5 FABRICATICN PROGRESS PAYMENTS ($)

| MCNTH BEFORE POWER | AMCUNT | P.C. OF TOTAL |
|---|---|---|
| 7 | 496400. | 20.00 |
| 6 | 4964C0. | 20.00 |
| 5 | 4964C0. | 20.00 |
| 4 | 496400. | 20.00 |
| 3 | 49640C. | 20.00 |
| TOTAL | 2482000. | 100.00 |

Figure B-1. Batch Description

*CINCAS*
BASE PROBLEM - CODE COMPARISON
BATCH E3C

BATCH MASS INVENTORY

1ST INSERTION 1/1983
1ST WITHDRAWAL 1/1986

| DATE | MWD/KG U | KG U | KG NF U | KG U235 | KG PU | P.C.ENR | $ U | $ PU | $ U + PU |
|---|---|---|---|---|---|---|---|---|---|
| | *****END-OF-MONTH WEIGHTS***** | | | | | | *****MID-MONTH VALUES***** | | |
| STARTUP | 0.0 | 24820.0 | 24025.8 | 794.24 | 0.0 | 3.200 | 13671547. | 0. | 13671547. |
| 1983 | 10.000 | 24486.7 | 23881.7 | 604.52 | 51.667 | 2.470 | 9234147. | -31867. | 9202280. |
| 1984 | 20.000 | 24153.3 | 23737.7 | 415.61 | 103.334 | 1.721 | 4603832. | -65118. | 4538714. |
| 1985 | 30.000 | 23820.0 | 23593.7 | 226.29 | 155.000 | 0.950 | -26469. | -98371. | -124840. |
| DISCHARGE | 30.000 | 23820.0 | 23593.7 | 226.29 | 155.000 | 0.950 | -219405. | -99756. | -319161. |

Figure B-2. Batch Mass Inventory

* CINCAS *

BATCH FUEL COSTS, $

BASE PROBLEM - CODE COMPARISON
BATCH 83C

NON-PRESENT-WORTHED PERIOD COSTS — STRAIGHT LINE UNIT OF PRODUCTION METHOD

********************MID-MONTH INVENTORY COSTS************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 1293135. | -1893. | 246928. | 11378. | 1549545. |
| 1984 | 765887. | -5680. | 148156. | 11378. | 919742. |
| 1985 | 238640. | -9466. | 49386. | 11378. | 289938. |
| COLUMN TOTALS | 2297662. | -17039. | 444470. | 34133. | 2759223. |
| PRESENT WORTHS TO 1/1983 | 2051758. | -13564. | 396211. | 28799. | 2463200. |

****************************END-OF-MONTH EXPENSE COSTS*******************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 3933781. | -620003. | 867416. | 198500. | 1111602. | 39700. | 5530993. | 7080542. |
| 1984 | 3933781. | -620003. | 867416. | 198500. | 1111602. | 39700. | 5530993. | 6450734. |
| 1985 | 3933781. | -620003. | 867416. | 198500. | 1111602. | 39700. | 5530993. | 5820532. |
| COLUMN TOTALS | 11801343. | -1860007. | 2602248. | 595501. | 3334806. | 119100. | 16592979. | 19352208. |
| PRESENT WORTHS TO 1/1983 | 9557293. | -1569262. | 2199619. | 502450. | 2813710. | 100490. | 14000211. | 16463429. |

PRESENT-WORTHED
VALUES FOR CASH FLOWS

| | PROGRESS PAYMENTS URANIUM | PROGRESS PAYMENTS FABRICATION | SHIPPING CHARGE | REPROCESSING CHARGE | RECONVERSION CHARGE | URANIUM SALE | PLUTONIUM SALE | TOTAL |
|---|---|---|---|---|---|---|---|---|
| | 13671546. | 2602242. | 396750. | 2159736. | 77133. | -1211230. | -1204605. | 16491555. |
| BEGINNING OF MONTH FLOW DATES | | | 8/1986 | 11/1986 | 11/1986 | 11/1986 | 11/1986 | |

Figure B-3. Batch Fuel Costs, $

* CINCAS *

BATCH FUEL COSTS, $

BASE PROBLEM - CODE COMPARISON
BATCH 83C

ALL PERIOD COSTS PRESENT-WORTHED TO 1/1983 STRAIGHT LINE UNIT OF PRODUCTION METHOD

**********************MID-MONTH INVENTORY COSTS***********************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 1221440. | -1748. | 233221. | 10706. | 1463616. |
| 1984 | 647608. | -4742. | 125251. | 9559. | 777675. |
| 1985 | 182719. | -7074. | 37740. | 8535. | 221920. |
| PRESENT WORTHS TO 1/1983 | 2051758. | -13564. | 396211. | 28799. | 2463200. |

*****************************END-OF-MONTH EXPENSE COSTS********************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 3701527. | -583358. | 816202. | 166781. | 1045973. | 37356. | 5204442. | 6668060. |
| 1984 | 3304936. | -520891. | 728753. | 166769. | 933905. | 33354. | 4646822. | 5424499. |
| 1985 | 2950834. | -465081. | 650673. | 148901. | 833843. | 29780. | 4148549. | 4370871. |
| PRESENT WORTHS TO 1/1983 | 9557293. | -1569362. | 2155619. | 502450. | 2813710. | 100490. | 14000211. | 16463429. |

Figure B-4. Batch Fuel Costs, Present Worthed $

* CINCAS *

BATCH FUEL COSTS, MILLS/KWHE

BASE PROBLEM - CODE COMPARISON
BATCH 83A

NON-PRESENT-WORTHED PERIOD COSTS STRAIGHT LINE UNIT OF PRODUCTION METHOD

********************MID-MONTH INVENTORY COSTS**********************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 0.5346 | 0.0102 | 0.0754 | 0.2818 | 0.9021 |
| BURNUP AVERAGES | 0.5346 | 0.0102 | 0.0754 | 0.2818 | 0.9021 |
| LEVELIZED | 0.5355 | 0.0100 | 0.0768 | 0.2818 | 0.9081 |

***************************END-OF-MONTH EXPENSE COSTS*******************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 2.5397 | -0.3174 | 1.3228 | 0.3114 | 1.7439 | 0.0623 | 5.6636 | 6.5657 |
| BURNUP AVERAGES | 2.5397 | -0.3174 | 1.3228 | 0.3114 | 1.7439 | 0.0623 | 5.6636 | 6.5657 |
| LEVELIZED | 2.5397 | -0.3174 | 1.3228 | 0.3114 | 1.7439 | 0.0623 | 5.6636 | 6.5717 |

LEVELIZED
VALUES FOR CASH FLOWS

| | PROGRESS PAYMENTS URANIUM | PROGRESS PAYMENTS FABRICATION | SHIPPING CHARGE | REPROCESSING CHARGE | RECONVERSION CHARGE | URANIUM SALE | PLUTONIUM SALE | TOTAL |
|---|---|---|---|---|---|---|---|---|
| | 7.3913 | 1.4069 | 0.2766 | 1.5056 | 0.0538 | -3.8119 | -0.2741 | 6.5481 |
| BEGINNING OF MONTH FLOW DATES | | | 8/1984 | 11/1984 | 11/1984 | 11/1984 | 11/1984 | |

Figure B-5. Batch Summary, Batch 83A

* CINCAS *

BATCH FUEL COSTS, MILLS/KWHE

BASE PROBLEM - CODE COMPARISON
BATCH 83B

NON-PRESENT-WORTHED PERIOD COSTS — STRAIGHT LINE UNIT OF PRODUCTION METHOD

*********************MID-MONTH INVENTORY COSTS************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 0.6195 | 0.0067 | 0.1131 | 0.0704 | 0.8096 |
| 1984 | 0.2746 | 0.0201 | 0.0377 | 0.0704 | 0.4028 |
| BURNUP AVERAGES | 0.4471 | 0.0134 | 0.0754 | 0.0704 | 0.6062 |
| LEVELIZED | 0.4600 | 0.0129 | 0.0782 | 0.0704 | 0.6215 |

******************************END-OF-MONTH EXPENSE COSTS**************************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 2.1845 | -0.3179 | 0.6619 | 0.1536 | 0.8601 | 0.0307 | 3.5729 | 4.3825 |
| 1984 | 2.1845 | -0.3179 | 0.6619 | 0.1536 | 0.8601 | 0.0307 | 3.5729 | 3.9757 |
| BURNUP AVERAGES | 2.1845 | -0.3179 | 0.6619 | 0.1536 | 0.8601 | 0.0307 | 3.5729 | 4.1791 |
| LEVELIZED | 2.1845 | -0.3179 | 0.6619 | 0.1536 | 0.8601 | 0.0307 | 3.5729 | 4.1944 |

LEVELIZED
VALUES FOR CASH FLOWS

| | PROGRESS PAYMENTS URANIUM | PROGRESS PAYMENTS FABRICATION | SHIPPING CHARGE | REPROCESSING CHARGE | RECONVERSION CHARGE | URANIUM SALE | PLUTONIUM SALE | TOTAL |
|---|---|---|---|---|---|---|---|---|
| | 3.9048 | 0.7432 | 0.1287 | 0.7005 | 0.0250 | -1.0531 | -0.2589 | 4.1903 |
| BEGINNING OF MONTH FLOW DATES | | | 8/1985 | 11/1985 | 11/1985 | 11/1985 | 11/1985 | |

Figure B-6. Batch Summary, Batch 83B

* CINCAS *

BATCH FUEL COSTS, MILLS/KWHE

BASE PROBLEM - CODE COMPARISON
BATCH 83C

NON-PRESENT-WORTHED PERIOD COSTS — STRAIGHT LINE UNIT OF PRODUCTION METHOD

**********************MID-MONTH INVENTORY COSTS************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 0.6578 | -0.0010 | 0.1256 | 0.0058 | 0.7883 |
| 1984 | 0.3396 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1985 | 0.1214 | -0.0048 | 0.0251 | 0.0058 | 0.1475 |
| BURNUP AVERAGES | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| LEVELIZED | 0.4124 | -0.0027 | 0.0756 | 0.0058 | 0.4950 |

*****************************END-OF-MONTH EXPENSE COSTS**************************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.6020 |
| 1984 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1985 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 2.9612 |
| BURNUP AVERAGES | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| LEVELIZED | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.3087 |

LEVELIZED
VALUES FOR CASH FLOWS

| | PROGRESS PAYMENTS URANIUM | PROGRESS PAYMENTS FABRICATION | SHIPPING CHARGE | REPROCESSING CHARGE | RECONVERSION CHARGE | URANIUM SALE | PLUTONIUM SALE | TOTAL |
|---|---|---|---|---|---|---|---|---|
| | 2.7476 | 0.5230 | 0.0757 | 0.4341 | 0.0155 | -0.2434 | -0.2421 | 3.3144 |
| BEGINNING OF MONTH FLOW DATES | | | 8/1986 | 11/1986 | 11/1986 | 11/1986 | 11/1986 | |

Figure B-7. Batch Summary, Batch 83C

* CINCAS *

BASE PROBLEM - CODE COMPARISON

CASE MASS INVENTORY

| DATE | KG U | KG NF U | KG U235 | KG PU | $ U | $ PU | $ U + PU |
|---|---|---|---|---|---|---|---|
| | ***********END-OF-MONTH WEIGHTS********** | | | | *********MID-MONTH VALUES********* | | |
| 1983 | 73458.9 | 71651.8 | 1807.25 | 155.740 | 22357552. | 528437. | 22885984. |
| 1984 | 72792.9 | 71361.8 | 1431.13 | 259.145 | 15849804. | 356669. | 16206473. |
| 1985 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1986 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1987 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1988 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1989 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1990 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1991 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1992 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1993 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1994 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1995 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1996 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1997 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1998 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 1999 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2000 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2001 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2002 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2003 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2004 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2005 | 72459.9 | 71213.1 | 1246.82 | 310.001 | 13811510. | -195355. | 13616154. |
| 2006 | 72459.8 | 71215.4 | 1244.32 | 310.406 | 12543076. | 58512. | 12601588. |
| 2007 | 72458.8 | 71222.0 | 1236.80 | 311.145 | 7143051. | 693585. | 7836636. |

Figure B-8. Case Mass Inventory

* CINCAS *
CASE FUEL COSTS, $
BASE PROBLEM - CODE COMPARISON

NON-PRESENT WORTHED PERIOD COSTS

**********************MID-MONTH INVENTORY COSTS***********************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 3561867. | 21394. | 617320. | 703737. | 4914286. |
| 1984 | 2593835. | 31994. | 469163. | 161078. | 3261069. |
| 1985 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1986 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1987 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1988 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1989 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1990 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1991 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1992 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1993 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1994 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1995 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1996 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1997 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1998 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 1999 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2000 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2001 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2002 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2003 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2004 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2005 | 2297660. | -17039. | 444470. | 34133. | 2759225. |
| 2006 | 2222301. | -1956. | 419777. | 161078. | 2801202. |
| 2007 | 1829408. | 50200. | 271621. | 703707. | 2854932. |
| COLUMN TOTALS | 58463056. | -246178. | 11111750. | 2446345. | 71775040. |

PRESENT WORTHS TO 1/1983 FOR ALL MONTHS IN CASE LEVELIZING PERIOD

| | | | | |
|---|---|---|---|---|
| 20528768. | -48926. | 3870391. | 1069138. | 25418832. |

***************************END-OF-MONTH EXPENSE COSTS*******************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 13220304. | -1868871. | 4770780. | 1112559. | 6230330. | 222512. | 23687616. | 28601856. |
| 1984 | 12161688. | -1854872. | 3035953. | 698513. | 3913909. | 139782. | 18095360. | 21346416. |
| 1985 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1986 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1987 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1988 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1989 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1990 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1991 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1992 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1993 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1994 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |

Figure B-9. Case Fuel Costs, $

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1995 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1996 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1997 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1998 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 1999 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2000 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2001 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2002 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2003 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2004 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2005 | 11801341. | -1860004. | 2602248. | 595502. | 3334802. | 119100. | 16592588. | 19352208. |
| 2006 | 12161668. | -1864872. | 3035953. | 658913. | 3913909. | 135782. | 18085360. | 20886560. |
| 2007 | 13220304. | -1868871. | 4770780. | 1112559. | 6230330. | 222512. | 23687616. | 26542512. |
| COLUMN TOTALS | 298591488. | -46527488. | 70260512. | 16128465. | 90219264. | 3225687. | 431957440. | 503772160. |

PRESENT WORTHS TO 1/1983 FOR ALL MONTHS IN CASE LEVELIZING PERIOD

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 99255040. | -15387434. | 24077120. | 5534735. | 30993424. | 1106939. | 145623360. | 171044000. |

PRESENT-WORTHED
VALUES FOR THOSE CASH FLOWS WITHIN CASE LEVELIZING PERIOD

| URANIUM | PROGRESS PAYMENTS FABRICATION | SHIPPING CHARGES | REPROCESSING CHARGES | RECONVERSION CHARGES | URANIUM SALES | PLUTONIUM SALES | TOTAL |
|---|---|---|---|---|---|---|---|
| 147437824. | 28062624. | 4458879. | 24272128. | 866865. | -21945184. | -11927110. | 171226000. |

Figure B-9. Case Fuel Costs, $

* CINCAS *
CASE FUEL COSTS, $
BASE PROBLEM - CODE COMPARISON

ALL PERIOD COSTS PRESENT-WORTHED TO 1/1983
COSTS NOT WITHIN CASE LEVELIZING PERIOD ARE SET TO ZERO

**********************MID-MONTH INVENTORY COSTS**********************

| TIME | URANIUM | PLUTONIUM | FABRICATION | POST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 3371130. | 28957. | 585666. | 662160. | 4647942. |
| 1984 | 2157039. | 26732. | 396887. | 135328. | 2755985. |
| 1985 | 1734662. | -12701. | 335493. | 25604. | 2083057. |
| 1986 | 1548806. | -11340. | 299548. | 22861. | 1859875. |
| 1987 | 1382864. | -10125. | 267453. | 20411. | 1660602. |
| 1988 | 1234700. | -9040. | 238798. | 18224. | 1482681. |
| 1989 | 1102411. | -8072. | 213212. | 16272. | 1323823. |
| 1990 | 984296. | -7207. | 190368. | 14528. | 1181984. |
| 1991 | 878836. | -6435. | 169971. | 12972. | 1055344. |
| 1992 | 784675. | -5745. | 151760. | 11582. | 942272. |
| 1993 | 700603. | -5130. | 135500. | 10341. | 841314. |
| 1994 | 625539. | -4580. | 120982. | 9233. | 751174. |
| 1995 | 558517. | -4089. | 108020. | 8244. | 670691. |
| 1996 | 498676. | -3651. | 96446. | 7361. | 598831. |
| 1997 | 445246. | -3260. | 86113. | 6572. | 534671. |
| 1998 | 397541. | -2911. | 76887. | 5868. | 477335. |
| 1999 | 354949. | -2599. | 68645. | 5239. | 426237. |
| 2000 | 316918. | -2320. | 61294. | 4678. | 380568. |
| 2001 | 282962. | -2072. | 54726. | 4177. | 339793. |
| 2002 | 252645. | -1850. | 48863. | 3729. | 303387. |
| 2003 | 225576. | -1652. | 43628. | 3330. | 270881. |
| 2004 | 201407. | -1475. | 38953. | 2973. | 241858. |
| 2005 | 179827. | -1317. | 34780. | 2654. | 215945. |
| 2006 | 155426. | -148. | 29371. | 11184. | 195833. |
| 2007 | 114698. | 3076. | 17154. | 43625. | 178553. |
| PRESENT WORTHS TO 1/1983 FOR ALL MONTHS IN CASE LEVELIZING PERIOD | 20526768. | -48926. | 3870391. | 1069138. | 25418832. |

****************************END-OF-MONTH EXPENSE COSTS*******************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 12439765. | -1758532. | 4489107. | 1046873. | 5862490. | 209375. | 22289056. | 26937008. |
| 1984 | 10217551. | -1566757. | 2550632. | 587186. | 3288242. | 117437. | 15194285. | 17950272. |
| 1985 | 8852511. | -1395242. | 1952015. | 446702. | 2501527. | 89340. | 12446850. | 14529514. |
| 1986 | 7904078. | -1245752. | 1742871. | 398841. | 2233506. | 79768. | 11113261. | 12973140. |
| 1987 | 7057168. | -1112279. | 1556134. | 356108. | 1994203. | 71222. | 9922555. | 11593159. |
| 1988 | 6301043. | -993107. | 1389406. | 317954. | 1780538. | 63591. | 8859425. | 10342107. |
| 1989 | 5625931. | -886702. | 1240542. | 283887. | 1589767. | 56777. | 7910201. | 9234025. |
| 1990 | 5023155. | -791659. | 1107627. | 253471. | 1419434. | 50694. | 7062680. | 8244667. |
| 1991 | 4484959. | -706874. | 988954. | 226313. | 1267352. | 45263. | 6305966. | 7361311. |
| 1992 | 4004430. | -631138. | 882595. | 202065. | 1131566. | 40413. | 5630328. | 6572601. |
| 1993 | 3575363. | -563516. | 788388. | 180416. | 1010328. | 36083. | 5027079. | 5868392. |
| 1994 | 3192307. | -503139. | 703918. | 161085. | 902078. | 32217. | 4488462. | 5239637. |
| 1995 | 2850273. | -449231. | 628498. | 143826. | 805427. | 28765. | 4007556. | 4678246. |

Figure B-10. Case Fuel Costs, Present Worthed $

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1996 | 2544887. | -401099. | 561159. | 128416. | 719131. | 25683. | 3578176. | 4177009. |
| 1997 | 2272222. | -358125. | 501035. | 114657. | 642082. | 22931. | 3194799. | 3729470. |
| 1998 | 2028768. | -319754. | 447353. | 102373. | 573287. | 20475. | 2852499. | 3329883. |
| 1999 | 1811401. | -285495. | 399422. | 91404. | 511864. | 19281. | 2546877. | 2973111. |
| 2000 | 1617323. | -254906. | 356627. | 81611. | 457021. | 16322. | 2273996. | 2654565. |
| 2001 | 1444039. | -227595. | 318417. | 72867. | 408055. | 14573. | 2030355. | 2370148. |
| 2002 | 1289321. | -203210. | 284301. | 65060. | 364335. | 13012. | 1812815. | 2116203. |
| 2003 | 1151180. | -181437. | 253840. | 58089. | 325299. | 11618. | 1618586. | 1889467. |
| 2004 | 1027840. | -161998. | 226643. | 51865. | 290445. | 10373. | 1445167. | 1687024. |
| 2005 | 917714. | -144641. | 202360. | 46308. | 259326. | 9262. | 1290327. | 1506273. |
| 2006 | 844407. | -129481. | 210792. | 48527. | 271750. | 9705. | 1255697. | 1451530. |
| 2007 | 819561. | -115856. | 295753. | 68970. | 386235. | 13794. | 1468455. | 1647007. |

PRESENT WORTHS TO 1/1983 FOR ALL MONTHS IN CASE LEVELIZING PERIOD

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 99295040. | -15387434. | 24017120. | 5534735. | 30993424. | 1106939. | 145623360. | 171044000. |

Figure B-10. Case Fuel Costs, Present Worthed $

* CINCAS *
CASE FUEL COSTS, MILLS/KWHE
BASE PROBLEM - CODE COMPARISON

NON-PRESENT WORTHED PERIOD COSTS

**********************MID-MONTH INVENTORY COSTS************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | FCST-IRR'N | INV SUB |
|---|---|---|---|---|---|
| 1983 | 0.6040 | 0.0053 | 0.1047 | 0.1193 | 0.8333 |
| 1984 | 0.4407 | 0.0054 | 0.0796 | 0.0273 | 0.5530 |
| 1985 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1986 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1987 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1988 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1989 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1990 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1991 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1992 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1993 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1994 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1995 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1996 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1997 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1998 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 1999 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2000 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2001 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2002 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2003 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2004 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2005 | 0.3896 | -0.0029 | 0.0754 | 0.0058 | 0.4679 |
| 2006 | 0.3768 | -0.0003 | 0.0712 | 0.0273 | 0.4750 |
| 2007 | 0.3102 | 0.0085 | 0.0461 | 0.1193 | 0.4841 |
| BURNUP AVERAGES | | | | | |
| | 0.3966 | -0.0017 | 0.0754 | 0.0166 | 0.4869 |
| LEVELIZED WITHIN CASE PERIOD | | | | | |
| | 0.4212 | -0.0010 | 0.0754 | 0.0219 | 0.5215 |

****************************END-OF-MONTH EXPENSE COSTS*********************************************

| TIME | URANIUM | PLUTONIUM | FABRICATION | SHIPPING | REPROCESSING | RECONVERSION | EXP SUB | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1983 | 2.2418 | -0.3169 | 0.8090 | 0.1687 | 1.0565 | 0.0377 | 4.0167 | 4.8501 |
| 1984 | 2.0623 | -0.3162 | 0.5148 | 0.1185 | 0.6637 | 0.0237 | 3.0668 | 3.6197 |
| 1985 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1986 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1987 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1988 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1989 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1990 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1991 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1992 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1993 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1994 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1995 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |

Figure B-11. Case Summary

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1996 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1997 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1998 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 1999 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 2000 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 2001 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5555 | 0.0202 | 2.8137 | 3.2816 |
| 2002 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 2003 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 2004 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 2005 | 2.0012 | -0.3154 | 0.4413 | 0.1010 | 0.5655 | 0.0202 | 2.8137 | 3.2816 |
| 2006 | 2.0623 | -0.3162 | 0.5148 | 0.1185 | 0.6637 | 0.0237 | 3.0668 | 3.5418 |
| 2007 | 2.2418 | -0.3169 | 0.8090 | 0.1887 | 1.0565 | 0.0377 | 4.0167 | 4.5009 |
| BURNUP AVERAGES | | | | | | | | |
| | 2.0254 | -0.3156 | 0.4766 | 0.1094 | 0.6127 | 0.0219 | 2.9303 | 3.4172 |
| LEVELIZED WITHIN CASE PERIOD | | | | | | | | |
| | 2.0371 | -0.3157 | 0.4939 | 0.1135 | 0.6358 | 0.0227 | 2.9875 | 3.5090 |

LEVELIZED
VALUES FOR THOSE CASH FLOWS WITHIN CASE LEVELIZING PERIOD

| PROGRESS PAYMENTS URANIUM | FABRICATION | SHIPPING CHARGES | REPROCESSING CHARGES | RECONVERSION CHARGES | URANIUM SALES | PLUTONIUM SALES | TOTAL |
|---|---|---|---|---|---|---|---|
| 3.0247 | 0.5757 | 0.0915 | 0.4980 | 0.0178 | -0.4502 | -0.2447 | 3.5128 |

1

Figure B-11. Case Summary

# APPENDIX C: COMPUTER CODE GEM

## General

Program GEM, "General Economic Model to Analyze Nuclear Fuel Cycle Costs," was designed for use by large utilities which may have several types of reactors. The structure of the code is such, however, that it can be used effectively by the fuel supplier and university students in addition to the utility [1]. It was written by John A. Hughes and Daniel F. Hang of the University of Illinois in 1973. The code listing, sample problems and manual were obtained from the Argonne Code Center, Argonne National Laboratories.

## Theoretical Basis

Calculational procedures are based on the discounted cash flow technique of Vondy [2]. This technique derives a formula for the levelized unit cost of energy in terms of cash flows and capital financing parameters (Fig. C-1). First it is extended to accept non-zero salvage value [3], and then adapted for discounting on a continuous basis. In addition to this cash flow technique, GEM also calculates costs on a yearly cash flow basis and by a technique called allocated costs. The basis for both these calculations is the modified cash flow method.

The transition from discrete to continuous discounting involves determination of the limit of the discount factor as the accounting period goes to zero. A comparison of the most significant discount parameters is shown in Table C-2. A more difficult problem arises when considering the continuous distribution of costs over the burn period. This distribution is based on the distribution of energy production, which is a difficult function to determine accurately. The problem is solved by dividing the burn period into periods of constant energy production. Then, during any period i of constant power

Table C-1. Levelized Unit Cost of Energy, Discount Technique

$$P = \frac{\sum_{n=0}^{N} (1+x)^{-n}\left[\frac{Z(n)}{(1-r)} - V(n) + O(n) - \frac{r}{1-r} D(n)\right]}{\sum_{n=1}^{N} (1+x)^{-n} Q(n)} ,$$

where

$$D(0) = O(0) = Q(0) = 0,$$

$$X = j(1-r)\, b + i(1-b) .$$

The terms are defined as:

Q(n) = amount of energy sold during the period,

Z(n) = investment,

V(n) = income other than sale of energy,

D(n) = depreciation,

O(n) = deductible operating costs,

P = unit selling price of energy to return all investment costs,

X = discount factor,

N = history life,

r = tax rate on taxible income,

i = required return on stock,

j = required return on bonds,

b = fractional indebtedness in bonds.

Table C-2. GEM Discounting Parameters

| Discrete Discounting | Continuous Discounting |
|---|---|
| $(1+x)^{-n}$ | $e^{-rt}$ |
| $x = a-jbR$ | $r = \ln(1+x)$ |
| $P_\infty = \frac{x}{1-R}$ | $P_{\infty,c} = \frac{r}{1-R}$ |

Where:

Inventory Cost = $P_\infty$ X Investment

$a = jb + i(1-b)$

$$q(t) = Q_i/(t_i - t_{i-1}) \qquad \text{(C-1)}$$

where

$Q_i$ = thermal energy produced in period i,

$t_i - t_{i-1}$ = length of period i.

Energy continuously discounted over n consecutive periods is

$$P(n) = \int_{t_o}^{t_n} q(t)\, e^{-t(t-t_o)}\, dt \; . \qquad \text{(C-2)}$$

Substituting Eq. (C-1) and integrating yields

$$P(n) = \sum_{l=1}^{n} Q_i \left[\frac{\exp\,(r(t_i-t_{i-i})) - 1}{r(t_i-t_{i-1})}\right] \exp\,(r(t_o-t_i)) \qquad \text{(C-3)}$$

This method is also used to distribute indirect costs over the burn period.

In the cash flow technique, the levelized cost of energy is interpreted as the ratio of the present worth of all cash flows to the present worth of all energy produced during the levelizing period. Table C-3 shows the equations used by GEM for calculating the cash flows. Recognizing that

$$\int_{T_n} dt\; C(t)\; e^{r(\eta-t)} = \sum_{k=1}^{NL} (CP_k + CB_k + CPO_k) \; , \qquad \text{(C-4)}$$

and that

$$\int_{T_n} dt\; P(t)\; e^{r(\eta-t)} = P(n) \; , \qquad \text{(C-5)}$$

one can calculate the levelized costs for whatever period desired for a single batch or the entire core.

The equations used for the allocated costs calculations are shown in Table C-4. This calculation takes the cash flows, divides them into inventory and expense costs, and allocates them to each burnup period according to the amount of energy produced during that period. The results are identical to those obtained from cash flow calculations.

Table C-3. Formulas for Economic Analysis, Code GEM

Levelized Costs

$$C'(T_N) = \frac{\int_{T_N} dt\ C(t)\ e^{r(\eta-t)}}{\int_{T_N} dt\ P(t)\ e^{r(\eta-t)}}$$

Cashflow Analysis

$$CP_k = P_\infty\ AI_k \sum_{i-1}^{n_k} (f1_{i,k} * ((1+x)^{d_i} - 1)/x)$$

$$CB_k = \frac{AF_k}{1-R} (1-\exp(-rt_{n,o}))$$

$$+ (AI_k - AF_k) * (1 - \frac{R}{1-R} * \sum_{i=1}^{n_k} \left\{ \frac{Q_i}{Q_t} \left( \frac{\exp(rt_{i,i-1}) - 1}{rt_{i,i-1}} \right) \exp(rt_{o,i}) \right\} ,$$

$$CPO_k = P_\infty\ AF_k \sum_{i=1}^{m_k} \left\{ f2_{i,k} \left( \frac{1 - (1+x)^{-(s_{i,k}-t_n)}}{x * (1+x)^{t_n - t_o}} \right) \right\}$$

Table C-4. Formulas for Allocated Cost Analysis, Code GEM

Expense Costs

$$BEC_k = \left((AI_k - AF_k)/Q_t + CP_k + CP_k/QPW\right) * \sum_{i=1}^{n} \left\{ Q_i \left( \frac{\exp(rt_{i,i-1}) - 1}{rt_{i,i-1}} \right) \exp(rt_{o,i}) \right\}$$

$k \neq 1$

$$BEC_1 = \sum_{k=2}^{NL} \left\{ (CPO_k/Q_{PW}) * \sum_{i=1}^{n} \left\{ Q_i \left( \frac{\exp(rt_{i,i-1}) - 1}{rt_{i,i-1}} \right) \exp(rt_{o,i}) \right\} \right\}$$

Inventory Costs

$$BIC_k = \sum_{i=1}^{NL} \left\{ P_{\infty,c} \exp(rt_{o,i-1}) * \left\{ A_{k,i-1} * (1 - \exp(rt_{i-1,i})) - \frac{(A_{k,i-1} - A_{k,i})}{rt_{i,i-1}} \left[ 1 - (rt_{i,i-1}) \exp(rt_{i-1,}) \right] \right\} \right\}$$

$$A_{k,i} = AI_k - (AI_k - AF_k) * \sum_{j=1}^{i} Q_j/Q_t$$

Code Capabilities

The method of analysis is independent of reactor type, and GEM is capable of handling PWR, BWR, and HTGR systems. The cash flow, yearly cash flow and allocated cost calculations are done initially on a batch basis. Fuel cycle costs are calculated on both a yearly and cumulative basis. Through case studies, it is possible to look at either a portion of the core or the entire nuclear output of a reactor throughout its lifetime. Since the sizes of the arrays in GEM are carried as variables, they can be changed to accomodate smaller or larger computers.

Input data are organized on a batch basis. There are sixteen types of cards which may be used to describe a batch's history. The primary options available are shown in Table C-6. Once certain data are inputed for a batch, it remains in effect until changed. For example, if the cost of $U_3O_8$ is specified for the first batch and not specified in following batches, the code automatically used the original cost for all subsequent calculations. This is also true of payment schedules, which are converted to lead times based on batch startup. The code manual states that the only card necessary is the ID card. But it should be noted that burnup data are not converted in the same manner as payments and if there is any shift in time of the burnup period, the code will not compensate. Therefore, the minimum number of cards necessary for a batch is two, the ID and a burnup card.

Code Results

The output for the sample problem in Appendix A is shown in the following figures:

Figure C-1. Case Input,

Figure C-2. Batch Description Page,

Table C-5. Symbols Used in GEM

| | |
|---|---|
| $AF_k$ = | Final value of kth component (if charge for service to be performed in post burn period, the negative of total charge). |
| $AI_k$ = | total initial worth of the kth cost component (zero if charge for service to be performed in post burn period). |
| $b$ = | debt to total capital ratio |
| $BEC_k$ = | expense costs for a typical kth cost component |
| $BIC_k$ = | inventory costs associated with a typical kth cost component time valued to startup |
| $C(t)$ = | fuel cost per unit time |
| $CB_k$ = | burn period cashflows for typical kth cost component |
| $CP_k$ = | preburn inventory charges time valued to startup for a typical kth cost component |
| $CPO_k$ = | postburn time period cash flows for a typical kth cost component referenced to batch startup |
| $d_i$ = | time between ith prepayment and startup date |
| $f1_{i,k}$ = | fraction of total initial investment for kth cost component paid by the ith prepayment |
| $f2_{i,k}$ = | fraction of total cost paid (received) by ith payment (sale) during postburn time zone associated with kth cost component |
| $i$ = | equity return rate |
| $j$ = | average bond interest rate |
| $m_k$ = | number of payments (sales) which make up the total payment (sale) associated with kth cost component during postburn period |
| $n_k$ = | total number of prepayments made for kth cost component |
| $Q_i$ = | thermal energy produced in period i |
| $Q_t$ = | total thermal energy of the batch |
| $Q_{PW}$ = | batch thermal energy time valued to startup |
| $R$ = | income tax rate |
| $s_{i,k}$ = | date that ith payment (sale) takes place for kth cost component |
| $t_n$ = | shutdown date |
| $t_o$ = | startup date |
| $t_{i,k}$ = | $t_i - t_k$ |

Table C-6. Major User Options, GEM

| | |
|---|---|
| Economic Data | |
| | Allows different prices for initial and salvage Calculations |
| | Escalation of all costs in preburn and postburn periods |
| | Input bond interest rate, dividend rate, income tax rate and fraction of capital in bonds |
| | Parity value for discharged or recycled fuel |
| Mass Flow Data | |
| | Allows up to six periods of different power levels for each batch |
| | Recycled plutonium and uranium |
| | Treats plutonium storage separately |
| | Variable losses for fuel cycle processes |
| Input/Output | |
| | Input for one batch applies to all subsequent batches until changed |
| | Output in mills/kwhe or cents/MBTU |
| | Batch output and/or case summary page |

Figure C-3. Batch Economic Analysis Page,

Figure C-4. Case Description Page,

Figure c-5. Batch Summary Page,

Figure C-6. Yearly Batch Costs Page,

Figure c-7. Yearly Case Costs Page,

Figure C-8. Yearly and Cumulative Fuel Cycle Costs Page,

Figure C-9. Batch and Cumulative Fuel Cycle Costs Page,

Figure C-10. Case Evaluation Page.

References

1. JOHN A. HUGHES and DANIEL F. HANG, Program GEM, General Economic Model to Analyze Nuclear Fuel Cycle Costs, University of Illinois, Urbana, Ill., 1973.

2. D. R. VONDY, "Basis and Certain Features of the Discount Technique," ORNL 3686, Appendix F, Oak Ridge National Laboratory, 1965.

3. DANIEL F. HANG, "Fuel Cycle Economics," Education and Research in the Nuclear Fuel Cycle, D. M. Elliot and L. E. Weaver, ed., University of Oklahoma Press, Norman, Okla., 1972.

```
                                        ****************************************************************************************
                                        *                                                                                      *
                                        *                          INPUT TO CODE GEM2 (PWR )                                   *      PAGE   1
                                        *                                                                                      *
                                        *                       BASE PROBLEM - CODE COMPARISON                                 *
                                        *                                                                                      *
                                        ****************************************************************************************

          COLUMN          ........10........20........30........40........50........60........70........80

CONTROL CARD              PWR
DATA CARD NO.   1                                  BASE PROBLEM - CODE COMPARISON
DATA CARD NO.   2                 27      1982      2009         1         1      1983
DATA CARD NO.   3                  1         1         1         1         1         1
DATA CARD NO.   4           BATCH 83A          01/01/1983          01/01/1984
DATA CARD NO.   5              15.00     15.00      1.50      1.50     54.00     54.00        1.         1
DATA CARD NO.   6             100.00     25.00    140.00      5.00                                         2
DATA CARD NO.   7                                                                                          3
DATA CARD NO.   8             12000.    12000.                                                             4
DATA CARD NO.   9             24820.    24487.                        .21236                               5
DATA CARD NO.  10                  1         0         1                                                   6
DATA CARD NO.  11               3.20     2.450      100.      .711        .2                               7
DATA CARD NO.  12                10.        12        31      1983       .33                               8
DATA CARD NO.  13                                    .12                                                   9
DATA CARD NO.  14                  1         0         1                                                  10
DATA CARD NO.  15                  1         1         1         5                                        11
DATA CARD NO.  16         01/01/1982       1.0
DATA CARD NO.  17         03/01/1982       1.0
DATA CARD NO.  18         06/01/1982       1.0
DATA CARD NO.  19         06/01/1982        .2          07/01/1982        .2           08/01/1982       .2
DATA CARD NO.  20         09/01/1982        .2          10/01/1982        .2
DATA CARD NO.  21                  1         1         1         1         1                        1   14
DATA CARD NO.  22         10/01/1984       1.0
DATA CARD NO.  23         10/01/1984       1.0
DATA CARD NO.  24         07/01/1984       1.0
DATA CARD NO.  25         10/01/1984       1.0
DATA CARD NO.  26         10/01/1984       1.0
DATA CARD NO.  27           BATCH 83B          01/01/1983          01/01/1985
DATA CARD NO.  28             24820.    24154.                         .4306                               5
DATA CARD NO.  29               3.20      1.70      100.      .711        .2                               7
DATA CARD NO.  30                20.        12        31      1984       .33                          1    8
DATA CARD NO.  31           BATCH 83C          01/01/1983          01/01/1986
DATA CARD NO.  32             24820.    23820.                         .6507                               5
DATA CARD NO.  33               3.20       .95      100.      .711        .2                               7
DATA CARD NO.  34                30.        12        31      1985       .33                          1    8
DATA CARD NO.  35           BATCH 84           01/01/1984          01/01/1987
DATA CARD NO.  36                                                                                         10
DATA CARD NO.  37                30.        12        31      1986       .33                          1    8
DATA CARD NO.  38           BATCH 85           01/01/1985          01/01/1988
DATA CARD NO.  39                30.        12        31      1987       .33                          1    8
DATA CARD NO.  40           BATCH 86           01/01/1986          01/01/1989
DATA CARD NO.  41                30.        12        31      1988       .33                          1    8
DATA CARD NO.  42           BATCH 87           01/01/1987          01/01/1990
DATA CARD NO.  43                30.        12        31      1989       .33                          1    8
DATA CARD NO.  44           BATCH 88           01/01/1988          01/01/1991
DATA CARD NO.  45                30.        12        31      1990       .33                          1    8
```

Figure C-1. Case Input

```
****************************************************************************************   PAGE  2
*                                                                                      *
*                              INPUT TO CODE GEM2 (PWR )                               *
*                                                                                      *
*                        BASE PROBLEM - CODE COMPARISON                                *
*                                                                                      *
****************************************************************************************

        COLUMN          ........10........20........30........40........50........60........70........80

DATA CARD NO.   46      BATCH 89         01/01/1989          01/01/1992
DATA CARD NO.   47            30.     12          31     1991       .33                        1    8
DATA CARD NO.   48      BATCH 90         01/01/1990          01/01/1993
DATA CARD NO.   49            30.     12          31     1992       .33                        1    8
DATA CARD NO.   50      BATCH 91         01/01/1991          01/01/1994
DATA CARD NO.   51            30.     12          31     1993       .33                        1    8
DATA CARD NO.   52      BATCH 92         01/01/1992          01/01/1995
DATA CARD NO.   53            30.     12          31     1994       .33                        1    8
DATA CARD NO.   54      BATCH 93         01/01/1993          01/01/1996
DATA CARD NO.   55            30.     12          31     1995       .33                        1    8
DATA CARD NO.   56      BATCH 94         01/01/1994          01/01/1997
DATA CARD NO.   57            30.     12          31     1996       .33                        1    8
DATA CARD NO.   58      BATCH 95         01/01/1995          01/01/1998
DATA CARD NO.   59            30.     12          31     1997       .33                        1    8
DATA CARD NO.   60      BATCH 96         01/01/1996          01/01/1999
DATA CARD NO.   61            30.     12          31     1998       .33                        1    8
DATA CARD NO.   62      BATCH 97         01/01/1997          01/01/2000
DATA CARD NO.   63            30.     12          31     1999       .33                        1    8
DATA CARD NO.   64      BATCH 98         01/01/1998          01/01/2001
DATA CARD NO.   65            30.     12          31     2000       .33                        1    8
DATA CARD NO.   66      BATCH 99         01/01/1999          01/01/2002
DATA CARD NO.   67            30.     12          31     2001       .33                        1    8
DATA CARD NO.   68      BATCH 00         01/01/2000          01/01/2003
DATA CARD NO.   69            30.     12          31     2002       .33                        1    8
DATA CARD NO.   70      BATCH 01         01/01/2001          01/01/2004
DATA CARD NO.   71            30.     12          31     2003       .33                        1    8
DATA CARD NO.   72      BATCH 02         01/01/2002          01/01/2005
DATA CARD NO.   73            30.     12          31     2004       .33                        1    8
DATA CARD NO.   74      BATCH 03         01/01/2003          01/01/2006
DATA CARD NO.   75            30.     12          31     2005       .33                        1    8
DATA CARD NO.   76      BATCH 04         01/01/2004          01/01/2007
DATA CARD NO.   77            30.     12          31     2006       .33                        1    8
DATA CARD NO.   78      BATCH 05         01/01/2005          01/01/2008
DATA CARD NO.   79            30.     12          31     2007       .33                        1    8
DATA CARD NO.   80      BATCH 06         01/01/2006          01/01/2008
DATA CARD NO.   81         24820.   24154.                             .4306                        5
DATA CARD NO.   82           3.20    1.70       100.     .711       .2                              7
DATA CARD NO.   83            20.     12          31     2007       .33                        1    8
DATA CARD NO.   84      BATCH 07         01/01/2007          01/01/2008
DATA CARD NO.   85         24820.   24487.                             .21236                       5
DATA CARD NO.   86           3.20    2.450      100.     .711       .2                              7
DATA CARD NO.   87            10.     12          31     2007       .33                        1    8
```

Figure C-1.  Case Input

INITIAL STARTUP DATE: JAN. 1, 1983 | BATCH NO. BATCH 83C | FINAL SHUTDOWN DATE: JAN. 1, 1986

ADJUSTED FUEL WORTHS (INCL. LOSSES)

| | PREBURN | POSTBURN** |
|---|---|---|
| U ($/KG U) | 504.04 | 78.53 |
| PU ($/KG PU) | 12000.00 | 12000.00 |
| FAB. ($/KG FUEL) | 100.00 | |
| TOTAL($/KG FUEL) | 604.04 | 156.10 |

** AFTER REPROCESSING AND RECONVERSION

************************ UNIT COST COMPONENTS (NO LOSSES INCL.) ************************

| | BASE PRICE PREBURN | BASE PRICE POSTBURN | ESCALATED | BASE DATE | ESCALATED PRICE PREBURN | ESCALATED PRICE POSTBURN |
|---|---|---|---|---|---|---|
| U ORE ($/LB U3O8) | 15.00 | 15.00 | NO | | | |
| U CONV.($/LB U) | 1.50 | 1.50 | NO | | | |
| SEP. WK. ($/KG SEP WK) | 54.00 | 54.00 | NO | | | |
| PU ($/KG PU) | 12000.00 | 12000.00 | NO | | | |
| FAB. ($/KG FUEL) | 100.00 | | NO | | | |
| REPROC. ($/KG FUEL) | | 140.00 | NO | | | |
| RECONV. ($/KG U) | | 5.00 | NO | | | |
| SHIP. ($/KG FUEL) | | 25.00 | NO | | | |

NOTE: U COSTS BASED ON FRESH U, FOR RECY. OR SPENT U APPLY PAIRITY FACTOR OF 1.000

LOSSES (PERCENT OF FEED)

| | |
|---|---|
| U3O8 TO UF6 | 0.0 |
| FABRICATION | 0.0 |
| URANIUM REP. | 0.0 |
| PLUTONIUM REP. | 0.0 |

------ECONOMIC PARAMETERS-----

| | |
|---|---|
| BOND INTEREST RATE | 0.0 |
| DEBT RATIO | 0.0 |
| EQUITY RETURN RATE | 0.1200 |
| INCOME TAX RATE | 0.0 |
| ANNUAL DISCOUNT RATE | 0.1200 |
| ANNUAL FIXED CHARGE RATE | 0.1200 |

TOTAL PAYMENTS/SALES/TRANSFERS (NON-TIMEVALUED $1000)

| | PREBURN | POSTBURN |
|---|---|---|
| URANIUM | 12510.178 | -1858.297 |
| PLUTONIUM | 0.0 | -1659.961 |
| FABRICATION | 2482.000 | 0.0 |
| SPENT FUEL SHIPPING | 0.0 | 595.500 |
| REPROCESSING | 0.0 | 3334.800 |
| RECONVERSION | 0.0 | 118.325 |
| TOTAL | 14992.178 | 330.367 |

***************** EXPOSURE TABLE *****************

| | INITIAL | FINAL | PC OF FUEL |
|---|---|---|---|
| BURNUP(MWD/KG) | 0.0 | 30.000 | |
| FUEL (KG) | 24820. | 23820. | |
| WT P.C. PU | 0.0 | 0.651 | |
| WT P.C. U235 | 3.200 | 0.950 | 100.000 |

PREPAYMENT SCHEDULE ( DATE, FRACTION OF TOTAL PAYMENT OR TRANSFER )

| | | | | | |
|---|---|---|---|---|---|
| URANIUM | 1/ 1/1982 0.45, | 3/ 1/1982 0.04, | 6/ 1/1982 0.51, | | |
| FABRICATION | 6/ 1/1982 0.20, | 7/ 1/1982 0.20, | 8/ 1/1982 0.20, | 9/ 1/1982 0.20, | 10/ 1/1982 0.20, |

POSTPAYMENT SCHEDULE ( DATE, FRACTION OF TOTAL PAYMENT OR SALE OR TRANSFER)

| | |
|---|---|
| URANIUM | 10/ 2/1986 1.00, |
| PLUTONIUM | 10/ 2/1986 1.00, |
| SPENT FUEL SHIPPING | 7/ 2/1986 1.00, |
| REPROCESSING | 10/ 2/1986 1.00, |
| RECONVERSION | 10/ 2/1986 1.00, |

Figure C-2. Batch Description Page

INITIAL STARTUP DATE: JAN. 1, 1983 BATCH NO. BATCH 83C FINAL SHUTDOWN DATE: JAN. 1, 1986

TOTAL BATCH COSTS LEVELIZED OVER THE BURN PERIOD (MILLS/KWHE)

TOTAL LEVELIZED COST = 3.3016 MILLS/KWHE TOTAL ENERGY = 4999318590. KWHE

| COST COMPONENT | PREBURN | BURN | POSTBURN | TOTAL | EXPENSE | INVENTORY | TOTAL |
|---|---|---|---|---|---|---|---|
| | ****CASHFLOWS**** | | | | ****ALLOCATED COSTS**** | | |
| POST IRRADIATION | | | | | -0.0016 | | -0.0016 |
| URANIUM | 0.2331 | 2.2379 | 0.0216 | 2.4925 | 2.0393 | 0.4315 | 2.4709 |
| PLUTONIUM | 0.0 | -0.2647 | 0.0216 | -0.2431 | -0.3154 | 0.0506 | -0.2648 |
| FABRICATION | 0.0242 | 0.4565 | 0.0 | 0.5207 | 0.4451 | 0.0756 | 0.5207 |
| SPENT FUEL SHIPPING | 0.0 | 0.0848 | -0.0047 | 0.0801 | 0.1010 | -0.0162 | 0.0848 |
| REPROCESSING | 0.0 | 0.4746 | -0.0387 | 0.4359 | 0.5655 | -0.0907 | 0.4748 |
| RECONVERSION | 0.0 | 0.0168 | -0.0014 | 0.0155 | 0.0201 | -0.0032 | 0.0168 |
| SUBTOTALS | 0.2573 | 3.0459 | -0.0016 | 3.3016 | 2.8540 | 0.4476 | 3.3016 |

YEARLY BATCH COSTS TIMEVALUED TO THE BEGINNING OF THE YEAR ($)

| YEAR | 1982 | 1983 | 1984 | 1985 | 1986 |
|---|---|---|---|---|---|
| URANIUM | 1040351. | 4510579. | 4140337. | 3739487. | 151555. |
| PLUTONIUM | 0. | -553560. | -488305. | -419523. | 151691. |
| FABRICATION | 108025. | 1004619. | 918229. | 825067. | 0. |
| SPENT FUEL SHIPPING | 0. | 177232. | 156340. | 134318. | -32718. |
| REPROCESSING | 0. | 992500. | 875502. | 752179. | -271972. |
| RECONVERSION | 0. | 35216. | 31064. | 26689. | -9650. |
| YEARLY SUBTOTALS | 1148375. | 6166586. | 5633167. | 5058217. | -11095. |
| ENERGY (KWHE) | 0.0 | 0.186D 10 | 0.186D 10 | 0.185D 10 | 0.0 |

Figure C-3. Batch Economic Analysis Page

```
CASE STUDY
1982 TO 2009

BASE PROBLEM - CODE COMPARISON

NUMBER OF BATCHES =    27
```

Figure C-4. Case Description Page

BASE PROBLEM - CODE COMPARISON

BATCH SUMMARY PAGE

| | | | ***TIMEVALUED TO STARTUP*** | | ---ALLOC. COST--- | | ----------CASHFLOW---------- | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **************************MILLS/KWHE************************ | | | | | |
| BATCH NO. | STARTUP | SHUTDOWN | ENERGY--KWHE | TOTAL COST--$ | EXPENSE | INVENTORY | PREBURN | BURN | POSTBURN | TOTAL |
| BATCH 83A | 1/ 1/1983 | 1/ 1/1984 | 1858730742. | 12091533. | 5.9209 | 0.5836 | 0.6920 | 5.6048 | 0.2085 | 6.5053 |
| BATCH 83B | 1/ 1/1983 | 1/ 1/1985 | 3517775904. | 14677507. | 3.6626 | 0.5096 | 0.3656 | 3.7624 | 0.0444 | 4.1724 |
| BATCH 83C | 1/ 1/1983 | 1/ 1/1986 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 84 | 1/ 1/1984 | 1/ 1/1987 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 85 | 1/ 1/1985 | 1/ 1/1988 | 5000051288. | 16505610. | 2.8539 | 0.4472 | 0.2572 | 3.0454 | -0.0016 | 3.3011 |
| BATCH 86 | 1/ 1/1986 | 1/ 1/1989 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 87 | 1/ 1/1987 | 1/ 1/1990 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 88 | 1/ 1/1988 | 1/ 1/1991 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 89 | 1/ 1/1989 | 1/ 1/1992 | 5000051288. | 16505610. | 2.8539 | 0.4472 | 0.2572 | 3.0454 | -0.0016 | 3.3011 |
| BATCH 90 | 1/ 1/1990 | 1/ 1/1993 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 91 | 1/ 1/1991 | 1/ 1/1994 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 92 | 1/ 1/1992 | 1/ 1/1995 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 93 | 1/ 1/1993 | 1/ 1/1996 | 5000051288. | 16505610. | 2.8539 | 0.4472 | 0.2572 | 3.0454 | -0.0016 | 3.3011 |
| BATCH 94 | 1/ 1/1994 | 1/ 1/1997 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 95 | 1/ 1/1995 | 1/ 1/1998 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 96 | 1/ 1/1996 | 1/ 1/1999 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 97 | 1/ 1/1997 | 1/ 1/2000 | 5000051288. | 16505610. | 2.8539 | 0.4472 | 0.2572 | 3.0454 | -0.0016 | 3.3011 |
| BATCH 98 | 1/ 1/1998 | 1/ 1/2001 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 99 | 1/ 1/1999 | 1/ 1/2002 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 00 | 1/ 1/2000 | 1/ 1/2003 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 01 | 1/ 1/2001 | 1/ 1/2004 | 5000051288. | 16505610. | 2.8539 | 0.4472 | 0.2572 | 3.0454 | -0.0016 | 3.3011 |
| BATCH 02 | 1/ 1/2002 | 1/ 1/2005 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 03 | 1/ 1/2003 | 1/ 1/2006 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 04 | 1/ 1/2004 | 1/ 1/2007 | 4999318990. | 16505540. | 2.8540 | 0.4476 | 0.2573 | 3.0459 | -0.0016 | 3.3016 |
| BATCH 05 | 1/ 1/2005 | 1/ 1/2008 | 5000051288. | 16505610. | 2.8539 | 0.4472 | 0.2572 | 3.0454 | -0.0016 | 3.3011 |
| BATCH 06 | 1/ 1/2006 | 1/ 1/2008 | 3518301461. | 14677010. | 3.6626 | 0.5089 | 0.3656 | 3.7617 | 0.0444 | 4.1716 |
| BATCH 07 | 1/ 1/2007 | 1/ 1/2008 | 1858730742. | 12091533. | 5.9209 | 0.5836 | 0.6920 | 5.6048 | 0.2085 | 6.5053 |

Figure C-5. Batch Summary Page

BASE PROBLEM - CODE COMPARISON

YEARLY BATCH COSTS TIMEVALUED TO THE BEGINNING OF THE YEAR ($)

| BATCH NO. | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 |
|---|---|---|---|---|---|---|---|---|---|---|
| BATCH 83A | 1148375. | 10416312. | 434134. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 83B | 1148375. | 7215045. | 6629556. | 155865. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 83C | 1148375. | 6166586. | 5633167. | 5058217. | -11095. | 0. | 0. | 0. | 0. | 0. |
| BATCH 84 | 0. | 1148375. | 6181816. | 5617853. | 5058217. | -11095. | 0. | 0. | 0. | 0. |
| BATCH 85 | 0. | 0. | 1148019. | 6170755. | 5623021. | 5062873. | -11095. | 0. | 0. | 0. |
| BATCH 86 | 0. | 0. | 0. | 1148375. | 6166586. | 5619352. | 5072119. | -11095. | 0. | 0. |
| BATCH 87 | 0. | 0. | 0. | 0. | 1148375. | 6166586. | 5633167. | 5058217. | -11095. | 0. |
| BATCH 88 | 0. | 0. | 0. | 0. | 0. | 1148375. | 6181816. | 5617853. | 5058217. | -11095. |
| BATCH 89 | 0. | 0. | 0. | 0. | 0. | 0. | 1148019. | 6170755. | 5623021. | 5062873. |
| BATCH 90 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1148375. | 6166586. | 5619352. |
| BATCH 91 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1148375. | 6166586. |
| BATCH 92 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1148375. |
| BATCH 93 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 94 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 95 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 96 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 97 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 98 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 99 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 00 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 01 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 02 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 03 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 04 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 05 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 06 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 07 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| YEARLY SUBTOTALS | 3445126. | 25046319. | 20027131. | 18191065. | 17985104. | 17986092. | 18024025. | 17984105. | 17985104. | 17986052. |
| ENERGY (KWHE) | 0.0 | 0.558D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 |

Figure C-6. Yearly Batch Costs Page

BASE PROBLEM - CODE COMPARISON

YEARLY BATCH COSTS TIMEVALUED TO THE BEGINNING OF THE YEAR ($)

| BATCH NO. | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
|---|---|---|---|---|---|---|---|---|---|---|
| BATCH 83A | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 83B | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 83C | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 84 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 85 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 86 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 87 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 88 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 89 | -11095. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 90 | 5072119. | -11095. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 91 | 5633167. | 5058217. | -11095. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 92 | 6181816. | 5617853. | 5058217. | -11095. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 93 | 1148019. | 6170755. | 5623021. | 5062873. | -11095. | 0. | 0. | 0. | 0. | 0. |
| BATCH 94 | 0. | 1148375. | 6166586. | 5619352. | 5072119. | -11095. | 0. | 0. | 0. | 0. |
| BATCH 95 | 0. | 0. | 1148375. | 6166586. | 5633167. | 5058217. | -11095. | 0. | 0. | 0. |
| BATCH 96 | 0. | 0. | 0. | 1148375. | 6181816. | 5617853. | 5058217. | -11095. | 0. | 0. |
| BATCH 97 | 0. | 0. | 0. | 0. | 1148019. | 6170755. | 5623021. | 5062873. | -11095. | 0. |
| BATCH 98 | 0. | 0. | 0. | 0. | 0. | 1148375. | 6166586. | 5619352. | 5072119. | -11095. |
| BATCH 99 | 0. | 0. | 0. | 0. | 0. | 0. | 1148375. | 6166586. | 5633167. | 5058217. |
| BATCH 00 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1148375. | 6181816. | 5617853. |
| BATCH 01 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1148019. | 6170755. |
| BATCH 02 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1148375. |
| BATCH 03 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 04 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 05 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 06 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 07 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| YEARLY SUBTOTALS | 18024025. | 17984105. | 17985104. | 17986092. | 18024025. | 17984105. | 17985104. | 17986092. | 18024025. | 17984105. |
| ENERGY (KWHE) | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 |

Figure C-6. Yearly Batch Costs Page

BASE PROBLEM - CODE COMPARISON

YEARLY BATCH COSTS TIMEVALUED TO THE BEGINNING OF THE YEAR ($)

| BATCH NO. | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|
| BATCH 83A | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 83B | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 83C | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 84 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 85 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 86 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 87 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 88 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 89 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 90 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 91 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 92 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 93 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 94 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 95 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 96 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 97 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 98 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 99 | -11095. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 00 | 5058217. | -11095. | 0. | 0. | 0. | 0. | 0. | 0. |
| BATCH 01 | 5623021. | 5062873. | -11095. | 0. | 0. | 0. | 0. | 0. |
| BATCH 02 | 6166536. | 5619352. | 5072119. | -11095. | 0. | 0. | 0. | 0. |
| BATCH 03 | 1148375. | 6166586. | 5633167. | 5058217. | -11095. | 0. | 0. | 0. |
| BATCH 04 | 0. | 1148375. | 6181816. | 5617853. | 5058217. | -11095. | 0. | 0. |
| BATCH 05 | 0. | 0. | 1148019. | 6170755. | 5623021. | 5062873. | -11095. | 0. |
| BATCH 06 | 0. | 0. | 0. | 1148375. | 7322876. | 6620614. | 155869. | 0. |
| BATCH 07 | 0. | 0. | 0. | 0. | 1148375. | 10416312. | 434134. | 0. |
| YEARLY SUBTOTALS | 17585104. | 17586052. | 18024025. | 17584105. | 19141394. | 22088705. | 618907. | 0. |
| ENERGY (KWHE) | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.0 | 0.0 |

Figure C-6. Yearly Batch Costs Page

BASE PROBLEM - CODE COMPARISON

YEARLY CASE COSTS TIMEVALUED TO THE BEGINNING OF THE YEAR ($)

| YEAR | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 |
|---|---|---|---|---|---|---|---|---|---|
| URANIUM | 3121052. | 14990244. | 14674916. | 13835277. | 13574677. | 13575363. | 13603395. | 13573982. | 13574677. |
| PLUTONIUM | 0. | -1668063. | -1482637. | -1358750. | -1308970. | -1309089. | -1312224. | -1308848. | -1308970. |
| FABRICATION | 324074. | 4568608. | 3274321. | 2854119. | 2854281. | 2854441. | 2860654. | 2854119. | 2854231. |
| SPENT FUEL SHIPPING | 0. | 993563. | 537555. | 434441. | 434939. | 434977. | 435981. | 434900. | 434939. |
| REPROCESSING | 0. | 5563951. | 2919294. | 2342874. | 2346905. | 2347120. | 2352740. | 2346688. | 2346905. |
| RECONVERSION | 0. | 158017. | 103643. | 83108. | 83273. | 83280. | 83480. | 83265. | 83273. |
| YEARLY SUBTOTALS | 3445126. | 25046319. | 20027131. | 18191069. | 17985104. | 17986092. | 18024025. | 17984105. | 17985104. |
| ENERGY (KWHE) | 0.0 | 0.558D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 |

| YEAR | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|---|---|---|
| URANIUM | 13575363. | 13603395. | 13573982. | 13574677. | 13575363. | 13603395. | 13573982. | 13574677. | 13575363. |
| PLUTONIUM | -1309089. | -1312224. | -1308848. | -1308970. | -1309089. | -1312224. | -1308848. | -1308970. | -1309089. |
| FABRICATION | 2854441. | 2860654. | 2854119. | 2854281. | 2854441. | 2860654. | 2854119. | 2854281. | 2854441. |
| SPENT FUEL SHIPPING | 434977. | 435981. | 434900. | 434939. | 434977. | 435981. | 434900. | 434939. | 434977. |
| REPROCESSING | 2347120. | 2352740. | 2346688. | 2346905. | 2347120. | 2352740. | 2346688. | 2346905. | 2347120. |
| RECONVERSION | 83280. | 83480. | 83265. | 83273. | 83280. | 83480. | 83265. | 83273. | 83280. |
| YEARLY SUBTOTALS | 17986092. | 18024025. | 17984105. | 17985104. | 17986092. | 18024025. | 17984105. | 17985104. | 17986092. |
| ENERGY (KWHE) | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 |

| YEAR | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| URANIUM | 13603395. | 13573982. | 13574677. | 13575363. | 13603395. | 13573982. | 13734037. | 12928081. | 1270833. |
| PLUTONIUM | -1312224. | -1308848. | -1308970. | -1309089. | -1312224. | -1308848. | -1313355. | -1315529. | 304371. |
| FABRICATION | 2860654. | 2854119. | 2854281. | 2854441. | 2860654. | 2854119. | 2225146. | 4547119. | 0. |
| SPENT FUEL SHIPPING | 435981. | 434900. | 434939. | 434977. | 435981. | 434900. | 527652. | 885515. | -59529. |
| REPROCESSING | 2352740. | 2346688. | 2346905. | 2347120. | 2352740. | 2346688. | 2866101. | 4870134. | -827346. |
| RECONVERSION | 83480. | 83265. | 83273. | 83280. | 83480. | 83265. | 101814. | 173385. | -29421. |
| YEARLY SUBTOTALS | 18024025. | 17984105. | 17985104. | 17986092. | 18024025. | 17984105. | 19141394. | 22088705. | 618907. |
| ENERGY (KWHE) | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.558D 10 | 0.557D 10 | 0.557D 10 | 0.557D 10 | 0.0 |

Figure C-7. Yearly Case Costs Page

BASE PROBLEM - CODE COMPARISON

YEARLY CASE COSTS TIMEVALUED TO THE BEGINNING OF THE YEAR ($)

| | |
|---|---|
| YEAR | 2009 |
| URANIUM | 0. |
| PLUTONIUM | 0. |
| FABRICATION | 0. |
| SPENT FUEL SHIPPING | 0. |
| REPROCESSING | 0. |
| RECONVERSION | 0. |
| YEARLY SUBTOTALS | 0. |
| ENERGY (KWHE) | 0.0 |

Figure C-7. Yearly Case Costs Page

EASE PROBLEM - CODE COMPARISON

YEARLY AND CUMULATIVE FUEL CYCLE COSTS

| | ***** YEARLY COSTS ***** TIMEVALUED TO BEGINNING OF YEAR | | | ***** CUMULATIVE COSTS ***** TIMEVALUED TO JAN. 1, 1983 | | |
|---|---|---|---|---|---|---|
| YEAR | FUEL COSTS 10X6 $ | ENERGY 10X9 KWHE | LEVL. COSTS MILLS/KWHE | FUEL COSTS 10X6 $ | ENERGY 10X9 KWHE | LEVL. COSTS MILLS/KWHE |
| 1982 | 3.445126 | 0.0 | | 3.858541 | 0.0 | |
| 1983 | 25.046319 | 5.575626037 | 4.4921 | 28.904860 | 5.575626037 | 5.1941 |
| 1984 | 20.027131 | 5.584558592 | 3.5859 | 46.786728 | 10.562196208 | 4.4256 |
| 1985 | 18.191069 | 5.572232387 | 3.2646 | 61.283534 | 15.002966724 | 4.0849 |
| 1986 | 17.985104 | 5.572232387 | 3.2276 | 74.081002 | 18.967940430 | 3.9056 |
| 1987 | 17.986092 | 5.572227991 | 3.2278 | 85.507940 | 22.508092675 | 3.7990 |
| 1988 | 18.024025 | 5.584958592 | 3.2272 | 95.732081 | 25.676164362 | 3.7284 |
| 1989 | 17.984105 | 5.572232387 | 3.2275 | 104.837733 | 28.497478183 | 3.6788 |
| 1990 | 17.985104 | 5.572232387 | 3.2276 | 112.958230 | 31.016508380 | 3.6422 |
| 1991 | 17.986092 | 5.572227991 | 3.2278 | 120.229001 | 33.265640710 | 3.6142 |
| 1992 | 18.024025 | 5.584558592 | 3.2272 | 126.723611 | 35.278382509 | 3.5921 |
| 1993 | 17.984105 | 5.572232387 | 3.2275 | 132.508620 | 37.070821827 | 3.5745 |
| 1994 | 17.985104 | 5.572232387 | 3.2276 | 137.674054 | 38.671214075 | 3.5601 |
| 1995 | 17.986092 | 5.572227991 | 3.2278 | 142.286378 | 40.100134598 | 3.5483 |
| 1996 | 18.024025 | 5.584558592 | 3.2272 | 146.413173 | 41.378371302 | 3.5384 |
| 1997 | 17.984105 | 5.572232387 | 3.2275 | 150.088510 | 42.517645261 | 3.5300 |
| 1998 | 17.985104 | 5.572232387 | 3.2276 | 153.370243 | 43.534407724 | 3.5230 |
| 1999 | 17.986092 | 5.572227991 | 3.2278 | 156.300523 | 44.442230635 | 3.5167 |
| 2000 | 18.024025 | 5.584558592 | 3.2272 | 158.922362 | 45.254638645 | 3.5117 |
| 2001 | 17.984105 | 5.572232387 | 3.2275 | 161.257360 | 45.979125413 | 3.5073 |
| 2002 | 17.985104 | 5.572232387 | 3.2276 | 163.342333 | 46.624095742 | 3.5034 |
| 2003 | 17.986092 | 5.572227991 | 3.2278 | 165.204000 | 47.200854509 | 3.5000 |
| 2004 | 18.024025 | 5.584558592 | 3.2272 | 166.869709 | 47.716954205 | 3.4971 |
| 2005 | 17.984105 | 5.572232387 | 3.2275 | 168.353195 | 48.176540388 | 3.4945 |
| 2006 | 19.141394 | 5.574781658 | 3.4336 | 169.762970 | 48.537226524 | 3.4940 |
| 2007 | 22.088705 | 5.570244482 | 3.5655 | 171.215512 | 48.953522923 | 3.4975 |
| 2008 | 0.618907 | 0.0 | | 171.251851 | 48.953522923 | 3.4983 |
| 2009 | 0.0 | 0.0 | | 171.251851 | 48.953522923 | 3.4983 |

Figure C-8. Yearly and Cumulative Fuel Cycle Costs Page

BASE PROBLEM - CODE COMPARISON

BATCH AND CUMULATIVE FUEL CYCLE COSTS

| BATCH NUMBER | ****** BATCH COSTS ****** TIMEVALUED TO BATCH STARTUP FUEL COSTS 10X6 $ | ENERGY 10X9 KWHE | LEVL. COSTS MILLS/KWHE | ****** CUMULATIVE COSTS ****** TIMEVALUED TO JAN. 1, 1983 FUEL COSTS 10X6 $ | ENERGY 10X9 KWHE | LEVL. COSTS MILLS/KWHE |
|---|---|---|---|---|---|---|
| BATCH 83A | 12.091533 | 1.858730742 | 6.5053 | 12.091533 | 1.858730742 | 6.5053 |
| BATCH 83B | 14.677507 | 3.517775904 | 4.1724 | 26.769040 | 5.376506646 | 4.9789 |
| BATCH 83C | 16.505540 | 4.999318990 | 3.3016 | 43.274580 | 10.375825636 | 4.1707 |
| BATCH 84 | 16.505540 | 4.999318990 | 3.3016 | 58.011667 | 14.839503305 | 3.9093 |
| BATCH 85 | 16.505610 | 5.000051288 | 3.3011 | 71.165756 | 18.824276157 | 3.7805 |
| BATCH 86 | 16.505540 | 4.999318990 | 3.3016 | 82.910426 | 22.381587987 | 3.7044 |
| BATCH 87 | 16.505540 | 4.999318990 | 3.3016 | 93.396738 | 25.557759263 | 3.6543 |
| BATCH 88 | 16.505540 | 4.999318990 | 3.3016 | 102.759517 | 28.393626474 | 3.6191 |
| BATCH 89 | 16.505610 | 5.000051288 | 3.3011 | 111.116582 | 30.925235500 | 3.5931 |
| BATCH 90 | 16.505540 | 4.999318990 | 3.3016 | 118.578215 | 33.185269652 | 3.5732 |
| BATCH 91 | 16.505540 | 4.999318990 | 3.3016 | 125.240387 | 35.203157288 | 3.5576 |
| BATCH 92 | 16.505540 | 4.999318990 | 3.3016 | 131.188755 | 37.004842678 | 3.5452 |
| BATCH 93 | 16.505610 | 5.000051288 | 3.3011 | 136.498172 | 38.613226517 | 3.5350 |
| BATCH 94 | 16.505540 | 4.999318990 | 3.3016 | 141.238703 | 40.049073194 | 3.5266 |
| BATCH 95 | 16.505540 | 4.999318990 | 3.3016 | 145.471319 | 41.331079156 | 3.5197 |
| BATCH 96 | 16.505540 | 4.999318990 | 3.3016 | 149.250441 | 42.475727336 | 3.5133 |
| BATCH 97 | 16.505610 | 5.000051288 | 3.3011 | 152.623624 | 43.497567023 | 3.5088 |
| BATCH 98 | 16.505540 | 4.999318990 | 3.3016 | 155.635382 | 44.409750264 | 3.5045 |
| BATCH 99 | 16.505540 | 4.999318990 | 3.3016 | 158.324451 | 45.224275301 | 3.5009 |
| BATCH 00 | 16.505540 | 4.999318990 | 3.3016 | 160.725406 | 45.951494084 | 3.4977 |
| BATCH 01 | 16.505610 | 5.000051288 | 3.3011 | 162.868459 | 46.600690078 | 3.4950 |
| BATCH 02 | 16.505540 | 4.999318990 | 3.3016 | 164.781691 | 47.180244466 | 3.4926 |
| BATCH 03 | 16.505540 | 4.999318990 | 3.3016 | 166.490313 | 47.697703741 | 3.4905 |
| BATCH 04 | 16.505540 | 4.999318990 | 3.3016 | 168.015689 | 48.159720551 | 3.4887 |
| BATCH 05 | 16.505610 | 5.000051288 | 3.3011 | 169.377216 | 48.572168661 | 3.4871 |
| BATCH 06 | 14.677010 | 3.518301461 | 4.1716 | 170.458187 | 48.831293750 | 3.4908 |
| BATCH 07 | 12.091533 | 1.858730742 | 6.5053 | 171.253319 | 48.953522923 | 3.4983 |

Figure C-9. Batch and Cumulative Fuel Cycle Costs Page

BASE PROBLEM - CODE COMPARISON

ALL ENTRIES TIMEVALUED TO 1/ 1/1983

TOTAL CASE COSTS LEVELIZED OVER THE PERIOD 1/ 1/1982 TO 10/ 1/2008 (MILLS/KWHE)

| COST COMPONENT | PREBURN | BURN | POSTBURN | TOTAL | EXPENSE | INVENTORY | TOTAL |
|---|---|---|---|---|---|---|---|
| | ******* | CASHFLOWS | ******* | | ******* | ALLOCATED COSTS | ******* |
| POST IRRADIATION | | | | | 0.0105 | | 0.0105 |
| URANIUM | 0.2566 | 2.2645 | 0.0400 | 2.5610 | 2.0758 | 0.4451 | 2.5209 |
| PLUTONIUM | 0.0 | -0.2675 | 0.0218 | -0.2457 | -0.3156 | 0.0480 | -0.2676 |
| FABRICATION | 0.0266 | 0.5465 | 0.0 | 0.5732 | 0.4978 | 0.0754 | 0.5732 |
| SPENT FUEL SHIPPING | 0.0 | 0.0972 | -0.0053 | 0.0919 | 0.1136 | -0.0163 | 0.0973 |
| REPROCESSING | 0.0 | 0.5446 | -0.0444 | 0.5002 | 0.6359 | -0.0912 | 0.5447 |
| RECONVERSION | 0.0 | 0.0193 | -0.0016 | 0.0178 | 0.0226 | -0.0032 | 0.0193 |
| SUBTOTALS | 0.2832 | 3.2046 | 0.0105 | 3.4983 | 3.0404 | 0.4578 | 3.4983 |

TOTAL COSTS = 171253319. DOLLARS
TOTAL ENERGY = 48953522923. KWHE
LEVELIZED COSTS = 3.4983 MILLS/KWHE

Figure C-10. Case Evaluation Page

# APPENDIX D: COMPUTER CODE GACOST

## General

GACOST is a very flexible computer code for calculating fuel costs developed by Gulf General Atomic Company. It calculates total fuel cycle costs and running costs on the basis of given mass flows, in-core residence times, capacity factors, reactor power, ore costs, and fuel handling costs. Accompanying the code in a manual which contains both a description of the code and a basic course in the theory of fuel cycle cost calculations.

## Theoretical Procedure

GACOST uses as a theoretical basis the discounted energy cost method as opposed to the discounted cash flow method. To illustrate the difference between these two method, consider first the discounted cash flow equation for the levelized cost of fuel,

$$P = \frac{\sum_{i=1}^{n} X(i)\ PWF(i)}{\sum_{i=1}^{n} E(i)\ PWF(i)} \qquad \text{(D-1)}$$

This equation states that the levelized cost of energy is the ratio of the present worth of all cash flows to the present worth of all energy production over the levelizing period. In this formula the index i represents an accounting period and X(i) represents the net cash flow in that accounting period.

Now consider each accounting period separately. Each cost component has a definite value at the beginning of the period and another smaller value at the end of the period. The net change in this value must be offset by the sale of energy during the period. The unit energy price necessary to do this can be calculated by the following procedure. First, present worth the value of the component at the beginning of the accounting period to the midpoint of the accounting period. Next, present worth the value of the component at the end of the accounting period back to the midpoint of the accounting period. The total cost to be accounted for is then the difference between these two values. Similarly, if the energy production is assumed uniform over the entire accounting period, it is equivalent to a single total energy production at the midpoint of the interval. Then, for any accounting period n, the cost of a particular cost component is

$$CRIS(s,n) = \frac{P_i * PWF(I_{ic},-\ell_n/2) - P_f * PWF(I_{ic},\ell_n/2)}{E(s,n)} \qquad \text{(D-2)}$$

where $I_{ic}$ is the interest rate, $\ell_n$ is the length of the accounting period, and the index s indicates the batch.

To calculate total costs it is necessary only to take the energy weighted sums. For instance, the total cost in a particular accounting period is

$$FCR(n) = \frac{\sum_{s=1}^{S} FC(s,n) * E(s,n)}{\sum_{s=1}^{S} E(s,n)} \qquad \text{(D-3)}$$

where FC(s,n) is the total cost of all components, or

$$FC(s,n) = \sum_{j=1}^{J} CRIS_j(s,n) \qquad \text{(D-4)}$$

If you now define

$$E(n) = \sum_{s=1}^{S} E(s,n) \qquad \text{(D-5)}$$

the levelized cost of fuel over several time periods is simply

$$FCC(0\text{-}L\ intervals) = \frac{\sum_{n=1}^{L} FCR(n) * E(n) * PWF(I,T_n)}{\sum_{n=1}^{L} E(n) * PWF(I,T_n)} \qquad (D\text{-}6)$$

A summary of the steps used in the discounted energy method is shown in Tables D-1 and D-2. According to the manual provided with the code, this method provides the following advantages over the discounted cash flow method.

1. Capability to use different working capital rates during pre-irradiation, in-core, and post-irradiation time intervals.
2. Fuel cycle costs for individual batches are calculated.
3. Fuel cycle costs per reload interval are calculated.
4. It is more convenient to model various amortization and fuel contract options.

The amortization of costs referred to in 4, above, pertains to the determination of the cost component value at the beginning and end of each accounting period. The code input allows the user to designate the value of the cost component at insertion and removal. The code then uses these values to determine appropriate accounting period values by one of two methods.

1. Constant Running Cost Per Segment. There are two costs associated with a cost component, the direct costs and indirect cost. In GACOST, the direct costs are reduced to a per unit energy basis for each accounting period. Selection of this method of amortization is equivalent to selecting a straight line method of depreciation.

2. Constant Total Cost Per Segment. In this method the sum of the running costs and indirect costs are kept constant.

Amortization method 1 provides a smaller total cost since the invested principle is retired at a faster rate. However, it can lead to a higher levelized cost since a greater amount of payment is made early in the batch

Table D-1. Primary Calculational Steps in the Discounted Energy Cost Method

1. Calculate unit energy cost for each cost component for each batch in each accounting period.
2. Sum cost components to obtain unit energy cost for each batch in each accounting period.
3. Calculate total accounting period cost by taking an energy weighted sum of accounting period batch costs.
4. Calculate levelized cost by taking an energy weighted present worth sum of total accounting period costs.

Table D-2. Formulas Used for Calculation of Fuel Cycle Costs, Discounted Energy Cost Method

$$CRIS(s,n) = \frac{P_i * PWF(I_{ic},-\ell_n/2) - P_f * PWF(I_{ic},\ell_n/2)}{E(s,n)}$$

$$FC(s,n) = \sum_{j=1}^{J} CRIS_j(s,n)$$

$$E(n) = \sum_{s=1}^{S} E(s,n)$$

$$FCR(n) = \frac{\sum_{s=1}^{S} FC(s,n)\ E(s,n)}{E(n)}$$

$$FCC(\text{0-L intervals}) = \frac{\sum_{n=1}^{L} FCR(n)\ E(n)\ PWF(I,T_n)}{\sum_{n=1}^{L} E(n)\ PWF(I,T_n)}$$

history and therefore receives more emphasis in present worth calculations. It should be noted that these amortization methods are for all cost components except fuel depletion. In fuel depletion it is necessary to account for the value of the fuel at discharge. To calculate this discharge value, GACOST allows time dependent input of cost data and the application of amortization methods 1 and 2.

The initial value of each cost component (including fuel) is increased by the capital charges on payments made prior to insertion in the core. These charges are defined as the difference between the actual value of the investment at startup and the value of the prepayments present-worthed to startup, or

$$PRW = EXPNX \left\{ \sum_{j=1}^{J} X_j * PWF(I_{pre}, -TPAY_j) - \sum_{j-1}^{J} X_j \right\} \tag{D-7}$$

Similarly, the value of the fuel at discharge must be decreased by the capital charges to be paid while it undergoes reprocessing, or

$$POSTWC = VTOT \left\{ 1.0 - PWF(I_{post}, TCOOL) * PWF(I', TBYB) \right\} \tag{D-8}$$

Other cost components which have payments or receipts in the post-irradiation period are treated in the same manner.

## Code Capabilities

GACOST was developed by the only major vendor of thorium fuel cycle reactors. This fact and the necessity to handle uranium fuel cycles have probably combined to produce the single most outstanding feature of the code. It has the capability of handling any imaginable fuel cycle, from a simple uranium thermal reactor to a recycle, uranium-thorium breeder. This capability includes comprehensive adjustments for recycle fuel poisons such as $U^{236}$ and $U^{232}$. The code combines this capability with several methods of inputing mass flow data and an internal auditing system which insures the correspondence of energy production and mass flow data. Although the system is large enough to be cumbersome, it provides excellent flexibility for fuel cycle design studies.

The other major feature of GACOST is the treatment of inputed cost data. In addition to accepting costs on a periodic basis, GACOST will also escalate all costs based on inputed material and labor costs rates of escalation. Additionally, the code will adjust downward the fuel element fabrication costs according to an analytical learning curve specified by the user.

The limitations of GACOST are primarily in the area of capital charges. Although the discounted energy cost method allows different interest rates in different portions of the cycle for each batch of fuel, the interest rates is an overall figure which does not allow for the investigation of the effect of, for example, changing capital structure on the fuel cycle cost. The output of GACOST is also limited by the calculational method with few exceptions calculated values are output in mills/kwhe, which may be an inconvenient number for comparison of, for example, shipping costs for two batches or several years. With this exception, however, the output of GACOST is well organized and subject to extensive user editing.

The major options offered by GACOST are shown in Table D-4.

Code Results

The output for the sample problem in Appendix A is in the following figures:

Figure D-1. Table 2. Plant Characteristics,

Figure D-2. Table 4. Progress Payments,

Figure D-3. Table 5. Time Characteristics,

Table D-3. Symbols Used in GACOST

| | | |
|---|---|---|
| CRIS(s,n) | = | Component fuel cycle cost per reload interval n per segment s, m/kwh |
| E(n) | = | Total energy produced by the core during reload interval n, kwh(e) |
| E(s,n) | = | Energy produced by segment s during reload interval n, kwhe |
| EXPNX | = | Total expense of product or service |
| FC(s,n) | = | Fuel cycle cost for segment s during reload interval (or accounting period) n, m/kwh. |
| FCC(O=L) | = | Average fuel cycle cost for the core levelized over the first L reload intervals. |
| FCR(n) | = | Average fuel cycle cost for the core levelized over the first Y years |
| I' | = | Interest rate applicable during post-irradiation period; equals WCRC($I_{post}$) in normal fuel cycle or equal WCRG($I_v$) for "buyback" cycle |
| $I_{ic}$ | = | In-core working capital rate |
| $I_{pre}$ | = | Pre-irradiation working capital interest rate |
| $I_{post}$ | = | Post-irradiation working capital rate used in the non "buyback" cycle |
| n | = | Duration of reload interval n, years |
| $P_i$ | = | Principal value at the beginning of a reload interval |
| $P_f$ | = | Principal value at the end of a reload interval |
| POSTWC(s) | = | Fuel post-irradiation working capital expense of segment s |
| PWF(I,y) | = | Present worth factor; equals the present worth of $1 received y years hence with an annual interest rate I, = $(1 + 1)^{-y}$ where I is a fraction |
| TBYB | = | Time interval from end of cooling period to time of sale |
| TCOOL(s) | = | Cooling time; the average time for spent fuel cooling prior to shipping segment s, years |
| $TPAY_j$ | = | (T(J)) Time interval between payment j and time segment commences power operation, years |
| VTOT | = | Final fuel value at time when segment is reprocessed |
| $X_j$ | = | Fraction of total expense corresponding to payment j |

Table D-4. Major User Options, GACOST

| | |
|---|---|
| Economic Data | |
| | Different interest rates for preburn, burn, postburn and present worth calculations |
| | Input Cost data on yearly or batch basis<br>Escalation of all cost data |
| | Fabrication learning curve |
| | Two methods of cost amortization |
| | Losses and fuel poison penalties input in tabular form |
| | Preburn indirect cost calculations optional |
| | Two methods for calculating Fabrication costs |
| Mass Flow Data | |
| | Accepts any number of fuel types in each fuel batch |
| | Four methods for fuel depletion |
| | Three methods for inputing energy production |
| | Capacity factors input by reload interval or year |
| Input/Output | |
| | Selection of 31 separate output tables |

BASE PROBLEM - CODE COMPARISON

```
ELECTRICAL POWER (MW)..................      792.
NET EFFICIENCY.........................     0.330
NUMBER OF FUEL ELEMENTS................       204
NUMBER OF CORE REGIONS.................         3
NUMBER OF SEGMENTS.....................        27
NUMBER OF RELOAD-INTERVALS.............        25
NUMBER OF RELOAD-INTERVALS BEF. EQUILIB.       25
NUMBER OF RELOAD-INTERV. PER EQUIL.CYCLE        3
NUMBER OF FUEL TYPES...................         1
YEAR OF REACTOR STARTUP................      1983
MONTH OF REACTOR STARTUP...............         1

PRE-IRRADIATION WORKING CAPITAL RATE....    0.120
POST-IRRADIATION WORKING CAPITAL RATE...    0.120
IN-CORE WORKING CAPITAL RATE............    0.120
VENDOR WORKING CAPITAL RATE.............    0.120
DISCOUNT RATE...........................    0.120

USE FINAL WEIGHTS TO CALCULATE POST-IRRADIATION COSTS
THE IN-CORE DEVALUATION IS BASED ON THE ENERGY PRODUCED
THE ORE-,FABRICATION-,AND HANDLING-COST ARE CONSTANT  DURING EACH YEAR
THE ENERGY PER RELOAD-INTERVAL AND SEGMENT IS READ IN
THE RUNNING COSTS OF A SEGMENT IS CONSTANT DURING ITS RESIDENT-TIME IN THE REACTOR
```

Figure D-1. Table 2. Plant Characteristics

```
P R O G R E S S   P A Y M E N T S

X  :  FRACTION OF TOTAL PAYMENT
T  :  TIME OF PAYMENT PRIOR TO INSERTION

PURCHASE OF ORE
SEGMENT   1 TO  27                  1 PAYMENTS
T = 1.0000       X =  1.000

CONVERSION
SEGMENT   1 TO  27                  1 PAYMENTS
T = 0.8333       X =  1.000

ENRICHMENT
SEGMENT   1 TO  27                  1 PAYMENTS
T = 0.5833       X =  1.000

FABRICATION
SEGMENT   1 TO  27                  5 PAYMENTS
T = 0.5833       X =  0.200
T = 0.5000       X =  0.200
T = 0.4167       X =  0.200
T = 0.3333       X =  0.200
T = 0.2500       X =  0.200

PURCHASE OF RECYCLE FUEL
SEGMENT   1 TO  27                  0 PAYMENTS
T = 0.0          X =  1.000
```

Figure D-2. Table 4. Progress Payments

BASE PROBLEM - CODE COMPARISON

TIME CHARACTERISTICS
(YEARS)

| SEGMENT | * ORE *PURCHASE | PRE - CONVER-SION | IRRADIATION - SEPARA-TION | - TIME FABRI-CATION | PUR. RECY* | * IN CORE RESIDENCE | SPENT FUEL COOLING | SHIPPING | DELAY BEFORE REPRO. | CHEMICAL REPRO. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 1.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 2 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 2.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 3 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 4 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 5 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 6 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 7 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 8 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 9 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 10 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 11 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 12 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 13 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 14 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 15 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 16 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 17 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 18 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 19 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 20 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 21 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 22 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 23 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 24 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 25 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 3.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 26 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 2.000 | 0.333 | 0.250 | 0.0 | 0.250 |
| 27 | 1.000 | 0.833 | 0.583 | 0.583 | 0.0 | 1.000 | 0.333 | 0.250 | 0.0 | 0.250 |

Figure D-3. Table 5. Time Characteristics

R E L O A D - C H A R A C T E R I S T I C S
WHEN AND WHERE SEGMENT NUMBER I IS IN THE REACTOR

| RELOAD-TIME | | | CORE REGIONS | | |
|---|---|---|---|---|---|
| YEAR | MO. | TIME | 1 | 2 | 3 |
| 1983 | 0.0 | 0.0 | | | |
| | | | 1 | 2 | 3 |
| 1984 | 0.0 | 1.00 | | | |
| | | | 4 | 2 | 3 |
| 1985 | 0.0 | 2.00 | | | |
| | | | 4 | 5 | 3 |
| 1986 | 0.0 | 3.00 | | | |
| | | | 4 | 5 | 6 |
| 1987 | 0.0 | 4.00 | | | |
| | | | 7 | 5 | 6 |
| 1988 | 0.0 | 5.00 | | | |
| | | | 7 | 8 | 6 |
| 1989 | 0.0 | 6.00 | | | |
| | | | 7 | 8 | 9 |
| 1990 | 0.0 | 7.00 | | | |
| | | | 10 | 8 | 9 |
| 1991 | 0.0 | 8.00 | | | |
| | | | 10 | 11 | 9 |
| 1992 | 0.0 | 9.00 | | | |
| | | | 10 | 11 | 12 |
| 1993 | 0.0 | 10.00 | | | |
| | | | 13 | 11 | 12 |
| 1994 | 0.0 | 11.00 | | | |
| | | | 13 | 14 | 12 |
| 1995 | 0.0 | 12.00 | | | |
| | | | 13 | 14 | 15 |
| 1996 | 0.0 | 13.00 | | | |
| | | | 16 | 14 | 15 |
| 1997 | 0.0 | 14.00 | | | |
| | | | 16 | 17 | 15 |
| 1998 | 0.0 | 15.00 | | | |
| | | | 16 | 17 | 18 |
| 1999 | 0.0 | 16.00 | | | |
| | | | 19 | 17 | 18 |
| 2000 | 0.0 | 17.00 | | | |
| | | | 19 | 20 | 18 |
| 2001 | 0.0 | 18.00 | | | |
| | | | 19 | 20 | 21 |
| 2002 | 0.0 | 19.00 | | | |
| | | | 22 | 20 | 21 |
| 2003 | 0.0 | 20.00 | | | |
| | | | 22 | 23 | 21 |
| 2004 | 0.0 | 21.00 | | | |
| | | | 22 | 23 | 24 |
| 2005 | 0.0 | 22.00 | | | |
| | | | 25 | 23 | 24 |
| 2006 | 0.0 | 23.00 | | | |
| | | | 25 | 26 | 24 |
| 2007 | 0.0 | 24.00 | | | |
| | | | 25 | 26 | 27 |
| 2008 | 0.0 | 25.00 | | | |

Figure D-4. Table 6. Reload Characteristics

BASE PROBLEM - CODE COMPARISON

FUEL COST PARAMETERS BY YEAR

| YEAR | ENRICHMENT OF FEED U(%) | U308 ($/LB) | U3O8 CONVERSION TO UF6 ($/KG) | U AS UF6 ($/KGU) | SEPARATIVE WORK ($/KG) | VALUE U233/U235 | PLUTONIUM PARITY CALCULATED | PLUTONIUM VALUE ($/GM) | TAILS ENRICHMENT (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1980 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1981 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1982 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1983 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1984 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1985 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1986 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1987 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1988 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1989 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1990 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1991 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1992 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1993 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1994 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1995 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1996 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1997 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1998 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 1999 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2000 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2001 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2002 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2003 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2004 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2005 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2006 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2007 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2008 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2009 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2010 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2011 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2012 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2013 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2014 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2015 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2016 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2017 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2018 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2019 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |
| 2020 | 0.711 | 15.00 | 3.31 | 42.31 | 54.00 | 0.0 | 0.55 | 12.00 | 0.200 |

Figure D-5. Table 8. Fuel Handling Cost Parameters

BASE PROBLEM - CODE COMPARISON

FUEL COMPOSITION BY SEGMENT

| SEGMENT | FUEL TYPE | AT INSERTION KGU TOTAL | U 235 KG | U 236 KG | KG PU FISSILE | WT % U235/ TOTAL U | % FISSILE PU OF INITIAL U | AT DISCHARGE KGU TOTAL | U 235 KG | U 236 KG | KG PU FISSILE | % U OF INITIAL U | WT % U235/ TOTAL U | % FISSILE PU OF INITIAL U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 24486. | 599.9 | 0.0 | 52.0 | 98.65 | 2.45 | 0.21 |
| 2 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 24153. | 410.6 | 0.0 | 104.0 | 97.31 | 1.70 | 0.42 |
| 3 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 4 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 5 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 6 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 7 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 8 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 9 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 10 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 11 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 12 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 13 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 14 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 15 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 16 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 17 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 18 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 19 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 20 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 21 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 22 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 23 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 24 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 25 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 23820. | 226.3 | 0.0 | 155.0 | 95.97 | 0.95 | 0.62 |
| 26 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 24153. | 410.6 | 0.0 | 104.0 | 97.31 | 1.70 | 0.42 |
| 27 | 1 | 24820. | 794.2 | 0.0 | 0.0 | 3.20 | 0.0 | 24486. | 599.9 | 0.0 | 52.0 | 98.65 | 2.45 | 0.21 |

Figure D-6. Table 10. Source and Disposition of Fuel

BASE PROBLEM - CODE COMPARISON

FUEL VALUE (MILLIONS OF DOLLARS) (INCLUDING LOSSES AND PENALTIES)

| SEGMENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U235 MAKEUP | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 |
| TOTAL U CHARGED | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 |
| TOTAL FUEL LOADED | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 |
| U235 RETIRED | 8.691 | 5.090 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 |
| TOTAL U RETIRED | 8.691 | 5.090 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 |
| TOTAL U DISCHARGED | 8.691 | 5.050 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 |
| PLUTONIUM DISCHARGED | 0.624 | 1.248 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 |
| TOTAL FUEL DISCHARGED | 9.315 | 6.338 | 3.733 | 3.733 | 3.733 | 2.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 |

Figure D-7. Table 17. Fuel Values at Insertion and Discharge for Each Segment

BASE PROBLEM - CODE COMPARISON

| SEGMENT | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FUEL VALUE (MILLIONS OF DOLLARS) (INCLUDING LOSSES AND PENALTIES) | | | | | | | | | | | |
| U235 MAKEUP | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 |
| TOTAL U CHARGED | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 |
| TOTAL FUEL LOADED | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 | 12.526 |
| U235 RETIRED | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 |
| TOTAL U RETIRED | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 |
| TOTAL U DISCHARGED | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 | 1.873 |
| PLUTONIUM DISCHARGED | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 | 1.860 |
| TOTAL FUEL DISCHARGED | 3.733 | 3.733 | 3.733 | 3.723 | 3.733 | 2.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 |

Figure D-7. Table 17. Fuel Values at Insertion and Discharge for Each Segment

BASE PROBLEM - CODE COMPARISON

FUEL VALUE (MILLIONS OF DOLLARS) (INCLUDING LOSSES AND PENALTIES)

| SEGMENT | 25 | 26 | 27 |
|---|---|---|---|
| U235 MAKEUP | 12.526 | 12.526 | 12.526 |
| TOTAL U CHARGED | 12,526 | 12.526 | 12.526 |
| TOTAL FUEL LOADED | 12.526 | 12.526 | 12.526 |
| U235 RETIRED | 1.873 | 5.090 | 8.691 |
| TOTAL U RETIRED | 1.873 | 5.C50 | 8.651 |
| TOTAL U DISCHARGED | 1.873 | 5.C90 | 8.691 |
| PLUTONIUM DISCHARGED | 1.860 | 1.248 | 0.624 |
| TOTAL FUEL DISCHARGED | 3.733 | 6.338 | 9.315 |

Figure D-7. Table 17. Fuel Values at Insertion and Discharge for Each Segment

BASE PROBLEM - CODE COMPARISON

VALUES AND COSTS PER RELOAD-INTERVAL AND SEGMENT (WORKING CAPITALS INCLUDED IF SPECIFIED)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RELOAD-INTERVAL | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 |
| REGION | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| SEGMENT | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 5 | 3 | 4 | 5 | 6 |
| INITIAL TIME | 0.0 | 0.0 | 0.0 | 1.0000 | 1.0000 | 1.0000 | 2.0000 | 2.0000 | 2.0000 | 3.0000 | 3.0000 | 3.0000 |
| FINAL TIME | 1.0000 | 1.0000 | 1.0000 | 2.0000 | 2.0000 | 2.0000 | 3.0000 | 3.0000 | 3.0000 | 4.0000 | 4.0000 | 4.0000 |
| ENERGY PROD. KWH(E) XE+9 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 | 1.9657 |
| INITIAL VALUES ($ MILLIONS) | | | | | | | | | | | | |
| URANIUM 233 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| URANIUM 235 | 13.6904 | 13.6904 | 13.6904 | 13.6904 | 5.3904 | 9.7514 | 9.7514 | 13.6904 | 5.8124 | 5.8124 | 9.7514 | 13.6904 |
| PLUTONIUM | 0.0 | 0.0 | 0.0 | 0.0 | 0.6240 | 0.6200 | 0.6200 | 0.0 | 1.2400 | 1.2400 | 0.6200 | 0.0 |
| FUEL | 13.6904 | 13.6904 | 13.6904 | 13.6904 | 10.0144 | 10.3714 | 10.3714 | 13.6904 | 7.0524 | 7.0524 | 10.3714 | 13.6904 |
| FABRICATION | 2.6022 | 2.6022 | 2.6022 | 2.6022 | 1.3011 | 1.7348 | 1.7348 | 2.6022 | 0.8674 | 0.8674 | 1.7348 | 2.6022 |
| SHIPPING | 0.6134 | 0.6064 | 0.5994 | 0.5994 | 0.3032 | 0.3996 | 0.3996 | 0.5994 | 0.1998 | 0.1998 | 0.3996 | 0.5994 |
| STORAGE | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| REPROCESSING | 3.5580 | 3.5173 | 3.4764 | 3.4764 | 1.7586 | 2.3176 | 2.3176 | 3.4764 | 1.1588 | 1.1588 | 2.3176 | 3.4764 |
| FINAL VALUES ($ MILLIONS) | | | | | | | | | | | | |
| URANIUM 233 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| URANIUM 235 | 8.6907 | 9.3904 | 9.7514 | 9.7514 | 5.0903 | 5.8124 | 5.8124 | 9.7514 | 1.8734 | 1.8734 | 5.8124 | 9.7514 |
| PLUTONIUM | 0.6240 | 0.6240 | 0.6200 | 0.6200 | 1.2480 | 1.2400 | 1.2400 | 0.6200 | 1.8600 | 1.8600 | 1.2400 | 0.6200 |
| FUEL | 9.3147 | 10.0144 | 10.3714 | 10.3714 | 6.3383 | 7.0524 | 7.0524 | 10.3714 | 3.7334 | 3.7334 | 7.0524 | 10.3714 |
| FABRICATION | 0.0 | 1.3011 | 1.7348 | 1.7348 | 0.0 | 0.8674 | 0.8674 | 1.7348 | 0.0 | 0.0 | 0.8674 | 1.7348 |
| SHIPPING | 0.0 | 0.3032 | 0.3996 | 0.3996 | 0.0 | 0.1998 | 0.1998 | 0.3996 | 0.0 | 0.0 | 0.1998 | 0.3996 |
| STORAGE | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| REPROCESSING | 0.0 | 1.7586 | 2.3176 | 2.3176 | 0.0 | 1.1588 | 1.1588 | 2.3176 | 0.0 | 0.0 | 1.1588 | 2.3176 |
| RUNNING COSTS (MILLS/KWH) | | | | | | | | | | | | |
| URANIUM 233 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| URANIUM 235 | 2.5434 | 2.1875 | 2.0038 | 2.0038 | 2.1875 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 |
| PLUTONIUM | -0.3174 | -0.3174 | -0.3154 | -0.3154 | -0.3174 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 |
| FUEL | 2.2260 | 1.8701 | 1.6884 | 1.6884 | 1.8701 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 |
| FABRICATION COST | 1.3238 | 0.6619 | 0.4413 | 0.4413 | 0.6619 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 |
| SHIPPING COST | 0.3121 | 0.1542 | 0.1016 | 0.1016 | 0.1542 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 |
| STORAGE COST | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| REPROCESSING COST | 1.8100 | 0.8946 | 0.5895 | 0.5895 | 0.8946 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 |
| TOTAL RUNNING COST | 5.6719 | 3.5808 | 2.8208 | 2.8208 | 3.5808 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 |
| WORKING CAPITAL COSTS (MILLS/KWH) | | | | | | | | | | | | |
| URANIUM 233 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| URANIUM 235 | 0.9506 | 0.7691 | 0.7038 | 0.7038 | 0.5210 | 0.4766 | 0.4766 | 0.7038 | 0.2494 | 0.2494 | 0.4766 | 0.7038 |
| PLUTONIUM | 0.0420 | 0.0420 | 0.0417 | 0.0417 | 0.0780 | 0.0775 | 0.0775 | 0.0417 | 0.1132 | 0.1132 | 0.0775 | 0.0417 |
| FUEL | 1.0326 | 0.8110 | 0.7455 | 0.7455 | 0.5990 | 0.5541 | 0.5541 | 0.7455 | 0.3626 | 0.3626 | 0.5541 | 0.7455 |
| FABRICATION COST | 0.0772 | 0.1136 | 0.1258 | 0.1258 | 0.0386 | 0.0758 | 0.0758 | 0.1258 | 0.0257 | 0.0257 | 0.0758 | 0.1258 |
| SHIPPING COST | -0.0321 | -0.0175 | -0.0134 | -0.0134 | -0.0307 | -0.0212 | -0.0212 | -0.0134 | -0.0290 | -0.0290 | -0.0212 | -0.0134 |
| STORAGE COST | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| REPROCESSING COST | -0.2316 | -0.1235 | -0.0919 | -0.0919 | -0.1981 | -0.1358 | -0.1358 | -0.0919 | -0.1797 | -0.1797 | -0.1358 | -0.0919 |
| TOTAL WORKING CAPITAL COST | 0.8460 | 0.7838 | 0.7661 | 0.7661 | 0.4088 | 0.4729 | 0.4729 | 0.7661 | 0.1797 | 0.1797 | 0.4729 | 0.7661 |
| TOTAL COST (MILLS/KWH) | | | | | | | | | | | | |
| FUEL CYCLE COST | 6.5179 | 4.3646 | 3.5869 | 3.5869 | 3.9896 | 3.2937 | 3.2937 | 3.5869 | 3.0005 | 3.0005 | 3.2937 | 3.5869 |

Figure D-8. Table 20. Values and Costs Per Reload-Interval and Segment

BASE PROBLEM - CODE COMPARISON

EXPENDITURES, VALUES AND COSTS PER SEGMENT

| SEGMENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NUMBER OF FUEL ELEMENTS | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 |
| VOLUME FRACTION | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 |
| TIME SEGMENT LOADED | 0.0 | 0.0 | 0.0 | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 |
| TIME SEGMENT DISCHARGE | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 | 10.00 | 11.00 | 12.00 |
| ENERGY PRODUCED E+9KWH | 1.966 | 3.931 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 |
| ORE REQUIREMENT (TONS) | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 |
| UNITS SEPARATIVE WORK | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. |
| TAIL ENRICHMENT (%) | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 |
| EXPENDITURES AND SALES ($ MILLIONS) (WITHOUT WORKING CAPITALS) | | | | | | | | | | | | |
| PURCHASE OF ORE | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 |
| CONVERSION COST | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 |
| SEPARATIVE WORK | 6.362 | 6.352 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 |
| FABRICATION COST | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 |
| SHIPPING COST | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| REPROCESSING COST | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| BUYBACK VALUE | 4.912 | 2.106 | -0.345 | -0.345 | -0.345 | -0.345 | -0.345 | -0.345 | -0.345 | -0.345 | -0.345 | -0.345 |
| FINAL FUEL VALUE | 9.315 | 6.338 | 3.733 | 3.733 | 3.733 | 2.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 |
| RUNNING COST (MILLS/KWH) | | | | | | | | | | | | |
| URANIUM 235 | 2.5434 | 2.1875 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 |
| PLUTONIUM | -0.3174 | -0.3174 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 |
| FUEL | 2.2260 | 1.8701 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 |
| FABRICATION COST | 1.3238 | 0.6619 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 |
| SHIPPING COST | 0.2121 | 0.1542 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 |
| REPROCESSING COST | 1.8100 | 0.8946 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 |
| TOTAL RUNNING COST | 5.6718 | 3.5803 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 |
| WORKING CAPITAL COST (MILLS/KWH) | | | | | | | | | | | | |
| URANIUM 235 | 0.9906 | 0.6521 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 |
| PLUTONIUM | 0.0420 | 0.0590 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 |
| FUEL | 1.0326 | 0.7110 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 |
| FABRICATION COST | 0.0772 | 0.0782 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 |
| SHIPPING COST | -0.0321 | -0.0237 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 |
| REPROCESSING COST | -0.2316 | -0.1587 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 |
| TOTAL WORKING CAP COST | 0.8460 | 0.6069 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 |
| TOTAL COST (MILLS/KWH) | | | | | | | | | | | | |
| FUEL CYCLE COST | 6.5179 | 4.1877 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 |

Figure D-9. Table 22. Expenditures, Values and Costs Per Segment

BASE PROBLEM - CODE COMPARISON

EXPENDITURES, VALUES AND COSTS PER SEGMENT

| SEGMENT | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NUMBER OF FUEL ELEMENTS | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 |
| VOLUME FRACTION | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 | 0.3333 |
| TIME SEGMENT LOADED | 10.00 | 11.00 | 12.00 | 13.00 | 14.00 | 15.00 | 16.00 | 17.00 | 18.00 | 19.00 | 20.00 | 21.00 |
| TIME SEGMENT DISCHARGE | 13.00 | 14.00 | 15.00 | 16.00 | 17.00 | 18.00 | 19.00 | 20.00 | 21.00 | 22.00 | 23.00 | 24.00 |
| ENERGY PRODUCED E+9KWH | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 | 5.897 |
| ORE REQUIREMENT (TONS) | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 | 189.4 |
| UNITS SEPARATIVE WORK | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. | 118. |
| TAIL ENRICHMENT (%) | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.2000 |
| EXPENDITURES AND SALES ($ MILLIONS) (WITHOUT WORKING CAPITALS) | | | | | | | | | | | | |
| PURCHASE OF ORE | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 | 5.682 |
| CONVERSION COST | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 | 0.482 |
| SEPARATIVE WORK | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 | 6.362 |
| FABRICATION COST | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 | 2.4820 |
| SHIPPING COST | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| REPROCESSING COST | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| FINAL FUEL VALUE | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 | 3.733 |
| RUNNING COST (MILLS/KWH) | | | | | | | | | | | | |
| URANIUM 235 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 | 2.0038 |
| PLUTONIUM | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 | -0.3154 |
| FUEL | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 | 1.6884 |
| FABRICATION COST | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 | 0.4413 |
| SHIPPING COST | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 | 0.1016 |
| REPROCESSING COST | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 | 0.5895 |
| TOTAL RUNNING COST | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 | 2.8208 |
| WORKING CAPITAL COST (MILLS/KWH) | | | | | | | | | | | | |
| URANIUM 235 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 | 0.4937 |
| PLUTONIUM | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 | 0.0748 |
| FUEL | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 | 0.5685 |
| FABRICATION COST | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 | 0.0795 |
| SHIPPING COST | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 | -0.0206 |
| REPROCESSING COST | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 | -0.1325 |
| TOTAL WORKING CAP COST | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 | 0.4950 |
| TOTAL COST (MILLS/KWH) | | | | | | | | | | | | |
| FUEL CYCLE COST | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 | 3.3158 |

Figure D-9. Table 22. Expenditures, Values and Costs Per Segment

BASE PROBLEM - CODE COMPARISON

EXPENDITURES, VALUES AND COSTS PER SEGMENT

| SEGMENT | 25 | 26 | 27 |
|---|---|---|---|
| NUMBER OF FUEL ELEMENTS | 68 | 68 | 68 |
| VOLUME FRACTION | 0.3333 | 0.3333 | 0.3333 |
| TIME SEGMENT LOADED | 22.00 | 23.00 | 24.00 |
| TIME SEGMENT DISCHARGE | 25.00 | 25.00 | 25.00 |
| ENERGY PRODUCED E+9KWH | 5.897 | 3.931 | 1.966 |
| ORE REQUIREMENT (TONS) | 189.4 | 189.4 | 189.4 |
| UNITS SEPARATIVE WORK | 118. | 118. | 118. |
| TAIL ENRICHMENT (%) | 0.2000 | 0.2000 | 0.2000 |
| EXPENDITURES AND SALES ($ MILLIONS) (WITHOUT WORKING CAPITALS) | | | |
| PURCHASE OF ORE | 5.682 | 5.682 | 5.682 |
| CONVERSION COST | 0.482 | 0.482 | 0.482 |
| SEPARATIVE WORK | 6.362 | 6.362 | 6.362 |
| FABRICATION COST | 2.4820 | 2.4820 | 2.4820 |
| SHIPPING COST | 0.0 | 0.0 | 0.0 |
| REPROCESSING COST | 0.0 | 0.0 | 0.0 |
| BUYBACK VALUE | -0.345 | 2.106 | 4.912 |
| FINAL FUEL VALUE | 3.733 | 6.338 | 9.315 |
| RUNNING COST (MILLS/KWH) | | | |
| URANIUM 235 | 2.0038 | 2.1875 | 2.5434 |
| PLUTONIUM | -0.3154 | -0.3174 | -0.3174 |
| FUEL | 1.6884 | 1.8701 | 2.2260 |
| FABRICATION COST | 0.4413 | 0.6619 | 1.3238 |
| SHIPPING COST | 0.1016 | 0.1542 | 0.3121 |
| REPROCESSING COST | 0.5895 | 0.8946 | 1.8100 |
| TOTAL RUNNING COST | 2.8208 | 3.5808 | 5.6718 |
| WORKING CAPITAL COST (MILLS/KWH) | | | |
| URANIUM 235 | 0.4937 | 0.6521 | 0.9906 |
| PLUTONIUM | 0.0748 | 0.0590 | 0.0420 |
| FUEL | 0.5685 | 0.7110 | 1.0326 |
| FABRICATION COST | 0.0795 | 0.0782 | 0.0772 |
| SHIPPING COST | -0.0206 | -0.0237 | -0.0321 |
| REPROCESSING COST | -0.1325 | -0.1587 | -0.2216 |
| TOTAL WORKING CAP COST | 0.4950 | 0.6069 | 0.8460 |
| TOTAL COST (MILLS/KWH) | | | |
| FUEL CYCLE COST | 3.3158 | 4.1877 | 6.5179 |

Figure D-9. Table 22. Expenditures, Values and Costs Per Segment

LEVELIZED FUEL COSTS VS. TIME

| TIME (YEARS) | U233 R.C. | U235 R.C. | U R.C. | PU R.C. | FUEL R.C. | U233 W.C. | U235 W.C. | U W.C. | PU W.C. | FUEL W.C. | FUEL COST |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 - 1.00 | 0.0 | 2.245 | 2.245 | -0.317 | 1.928 | 0.0 | 0.821 | 0.821 | 0.042 | 0.863 | 2.791 |
| 0.0 - 2.00 | 0.0 | 2.160 | 2.160 | -0.316 | 1.844 | 0.0 | 0.701 | 0.701 | 0.053 | 0.754 | 2.598 |
| 0.0 - 3.00 | 0.0 | 2.114 | 2.114 | -0.316 | 1.798 | 0.0 | 0.635 | 0.635 | 0.060 | 0.695 | 2.493 |
| 0.0 - 4.00 | 0.0 | 2.091 | 2.091 | -0.316 | 1.775 | 0.0 | 0.602 | 0.602 | 0.064 | 0.666 | 2.440 |
| 0.0 - 5.00 | 0.0 | 2.077 | 2.077 | -0.316 | 1.761 | 0.0 | 0.582 | 0.582 | 0.066 | 0.648 | 2.409 |
| 0.0 - 6.00 | 0.0 | 2.068 | 2.068 | -0.316 | 1.752 | 0.0 | 0.569 | 0.569 | 0.067 | 0.636 | 2.389 |
| 0.0 - 7.00 | 0.0 | 2.062 | 2.062 | -0.316 | 1.746 | 0.0 | 0.560 | 0.560 | 0.068 | 0.628 | 2.374 |
| 0.0 - 8.00 | 0.0 | 2.057 | 2.057 | -0.316 | 1.741 | 0.0 | 0.553 | 0.553 | 0.069 | 0.622 | 2.363 |
| 0.0 - 9.00 | 0.0 | 2.053 | 2.053 | -0.316 | 1.738 | 0.0 | 0.548 | 0.548 | 0.070 | 0.618 | 2.355 |
| 0.0 -10.00 | 0.0 | 2.051 | 2.051 | -0.316 | 1.735 | 0.0 | 0.544 | 0.544 | 0.070 | 0.614 | 2.349 |
| 0.0 -11.00 | 0.0 | 2.048 | 2.048 | -0.316 | 1.733 | 0.0 | 0.541 | 0.541 | 0.071 | 0.611 | 2.344 |
| 0.0 -12.00 | 0.0 | 2.046 | 2.046 | -0.316 | 1.731 | 0.0 | 0.538 | 0.538 | 0.071 | 0.609 | 2.340 |
| 0.0 -13.00 | 0.0 | 2.045 | 2.045 | -0.316 | 1.729 | 0.0 | 0.536 | 0.536 | 0.071 | 0.607 | 2.336 |
| 0.0 -14.00 | 0.0 | 2.044 | 2.044 | -0.316 | 1.728 | 0.0 | 0.534 | 0.534 | 0.071 | 0.605 | 2.333 |
| 0.0 -15.00 | 0.0 | 2.043 | 2.043 | -0.316 | 1.727 | 0.0 | 0.532 | 0.532 | 0.071 | 0.604 | 2.331 |
| 0.0 -16.00 | 0.0 | 2.042 | 2.042 | -0.316 | 1.726 | 0.0 | 0.531 | 0.531 | 0.072 | 0.603 | 2.329 |
| 0.0 -17.00 | 0.0 | 2.041 | 2.041 | -0.316 | 1.725 | 0.0 | 0.530 | 0.530 | 0.072 | 0.602 | 2.327 |
| 0.0 -18.00 | 0.0 | 2.040 | 2.040 | -0.316 | 1.725 | 0.0 | 0.529 | 0.529 | 0.072 | 0.601 | 2.325 |
| 0.0 -19.00 | 0.0 | 2.040 | 2.040 | -0.316 | 1.724 | 0.0 | 0.528 | 0.528 | 0.072 | 0.600 | 2.324 |
| 0.0 -20.00 | 0.0 | 2.039 | 2.039 | -0.316 | 1.724 | 0.0 | 0.527 | 0.527 | 0.072 | 0.599 | 2.323 |
| 0.0 -21.00 | 0.0 | 2.039 | 2.039 | -0.316 | 1.723 | 0.0 | 0.527 | 0.527 | 0.072 | 0.599 | 2.322 |
| 0.0 -22.00 | 0.0 | 2.038 | 2.038 | -0.316 | 1.723 | 0.0 | 0.526 | 0.526 | 0.072 | 0.598 | 2.321 |
| 0.0 -23.00 | 0.0 | 2.038 | 2.038 | -0.316 | 1.722 | 0.0 | 0.526 | 0.526 | 0.072 | 0.598 | 2.320 |
| 0.0 -24.00 | 0.0 | 2.038 | 2.038 | -0.316 | 1.723 | 0.0 | 0.526 | 0.526 | 0.072 | 0.598 | 2.323 |
| 0.0 -25.00 | 0.0 | 2.040 | 2.040 | -0.316 | 1.724 | 0.0 | 0.526 | 0.526 | 0.072 | 0.598 | 2.322 |

Figure D-10. Table 23. Reload Interval Fuel Cycle Costs vs. Time

BASE PROBLEM - CCDE CCMPARISON

LEVELIZED FUEL CYCLE COSTS VS. TIME
MILLS/KWH

| TIME (YEARS) | FUEL FAB R.C. | FUEL BURNUP R.C. | SPENT FUEL SHIPPING | STORAGE R.C. | CHEM REPRG R.C. | RUNNING COST | FAB WRKG CAP | FUEL WRKG CAP | SHIPPING WRKG CAP | STCRAGE WRKG CAP | REPRO. WRKG CAP | WRKG CAP SUB-TOT | TOTAL FUEL CYC COST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 - 1.00 | 0.809 | 1.928 | 0.189 | 0.0 | 1.098 | 4.024 | 0.106 | 0.863 | -0.021 | 0.0 | -0.149 | 0.799 | 4.823 |
| 0.0 - 2.00 | 0.670 | 1.844 | 0.156 | 0.0 | 0.906 | 3.576 | 0.094 | 0.754 | -0.021 | 0.0 | -0.146 | 0.681 | 4.257 |
| 0.0 - 3.00 | 0.602 | 1.798 | 0.140 | 0.0 | 0.812 | 3.352 | 0.088 | 0.655 | -0.021 | 0.0 | -0.143 | 0.619 | 3.972 |
| 0.0 - 4.00 | 0.569 | 1.775 | 0.132 | 0.0 | 0.766 | 3.241 | 0.086 | 0.666 | -0.021 | 0.0 | -0.141 | 0.589 | 3.830 |
| 0.0 - 5.00 | 0.549 | 1.761 | 0.127 | 0.0 | 0.738 | 3.175 | 0.084 | 0.648 | -0.021 | 0.0 | -0.140 | 0.570 | 3.745 |
| 0.0 - 6.00 | 0.535 | 1.752 | 0.124 | 0.0 | 0.720 | 3.131 | 0.083 | 0.636 | -0.021 | 0.0 | -0.140 | 0.558 | 3.690 |
| 0.0 - 7.00 | 0.526 | 1.746 | 0.122 | 0.0 | 0.707 | 3.101 | 0.082 | 0.628 | -0.021 | 0.0 | -0.139 | 0.550 | 3.651 |
| 0.0 - 8.00 | 0.519 | 1.741 | 0.120 | 0.0 | 0.697 | 3.078 | 0.082 | 0.622 | -0.021 | 0.0 | -0.139 | 0.544 | 3.621 |
| 0.0 - 9.00 | 0.514 | 1.738 | 0.119 | 0.0 | 0.690 | 3.060 | 0.081 | 0.618 | -0.021 | 0.0 | -0.139 | 0.539 | 3.599 |
| 0.0 - 10.00 | 0.510 | 1.735 | 0.118 | 0.0 | 0.684 | 3.047 | 0.081 | 0.614 | -0.021 | 0.0 | -0.139 | 0.535 | 3.592 |
| 0.0 - 11.00 | 0.506 | 1.733 | 0.117 | 0.0 | 0.680 | 3.036 | 0.081 | 0.611 | -0.021 | 0.0 | -0.139 | 0.532 | 3.568 |
| 0.0 - 12.00 | 0.504 | 1.731 | 0.117 | 0.0 | 0.676 | 3.027 | 0.081 | 0.609 | -0.021 | 0.0 | -0.138 | 0.530 | 3.557 |
| 0.0 - 13.00 | 0.502 | 1.729 | 0.116 | 0.0 | 0.673 | 3.020 | 0.080 | 0.607 | -0.021 | 0.0 | -0.138 | 0.528 | 3.547 |
| 0.0 - 14.00 | 0.500 | 1.728 | 0.116 | 0.0 | 0.670 | 3.013 | 0.080 | 0.605 | -0.021 | 0.0 | -0.138 | 0.526 | 3.539 |
| 0.0 - 15.00 | 0.498 | 1.727 | 0.115 | 0.0 | 0.668 | 3.008 | 0.080 | 0.604 | -0.021 | 0.0 | -0.138 | 0.525 | 3.533 |
| 0.0 - 16.00 | 0.497 | 1.726 | 0.115 | 0.0 | 0.666 | 3.004 | 0.080 | 0.603 | -0.021 | 0.0 | -0.138 | 0.523 | 3.527 |
| 0.0 - 17.00 | 0.496 | 1.725 | 0.115 | 0.0 | 0.665 | 3.000 | 0.080 | 0.602 | -0.021 | 0.0 | -0.138 | 0.522 | 3.522 |
| 0.0 - 18.00 | 0.495 | 1.725 | 0.114 | 0.0 | 0.663 | 2.997 | 0.080 | 0.601 | -0.021 | 0.0 | -0.138 | 0.521 | 3.518 |
| 0.0 - 19.00 | 0.494 | 1.724 | 0.114 | 0.0 | 0.662 | 2.994 | 0.080 | 0.600 | -0.021 | 0.0 | -0.138 | 0.521 | 3.515 |
| 0.0 - 20.00 | 0.493 | 1.724 | 0.114 | 0.0 | 0.661 | 2.992 | 0.080 | 0.599 | -0.021 | 0.0 | -0.138 | 0.520 | 3.512 |
| 0.0 - 21.00 | 0.492 | 1.723 | 0.114 | 0.0 | 0.660 | 2.990 | 0.080 | 0.599 | -0.021 | 0.0 | -0.138 | 0.519 | 3.509 |
| 0.0 - 22.00 | 0.492 | 1.723 | 0.114 | 0.0 | 0.659 | 2.988 | 0.080 | 0.598 | -0.021 | 0.0 | -0.138 | 0.519 | 3.507 |
| 0.0 - 23.00 | 0.491 | 1.722 | 0.114 | 0.0 | 0.659 | 2.986 | 0.080 | 0.598 | -0.021 | 0.0 | -0.138 | 0.518 | 3.505 |
| 0.0 - 24.00 | 0.492 | 1.723 | 0.114 | 0.0 | 0.659 | 2.987 | 0.080 | 0.598 | -0.021 | 0.0 | -0.138 | 0.518 | 3.505 |
| 0.0 - 25.00 | 0.494 | 1.724 | 0.114 | 0.0 | 0.662 | 2.995 | 0.079 | 0.598 | -0.021 | 0.0 | -0.139 | 0.518 | 3.513 |

Figure D-11. Table 27. Levelized Fuel Cycle Costs vs. Time

BASE PROBLEM - CODE COMPARISON

YEARLY CASH FLOW (MILLIONS OF $)

| YEAR | PURCHASE, OF ORE | CONVERSION COST | SEPARATION COST | PURCHASE RECYCLE | FABRICATION COST | SHIPPING COST | STORAGE COST | REPROCESSING COST | SALE OF SPENT FUEL | TOTAL COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 1981 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1982 | 17.0466 | 1.4469 | 19.0846 | 0.0 | 7.4460 | 0.0 | 0.0 | 0.0 | 0.0 | 45.0241 |
| 1983 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | 0.0 | 15.0080 |
| 1984 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | 4.9124 | 10.0957 |
| 1985 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | 2.1058 | 12.9022 |
| 1986 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1987 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1988 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1989 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1990 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1991 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1992 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1993 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1994 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1995 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1996 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1997 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1998 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 1999 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2000 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2001 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2002 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2003 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2004 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2005 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2006 | 5.6822 | 0.4823 | 6.3615 | -0.0000 | 2.4820 | 0.0 | 0.0 | 0.0 | -0.3446 | 15.3526 |
| 2007 | 0.0 | 0.0 | 0.0 | -0.0000 | 0.0 | 0.0 | 0.0 | 0.0 | -0.3446 | 0.3446 |

Figure D-12. Table 19. Yearly Cash Flow

BASE PROBLEM - CODE COMPARISON

| SEGMENT NO. | FIRST CYCLE IN CORE | FINAL BURNUP (MWD/MWT) | BURNUP PER RELOAD INTERVAL FROM INITIAL LOADING (MWD/MWT) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 1 | 10000. | 10000. | | | | | | | | | |
| 2 | 1 | 20000. | 10000. | 10000. | | | | | | | | |
| 3 | 1 | 30000. | 10000. | 10000. | 10000. | | | | | | | |
| 4 | 2 | 30000. | | 10000. | 10000. | 10000. | | | | | | |
| 5 | 3 | 30000. | | | 10000. | 10000. | 10000. | | | | | |
| 6 | 4 | 30000. | | | | 10000. | 10000. | 10000. | | | | |
| 7 | 5 | 30000. | | | | | 10000. | 10000. | 10000. | | | |
| 8 | 6 | 30000. | | | | | | 10000. | 10000. | 10000. | | |
| 9 | 7 | 30000. | | | | | | | 10000. | 10000. | 10000. | |
| 10 | 8 | 30000. | | | | | | | | 10000. | 10000. | 10000. |
| 11 | 9 | 30000. | | | | | | | | | 10000. | 10000. |
| 12 | 10 | 30000. | | | | | | | | | | 10000. |
| 13 | 11 | 30000. | | | | | | | | | | |
| 14 | 12 | 30000. | | | | | | | | | | |
| 15 | 13 | 30000. | | | | | | | | | | |
| 16 | 14 | 30000. | | | | | | | | | | |
| 17 | 15 | 30000. | | | | | | | | | | |
| 18 | 16 | 30000. | | | | | | | | | | |
| 19 | 17 | 30000. | | | | | | | | | | |
| 20 | 18 | 30000. | | | | | | | | | | |
| 21 | 19 | 30000. | | | | | | | | | | |
| 22 | 20 | 30000. | | | | | | | | | | |
| 23 | 21 | 30000. | | | | | | | | | | |
| 24 | 22 | 30000. | | | | | | | | | | |
| 25 | 23 | 30000. | | | | | | | | | | |
| 26 | 24 | 20000. | | | | | | | | | | |
| 27 | 25 | 10000. | | | | | | | | | | |

Figure D-13. Burnup Per Reload Interval

BASE PROBLEM - CODE COMPARISON

| SEGMENT NO. | FIRST CYCLE IN CORE | FINAL BURNUP (MWD/MWT) | BURNUP PER RELOAD INTERVAL FROM INITIAL LOADING (MWD/MWT) 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 10000. | | | | | | | | | | |
| 2 | 1 | 20000. | | | | | | | | | | |
| 3 | 1 | 30000. | | | | | | | | | | |
| 4 | 2 | 30000. | | | | | | | | | | |
| 5 | 3 | 30000. | | | | | | | | | | |
| 6 | 4 | 30000. | | | | | | | | | | |
| 7 | 5 | 30000. | | | | | | | | | | |
| 8 | 6 | 30000. | | | | | | | | | | |
| 9 | 7 | 30000. | | | | | | | | | | |
| 10 | 8 | 20000. | | | | | | | | | | |
| 11 | 9 | 30000. | 10000. | | | | | | | | | |
| 12 | 10 | 30000. | 10000. | 10000. | | | | | | | | |
| 13 | 11 | 30000. | 10000. | 10000. | 10000. | | | | | | | |
| 14 | 12 | 30000. | | 10000. | 10000. | 10000. | | | | | | |
| 15 | 13 | 30000. | | | 10000. | 10000. | 10000. | | | | | |
| 16 | 14 | 30000. | | | | 10000. | 10000. | 10000. | | | | |
| 17 | 15 | 30000. | | | | | 10000. | 10000. | 10000. | | | |
| 18 | 16 | 30000. | | | | | | 10000. | 10000. | 10000. | | |
| 19 | 17 | 30000. | | | | | | | 10000. | 10000. | 10000. | |
| 20 | 18 | 30000. | | | | | | | | 10000. | 10000. | 10000. |
| 21 | 19 | 30000. | | | | | | | | | 10000. | 10000. |
| 22 | 20 | 30000. | | | | | | | | | | 10000. |
| 23 | 21 | 30000. | | | | | | | | | | |
| 24 | 22 | 30000. | | | | | | | | | | |
| 25 | 23 | 30000. | | | | | | | | | | |
| 26 | 24 | 20000. | | | | | | | | | | |
| 27 | 25 | 10000. | | | | | | | | | | |

Figure D-13. Burnup Per Reload Interval

BASE PROBLEM - CODE COMPARISON

| SEGMENT NO. | FIRST CYCLE IN CORE | FINAL BURNUP (MWD/MWT) | BURNUP PER RELOAD INTERVAL FROM INITIAL LOADING (MWD/MWT) 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 10000. | | | | | |
| 2 | 1 | 20000. | | | | | |
| 3 | 1 | 30000. | | | | | |
| 4 | 2 | 30000. | | | | | |
| 5 | 3 | 30000. | | | | | |
| 6 | 4 | 30000. | | | | | |
| 7 | 5 | 30000. | | | | | |
| 8 | 6 | 30000. | | | | | |
| 9 | 7 | 30000. | | | | | |
| 10 | 8 | 30000. | | | | | |
| 11 | 9 | 30000. | | | | | |
| 12 | 10 | 30000. | | | | | |
| 13 | 11 | 30000. | | | | | |
| 14 | 12 | 30000. | | | | | |
| 15 | 13 | 30000. | | | | | |
| 16 | 14 | 30000. | | | | | |
| 17 | 15 | 30000. | | | | | |
| 18 | 16 | 30000. | | | | | |
| 19 | 17 | 30000. | | | | | |
| 20 | 18 | 30000. | | | | | |
| 21 | 19 | 30000. | 10000. | | | | |
| 22 | 20 | 30000. | 10000. | 10000. | | | |
| 23 | 21 | 30000. | 10000. | 10000. | 10000. | | |
| 24 | 22 | 30000. | | 10000. | 10000. | 10000. | |
| 25 | 23 | 30000. | | | 10000. | 10000. | 10000. |
| 26 | 24 | 20000. | | | | 10000. | 10000. |
| 27 | 25 | 10000. | | | | | 10000. |

Figure D-13. Burnup Per Reload Interval

# TECHNIQUES FOR CALCULATION OF NUCLEAR FUEL COSTS

by

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B.S., United States Military Academy, 1969

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

Master of Science

Department of Nuclear Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1976

ABSTRACT

Nuclear fuel is characterized by extended and costly initial preparation, long period of energy production and high residual value. Complex computer codes are normally used to estimate the levelized nuclear fuel cycle costs over the reactor lifetime. A method was developed to calculate levelized costs which are easily done by hand or adapted to a desk calculator. The results of this method are compared with results from existing computer codes. The limitations of the method are illustrated by calculation of periodic levelized costs.

Three existing computer codes are compared using a sample problem. Use of these codes allows comparison of discrete discounting, continuous discounting, the discounted worth of money technique, the discounted energy method, and two different methods of input/output control.