TECHNIQUES FOR CALCULATION OF NUCLEAR FUEL COSTS

by

WILLIAM JOSEPH JOHNSON

B.S., United States Military Academy, 1969

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

Approved:

N. Dean Eckhoff
Major Professor

205

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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

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,

$$E = mc^2 \ . \tag{2.1}$$

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.,

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

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,

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

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

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

Therefore,

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

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

$$F(n) = c\, E(n) - F'(n) . \qquad (2.11)$$

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

$$Y(n+1) = Y(n) + F(n) + x\,Y(n) \tag{2.12}$$

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:

$$Y(n+1) = (1+x)\,Y(n) + F(n)\ , \tag{2.13}$$

$$Y(a) = (1+x)\,Y(a-1) + F(a-1)\ , \tag{2.14}$$

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

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

Therefore

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

which is equivalent to

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

Therefore, the unit price of energy is

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

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.

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

where

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

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

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,

$0(n)$ = 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.

2.7 References

1. E. P. DEGARMO and J. R. CANADA, Engineering Economy, 5th ed., New York: Macmillan Publishing Co., Inc., 1973, p 464.

2. ALEXANDER SESONSKE, Nuclear Power Plant Design Analysis, Oak Ridge, Tennessee, USAEC Technical Information Center, 1973, p 26.

3. N. D. ECKHOFF, The Nuclear Fuel Cycle (A Draft Manuscript), Manhattan Kansas: Center for Energy Studies, Kansas State University, CES 11/I, 1975, Chap. 1, p 1.

4. WASH-1345, Power Plant Capital Costs: Current Trends and Sensitivity to Economic Parameters. Washington, D.C.: USAEC Division of Reactor Research and Development, 1974, p 2.

5. NUS-531, Guide for Economic Evaluation of Nuclear Reactor Plant Designs. Rockville, MD: NUS Corp., 1969, Appendix E.

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