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# An examination of the reduction of extraordinary fuel costs in the final cycles of pressurized water reactor operation

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by

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# INTRODUCTION

Because of the accident at Three Mile Island and the subsequent financial difficulties of its owners, the Nuclear Regulatory Commission has been considering regulation changes requiring utilities to assure funds for decommissioning their facilities are available before those facilities are scheduled to be decommissioned. This has caused many utilities to conduct studies of the costs of decommissioning their nuclear power plants. Although these studies are of varying degrees of completeness and complexity, none of them seems to consider the costs associated with the nuclear fuel cycle as a decommissioning cost. A recent Atomic Industrial Forum study[7] reports that, of the decommissioning studies surveyed, only one considered even the cost of removing spent fuel from the reactor site to be a decommissioning cost. Although studies of these fuel costs are undoubtedly being done by the utilities (one midwestern utility has completed such a study, but has not released its results), none of them has been released in the open literature. The report which has been completed shows that the extraordinary fuel costs associated with decommissioning can be quite high.

These extraordinary costs are not associated with the fabrication of the fuel for the final fuel cycles, since the fuel for the final cycles is identical to that used for any other reactor cycle. Rather, the additional fuel costs stem from the fact that only one portion of the core is replaced during any given refueling outage. For example, if a reactor in which one third of the fuel is replaced in a given refueling outage continues to operate in a "business as usual" manner until it is shut down for decommissioning, only one third of the core will be completely burned out. Another third of the core will be two thirds depleted, and another third will be only one third depleted. This is a considerable amount of unconsumed fuel and will be reflected in a higher cost per kilowatt hour of electricity produced by this fuel.

It is possible, however, to increase the burnup in the fuel through a fuel management scheme known as coastdown. Coastdown consists of operating the reactor for extended periods of time at power levels which are lower than the normal operating level of the reactor. In coastdown operations, the reactor is operated at its normal power level until insufficient excess reactivity remains in the core for the reactor to remain critical. The reactor power level is gradually decreased until either the reactor does not contain enough excess reactivity to operate at low power levels or until it is no longer economically feasible to operate the reactor at those levels. Replacement energy must be provided from some other source to make up the difference between the normal operating level of the reactor and the coastdown power level, but greater burnup will result.

Considered in this study are two types of coastdown scenarios. In the first scenario, it was assumed that coastdown would be used in only the final cycle. Three different coastdown power levels were used: 70%, 50% and 30% of normal operating power. In the second scenario, coastdown was used in the last two cycles. Again, coastdown power levels of 70%, 50% and 30% were used. In a third scenario, referred to as the baseline case, no coastdown is used in any cycle, and the fuel is simply removed from the reactor "as is" at the end of the final cycle of operation.

Until early in 1982, spent commercial power reactor fuel reprocessing was not permitted by the government of the United States. Thus, spent commercial power reactor fuel had no commercial value, and the objective of any study conducted would be to find a scheme which resulted in maximum burnup of the fuel. Since that time, however, the government has reversed its policy, and will permit commercial power reactor fuel reprocessing.

If reprocessing is permitted, the uranium and plutonium present in spent fuel gains a commercial value, and achieving maximum burnup may not be the most efficient method of reducing extraordinary fuel costs associated with decommissioning.

The purpose of this research is to examine the effects of these coastdown scenarios on the extraordinary fuel costs associated with decommissioning on a typical pressurized water reactor for each of the three reprocessing options (no reprocessing, uranium reprocessing, and both uranium and plutonium reprocessing) discussed above.

# LITERATURE REVIEW

## Background

As was mentioned in the introduction, not much work has been done in the area of extraordinary fuel costs associated with decommissioning. Much work has, however, been done on other areas of decommissioning. In order to put the research presented in the proper perspective, and to acquaint the reader unfamiliar with reactor decommissioning work, a review of the work done on the major decommissioning alternatives, and of several methods of financing, is presented in this chapter.

When licensing nuclear power plants, the Nuclear Regulatory Commission has traditionally assumed that any organization which could afford to construct and operate a nuclear power plant should be financially stable enough to be able to decommission the plant at the end of its life. The accident at the Three Mile Island nuclear generating station, and the subsequent financial difficulties of its owners, has caused the Nuclear Regulatory Commission to reconsider its position on this matter.

In order to assure the availability of funds for the decommissioning of nuclear facilities, the Nuclear Regulatory Commission is considering a requirement that utilities having nuclear power plants in operation or under construction set aside funds to pay for the decommissioning of the plant at the end of its life. This would assure that funds are available for decommissioning, and, under most of the funding options currently under study, would assure that the funds would be provided by the consumers who actually use the energy generated by the plant. Since most of the existing regulations which deal with decommissioning at all do so in only a limited fashion, the Nuclear Regulatory Commission would need to issue new regulations dealing with the decommissioning of nuclear facilities. Rather than issue one regulation dealing specifically with decommissioning requirements, they feel that since several current regulations would be impacted it would be less disruptive of existing processes and procedures to amend current regulations. The sections of Title 10 of the Code of Federal Regulations (which deals with nuclear energy) which would require major amendment under this plan are listed in Table 1.

## Funding Alternatives

The Nuclear Regulatory Commission has six basic alternatives under consideration for assuring that funds for decommissioning nuclear facilities are available. These six alternatives may be further classified into two basic groups. These two groups are plant specific funding arrangements and pooled funding approaches.

Plant specific alternatives include prepayment of decommissioning costs, external sinking funds, and internal reserves. In the prepayment alternative, cash or some other form of readily liquidable assets are deposited or set aside in an account controlled by the licensee or some public controlling body. These funds would be deposited before reactor startup, and could either cover the entire cost of decommissioning, or be of an amount such that the principal, plus any accumulated interest,

TABLE 1

PARTS OF TITLE 10 CODE OF FEDERAL REGULATIONS (10CFR)
REQUIRING AMENDMENT TO ENCOMPASS
DECOMMISSIONING REQUIREMENTS

| Part No. | Title |
| --- | --- |
| 30 | Rules Of General Applicability To Domestic Licensing Of Byproduct Material |
| 40 | Domestic Licensing Of Source Material |
| 50 | Domestic Licensing Of Production And Utilization Facilities |
| 51 | Licensing And Regulatory Policy And Procedures For Environmental Protection |
| 70 | Domestic Licensing Of Special Nuclear Material |

would be sufficient to cover the costs. The amount deposited would have to take into account inflation, and be sufficient to cover the cost of decommissioning the plant at any time during its life. The utility's decommissioning plan would have to be reviewed on a regular basis, and adjustments made to the fund accordingly. These adjustments would take into account both inflation and new developments in decommissioning technology. The Nuclear Regulatory Commission looks upon this method with a great deal of favor because it would, if the funds were controlled by a public controlling body, insure that funds would be available to decommission the plant regardless of the financial condition of the operating utility. If the funds are controlled by the licensee, the Nuclear Regulatory Commission feels that some method must be found to insure that funds earmarked for decommissioning could not be touched by creditors in the event of the financial insolvency of the licensee. The utilities operating nuclear facilities do not look as favorably upon this method of funding assurance because it requires them to tie up large amounts of capital for long periods of time with no return on their investment.

In the external sinking fund method, funds are accumulated over the estimated life of the plant to pay for decommissioning. This method requires a set amount of funds to be set aside annually or at some other fixed interval in some manner such that the accumulated funds, plus any interest, is sufficient to cover the costs of decommissioning the plant. The funds could be invested in several manners such as high grade corporate securities, federal debt obligations, or other assets. The fund would have to be administered separately from the utility's other assets, and the fund could either be built up from equal payments or by inflation adjusted, accelerated, or some other form of variable payments. As with the pre-payment method, the utility's decommissioning plan would have to be reviewed at regular intervals to insure that sufficient funds would be available for decommissioning. The Nuclear Regulatory Commission feels that, should a utility choose this method of funding decommissioning, some additional method, such as decommissioning insurance (discussed below) must be provided to assure that funds are available in the event the plant must be decommissioned prematurely.

The third plant specific funding alternative is the internal reserve. This method of funding is actually an unsegregated or unfunded reserve. This is an accounting procedure which generally uses a negative net salvage value for the plant and allows the estimated decommissioning costs to be accumulated over the life of the plant. When a utility depreciates a capital asset, such as a nuclear power plant, it sets the value of the asset at the replacement cost of the item, less any salvage value. When estimating the cost of a nuclear facility, this salvage value is assigned a negative value equal to the cost of decommissioning the facility. Thus, the net value of a nuclear facility equals the replacement cost of the facility plus the cost of decommissioning. This value is then divided by the estimated life of the plant, and the resulting value is the annual depreciation to be shown for the facility on the company's books. Several other accelerated depreciation alternatives are allowed by the Internal Revenue Service which can be helpful with the utility's income taxes, but the required funds needed by the time of decommissioning would be the same under all options.

Because the depreciation reserve accumulates on the company's books before it is actually needed for decommissioning, funds collected from the customers could be invested in the utility's assets. If decommissioning occurs as scheduled, the utility will have plant assets equal to the cost of decommissioning which are not encumbered by securities, and bonds could then be issued against the assets to pay for decommissioning. Since the assets are not segregated, this is not, strictly speaking, a funding method. In an alternate form of this method, assets are segregated, and this method becomes similar to the external sinking fund, except that the funds would be invested by the utility in its own assets. The utilities tend to favor this method over the other two plant specific funding alternatives because it does not require tying up a large amount of money. The Nuclear Regulatory Commission, however, looks upon this method with some disfavor because it feels that should the utility be in financial distress at the time of decommissioning, it may be hard for them to raise the funds necessary for decommissioning their facilities.

The Nuclear Regulatory Commission has been working with the Internal Revenue Service to come up with changes in tax regulations which would help ease the financial burden of decommissioning on the utilities. Under current regulations, funds set aside by utilities for decommissioning are still considered taxable assets. With the current corporate tax rate standing at nearly 50%, a utility would have to set aside nearly $2 for every $1 of anticipated decommissioning costs. The Nuclear Regulatory Commission is hoping to establish a tax exempt status for decommissioning funds from the Internal Revenue Service. If it is able to achieve this, the cost of these options would be greatly reduced, and perhaps their appeal to the utilities would be increased.

The second set of alternatives for funding decommissioning are the pooled approaches. These methods are surety bonding, decommissioning insurance, and funding from general revenues. The surety bonding method is not really a funding method, but rather an assurance that if the utility could not fund decommissioning costs on its own, they would be paid by the issuer of the bond. This method assumes that funds would be available from some other source, and is simply an additional way of assuring the availability of funds. In addition to the issuance of bonds, other forms of this assurance method could include bank letters or lines of credit, or any of several other bonding methods, or even a combination of several different bonding methods. Naturally, any bonding company would try to minimize the risk, and probably would not issue bonds to any utility which was in a questionable financial status. In addition, the Nuclear Regulatory Commission has contacted the ten largest bonding companies in the United States, and all of them responded that surety bonds for the time-span and amounts needed for commercial power reactors would be unavailable, except perhaps at an extremely high cost. For these reasons the Nuclear Regulatory Commission considers surety bonding to be an unviable method of assuring decommissioning funds for commercial nuclear power reactors, although it could be useful for some other types of nuclear facilities.

The second form of pooled funding is decommissioning insurance. This method could be used by itself, or coupled with other funding methods, such as the external sinking fund. This insurance could be of two types. In the first type, the costs of decommissioning would be paid for by the insurance when the reactor was shut down, whether the plant was decommissioned prematurely or on schedule. This is not, in the strictest sense, insurance, since the decommissioning of the plant at some time would be a certainty. In the second type of insurance, the costs of decommissioning are paid by the insurance only if the plant is being decommissioned prematurely. Some other form of funding, such as a sinking fund, would be used to fund decommissioning if the plant is decommissioned on schedule. The Nuclear Regulatory Commission feels that decommissioning insurance is much better suited than the other funding methods to cover drastic increases in decommissioning costs due to accidents or other causes.

The Nuclear Regulatory Commission contacted the major nuclear insurance suppliers[9] and asked them to evaluate the role of the nuclear insurance industry in providing decommissioning insurance. One of them replied that decommissioning insurance was probably unnecessary, and, in any case, violated the insurance principle of spreading risk among similarly exposed insureds. The others contacted replied that, although they saw some role for the nuclear insurance industry to play, particularly in providing insurance for premature shutdown, they were unsure exactly what that role should be and welcomed additional input from the Nuclear Regulatory Commission.

The Nuclear Regulatory Commission has found the analysis of the insurance option to be complicated by the fact that it is not yet clear that the insurance option will actually be available. Additionally, although the insurance pools have been evaluating the option, they have not yet reached any definite conclusions. It is also not yet clear that the pools would be willing, or even able, to provide the increased capacity required for decommissioning insurance. However, the nuclear insurance pools continue to express interest in the concept, and even if they declined to participate in decommissioning insurance, a captive insurance company could be established by the electric utility industry.

The final method of funding decommissioning would be to finance it out of general tax revenues. The Nuclear Regulatory Commission does not look favorably upon this method of decommissioning financing because it believes that the costs of decommissioning should, wherever possible, be borne by the persons who benefit from the facility. It also questions whether the political climate in the United States would allow the use of public funds in decommissioning activities. Thus, the Nuclear Regulatory Commission feels that, unless special usage taxes are earmarked specifically for decommissioning, this method should be dismissed.

Additional studies by the Nuclear Regulatory Commission show that these funding alternatives will all have little, if any, impact on the administrative staffing of nuclear facilities. There is also little additional impact on staffing if the plant is co-owned by several different utilities or if the area of jurisdiction of the utility extends across state boundaries.

## Decommissioning Options

When a nuclear power plant reaches the end of its life, three options are available to the operating utility. They may opt for extended life operations, replacement of the steam supply system with a new nuclear or non-nuclear system, or decommissioning.

The Nuclear Regulatory Commission considers extended life operations and replacement of the nuclear steam supply system with a new nuclear system to be modifications of the existing operating license, not decommissioning, and they are not discussed here. Replacement of the nuclear steam supply system by a non-nuclear system would require the nuclear components of the plant to be decommissioned using one of the decommissioning methods described below.

The Nuclear Regulatory Commission considers three different decommissioning options available to a utility. Since a number of different names have been used for each of these options in the past, it has proposed that the terms DECON, SAFSTOR, and ENTOMB be used exclusively in future literature, in order to end confusion with inconsistent nomenclature and meaning. DECON has been referred to as dismantlement in previous studies. SAFSTOR has been known alternately as layaway, mothballing, protective storage, and temporary entombment. ENTOMB has been referred to as entombment and permanent entombment.

DECON is defined by the Nuclear Regulatory Commission as, "to immediately remove all radioactive materials down to levels which are considered acceptable to permit the property to be released for unrestricted use."[3] DECON is the only one of the decommissioning options considered by the

Nuclear Regulatory Commission which leads to the termination of the license and release of the site for unrestricted use shortly after the termination of reactor operations. It is estimated that DECON would take about four years for a large pressurized water reactor.

Since DECON operations would take place soon after the facility ceases operation, personnel radiation exposures are generally higher than for the other decommissioning alternatives, since the others spread the decommissioning activities over a longer period of time, and thus allow for radioactive decay. In addition, larger amounts of money and waste disposal site space are also required in a relatively short time frame compared to SAFSTOR and ENTOMB.

Because of these factors, the primary advantage of DECON, that of termination of the operating license and making the site available for some other use, is accomplished with higher initial cost, personnel exposure, and waste disposal site space than for SAFSTOR or ENTOMB. Other advantages of this option are the availability of a work force highly knowledgeable about the site (the operating staff), and the elimination of the need for long term security, maintenance, and surveillance (both intrusion and radiation) of the site which would be required for the other two options. In this option, as with the others, non-radioactive equipment and structures need not be demolished or removed as part of the decontamination process. Additionally, once the radioactive components of the plant are decontaminated to levels permitting unrestricted use of the site, they may either be put to some other use or demolished at the owner's discretion.

The second decommissioning option available to a utility is SAFSTOR. SAFSTOR is defined by the Nuclear Regulatory Commission as, "Those activities required to place (preparation for safe storage) and maintain (safe storage) a radioactive facility in such condition that the risk to safety is within acceptable bounds and that the facility can be safely stored and subsequently decontaminated to levels which permit release of the facility for unrestricted use." The idea behind SAFSTOR is that, by doing minimal preparation to the facility (generally less than two years), and then sealing the facility shut for a period of 30 to 100 years, followed by decontamination in a method similar to DECON, radiation doses to decommissioning workers, and the public at large, can be greatly reduced. The Nuclear Regulatory Commission has chosen 100 years as the upper limit for SAFSTOR because after that time there will be little additional change in radiation levels for some time since the primary source of radiation will be from long lived radioisotopes. Additionally, the Nuclear Regulatory and Environmental Protection Agencies feel that 100 years is the maximum length of time that institutional control over a site can be maintained.

In NUREG-0586, Draft Generic Environmental Impact Statement on Decommissioning of Nuclear Facilities,[3] the Nuclear Regulatory Commission defines the following types of SAFSTOR:

1. Custodial SAFSTOR (layaway) requires a minimum cleanup and decontamination effort initially, followed by a period of continuing care with the active protection systems (principally the ventilation system) kept in service throughout the storage period. Full-time onsite surveillance by operating and security forces is required to carry out radiation monitoring, to maintain the equipment, and to prevent accidental

or deliberate intrusion into the facility and the subsequent exposure to radiation or the dispersal of radioactivity beyond the confines of the facility.

2. Passive SAFSTOR (protective storage, mothballing) requires a more comprehensive cleanup and decontamination effort initially, sufficient to permit deactivation of the active protective (ventilation) system during the continuing care period. The structures are strongly secured and electronic surveillance is provided to detect accidental or deliberate intrusion. Periodic monitoring and maintenance of the integrity of the structures is required.

3. Hardened SAFSTOR (temporary entombment) requires comprehensive cleanup and decontamination and the construction of barriers around areas containing significant quantities of radioactivity. These barriers are of sufficient strength to make accidental intrusion impossible and deliberate intrusion extremely difficult. Surveillance requirements are limited to detection of attack upon the barriers, to maintenance of the integrity of the structures, and to infrequent monitoring.

All SAFSTOR options require some action at the end of the safe storage period before the site can be released for unrestricted use. SAFSTOR is used as a means to satisfy the requirements for the protection of the public while minimizing initial commitments of capital, time radiation exposure to personnel, and waste disposal site space. Modifications to the facility are limited to those which will ensure the containment of radioactive or toxic materials, and to insure the security of the building against intruders. It is not intended that the facility will ever be reactivated. In addition to the reduced occupational radiation exposure to the decommissioning workers, there is the added benefit that the volume of material to be packaged and transported to waste disposal sites will be reduced.

The reduced initial cost and effort of preparing a facility for safe storage is balanced out somewhat by the need for continued capital outlay and effort for the monitoring program which must be provided by the utility. Another disadvantage to this method of decommissioning is the possible lack of personnel familiar with the facility at the end of the safe storage period. The Nuclear Regulatory Commission feels that this problem could be avoided by the creation of companies specializing in decommissioning nuclear facilities. Other disadvantages of this option include the fact that the site is tied up as a restricted area for an extended time period, thus requiring a continued need for security, surveillance, and maintenance.

The final decommissioning alternative, ENTOMB, is defined by the Nuclear Regulatory Commission as, "To encase and maintain property in a strong and structurally long-lived material (e.g., concrete) to assure retention until radioactivity decays to a level acceptable for releasing the facility for unrestricted use."[3] Unlike SAFSTOR, no decontamination procedure is needed at the end of the storage period. Instead, the period of entombment is chosen long enough that the radioisotopes present will decay to unrestricted levels. The basic requirement for ENTOMB is a structure which can last many half-lives of the most objectionable isotope present. The Nuclear Regulatory Commission feels that this option is unviable for several reasons. First, it feels that no man made structure could survive for the long period of time required for some of the long-lived activation products in nuclear power reactors to decay to unrestricted levels. Second, it feels that no organization or regulatory body can ensure control of an entombment site for the long periods of time needed before the site could be released to unrestricted use. Finally, it feels that the ENTOMB option would, in effect be creating an above ground low level nuclear waste burial ground, and it hesitates to endorse any decommissioning option which would lead to an increase in the number of these sites.

Of the options discussed above, the one most favored by the Nuclear Regulatory Commission is DECON. This option is favored for several reasons. The first is that DECON leads to termination of the operating license and release of the facility site to unrestricted use shortly after the facility ceases operation. Secondly, their studies show that, although DECON requires higher initial expenditures than SAFSTOR, when the cost of the long term monitoring and maintenance program required by SAFSTOR is taken into account, DECON is the cheaper of the two alternatives. Finally, although radiation exposure to individual workers will be lower in SAFSTOR than DECON, when the dosage of the monitoring and maintenace crews during SAFSTOR is taken into account, the total occupational exposure of the two options is virtually the same. The Nuclear Regulatory Commission considers ENTOMB to be an unsatisfactory alternative for nuclear power reactor decommissioning for the reasons discussed above, although it feels that it may be useful for some other types of facilities. It also feels that SAFSTOR would be a more appropriate method of decommissioning than DECON on multiple reactor sites where maintenance and monitoring crews would be readily available. To date, most of the experience in decommissioning has been in SAFSTOR, with only one facility, the Elk River nuclear power station, undergoing DECON and having its license terminated and its site released for unrestricted use.

# DEVELOPMENT OF THE PROBLEM

## Background

Until early in 1982, the policy of the United States government was to prohibit the reprocessing of commercial power reactor fuel. Since, before that time, it appeared that there would be no change in that policy, any studies of the extraordinary fuel costs associated with decommissioning would most likely have been made with the basic assumption that there would be no fuel reprocessing available at the time of decommissioning. The present administration has, however, reversed the policies of previous administrations, and announced that it would permit the reprocessing of spent commercial power reactor fuel. When the administration announced this change in policy, it also announced that the facilities for reprocessing would have to be provided by the private sector.

This decision tends to complicate the analysis of the problem of the extraordinary fuel costs associated with decommissioning. Since the administration made the announcement of its decision, no private corporation has announced a decision to enter the spent fuel reprocessing business, nor, at the time of this writing, does it appear that any will do so in the near future. However, the possibility still remains that, barring another reversal of government policy, some corporation will begin to reprocess spent fuel. Since it is impossible to predict whether reprocessing will be available at the time a plant is decommissioned, both cases must be considered.

## Details of Research

As discussed in the introduction, the analysis of extraordinary fuel costs is broken into three parts. These parts are single cycle coastdown, two cycle coastdown, and the "do nothing," or baseline case. In the baseline case, the reactor continues operating at its normal power level during all cycles until it is shut down for decommissioning. In the single cycle coastdown scenario, the reactor is operated, as in the baseline case, until the final cycle. In the final cycle, the reactor undergoes a coastdown to an average power level of 70%, 50%, or 30% of its normal operating power level. This will increase the burnup of the fuel, but it will also increase the replacement energy costs. In the two cycle coastdown scenario, the reactor is operated as in the baseline case until the second from last cycle. During the last two cycles of operation, the reactor undergoes a coastdown to 70%, 50%, or 30% of the normal operating power level. The combinations of these three coastdown power levels result in nine cases which must be considered. These combinations are listed in Table 2. In this table, Cycle N is the final cycle of reactor operation, and cycle N-1 is the next to last cycle of operation.

In this research, calculations were made for the baseline, single cycle coastdown, and two cycle coastdown cases for three different spent fuel recycling scenarios. In the first reprocessing scenario, it was assumed that only recycled uranium has a commercial value, that is, that there is no plutonium recycle. In the second scenario, it is assumed that recycled uranium and plutonium both have a commercial value, and in the final scenario, it is assumed that no spent commercial power reactor fuel

TABLE 2

COMBINATIONS OF COASTDOWN POWER LEVELS
FOR TWO CYCLE COASTDOWN

| Cycle N | Cycle N-1 | Cycle N | Cycle N-1 | Cycle N | Cycle N-1 |
|---|---|---|---|---|---|
| 70 | 70 | 50 | 70 | 30 | 70 |
| 70 | 50 | 50 | 50 | 30 | 50 |
| 70 | 30 | 50 | 30 | 30 | 30 |

reprocessing is available. In all cases, it is assumed that the commercial value, if any, of any fission products or transuranics (other than plutonium) which are recovered is just equal to their recovery costs. The reactor cross sections used in these calculations are those of a typical U.S. pressurized water reactor. Values used in the calculations are listed in Table 3, and lead and lag times are listed in Table 4.

After these calculations were completed, additional calculations were made while varying either the cost of yellowcake (uranium ore), cost of enrichment, or cost of permanent storage for the baseline, 30% final cycle coastdown, and 70% final two cycle coastdown for the no recycle option. One value lower and four values higher than those in Table 3 were used in the calculations. These calculations were made to show the effect of the cost of these items on the extraordinary fuel costs associated with decommissioning.

## Computer Code

The computer code used in making the calculations presented in this thesis was the CYCLOPS code. The CYCLOPS code was developed as a non-equilibrium fuel management optimization code with emphasis on accuracy of physics modeling and changing conditions in fuel economics, as well as realistic operating constraints. The physics model used a two-dimensional nodal method with axial buckling derived from diffusion theory as well as neutron transmission from assemblies at the corners of each assembly to improve accuracy. Fuel cycle cost analysis is on the basis of the accrual/discount method.[4]

TABLE 3

VALUES OF MATERIALS AND SERVICES USED
IN ECONOMICS CALCULATIONS

| ITEM | COST |
| --- | --- |
| Unit Cost For Yellowcake ($/lb) | 65.0 |
| Unit Cost For Conversion ($/kgU) | 5.5 |
| Unit Cost For Enrichment ($/SWU) | 125.0 |
| Unit Cost For Fabrication ($/kgU) | 150.0 |
| Unit Cost Of Transporting Fuel To Site ($/kgU) | 0.0 |
| Unit Cost Of Shipment To AFR Storage Site ($/kgU) | 30.0 |
| Unit Cost For Permanent Storage ($/kgU) | 375.0 |
| Unit Cost For Reprocessing ($/kgU) | 150.0 |

TABLE 4

LEAD AND LAG TIMES USED IN ECONOMICS CALCULATIONS

| ITEM | LEAD (LAG) TIME, YEARS |
|---|---|
| $U_3O_8$ Purchase And Conversion | 1.25 |
| Enrichment | 0.75 |
| Fabrication | 0.50 |
| Transportation | 0.33 |
| Refueling Outage Length | (0.083) |
| Onsite Storage And Shipping | (2.5) |
| Reprocessing Time | (1.0) |
| U And Pu Credit Time | (2.0) |
| AFR Storage Time | (5.0) |

The coastdown model was rather simplistic. Rather than decreasing reactor power gradually until insufficient excess reactivity remained for the reactor to remain critical, the program decreased the reactor power level to an average coastdown power level. The reactor then ran at that power level until a user specified burnup for the coastdown was reached. The code did not consider whether enough reactivity was available for the reactor to reach the specified burnup. Figure 1 shows the principal subroutines in the CYCLOPS program, as well as their relationship to each other within the code.

Reactivity During Coastdown

The coastdown burnup used for the calculations was 3000 megawatt days per metric ton of uranium. Since this burnup size was originally chosen as an educated guess, it was later decided to verify that enough excess reativity was obtained during the coastdown to actually reach a burnup of 3000 MWD/MTU.

By using the graph of the power coefficient vs. percent power for the reactor which supplied the reactor physics constants, one can determine the excess reactivity to be gained by decreasing the reactor power level. About one percent $\Delta k/k$ is equal to a concentration of 105 parts per million of soluable boron; therefore the equivalent boron concentration corresponding to that reactivity can then be found. Finally, by using a graph of burnup as a function of soluable boron concentration, it is possible to find the burnup which will result from a given power reduction.

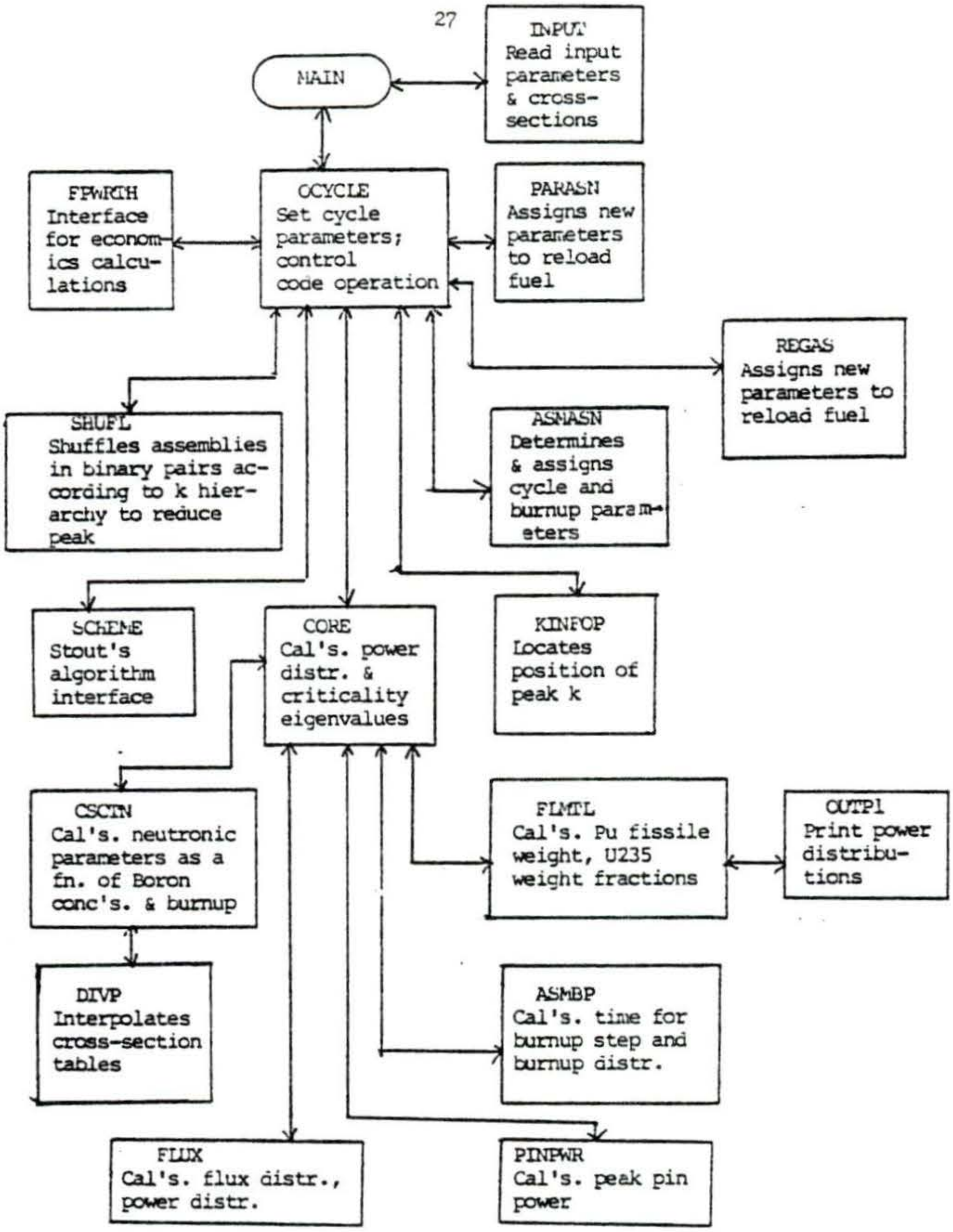


FIGURE 1

PRINCIPAL SUBROUTINES OF CYCLOPS (FROM 5)

These calculations show that it is not possible to reach a burnup of 3000 MWD/MTU solely by decreasing reactor power. However, since the plant will be shut down permanently following the coastdown operations, it is possible to gain additional reactivity by decreasing the temperature of the reactor coolant. Because of the temperature coefficient of reactivity, this will result in additional reactivity being available to extend coastdown operations. This will also result in less than saturated steam leaving the steam generators, which in turn could cause erosion to the turbine blades. However, since the plant will be decommissioned at the end of coastdown operations, it may be argued that damage to the turbines will be unimportant since they will be scrapped immediately after shutdown anyway, and the damage resulting will not be enough to endanger the safety of the plant.

# RESULTS AND DISCUSSION

The computer code used for these calculations did not actually output the fuel costs at the end of a given cycle of operation. Instead, at the end of each cycle, the code calculated the energy generated by each batch of fuel in the core and the cost per kilowatt hour of the energy produced by that batch of fuel to that point in time. In order to calculate the fuel costs at the end of a given cycle, these two quantities were multiplied together, and the product was summed over all batches in the core at the end of that cycle.

The program also made an extrapolation of the cost per kilowatt hour of energy produced by a given batch to the time the fuel in that batch was discharged from the core. Taking the extrapolated cost and multiplying it by the energy produced by that batch until the hypothetical shutdown, and summing over all batches in the core at the time of shutdown, one can determine the energy cost which would have occurred at the end of that cycle had shutdown not occurred. This calculation was made for each option (no recycle, uranium recycle, and uranium and plutonium recycle). The resulting value was used as a base for calculating the extraordinary fuel costs associated with decommissioning. The extraordinary fuel cost for a given trial was taken to be the difference between the fuel costs for that trial and the extrapolated cost for the no-coastdown trial of that recycling option.

At this point, some explanation of the notation used in some of the tables and figures in this chapter is necessary. In Figures 2 through 7, the notation "CYCLE N" refers to the final cycle of reactor operation before decommissioning, while the notation "CYCLE N-1" refers to the cycle immediately preceding Cycle N, or the next-to-last cycle of operation.

In Tables 5, 6, and 7, the column labeled "Fuel Cycle Cost" represents the total cost of fuel for that option less tax credits or plutonium or uranium recycling (if any). The column labeled "Replacement Energy Cost" gives the cost of replacement energy during coastdown, and the column labeled "Total Cost" is the sum of the fuel cycle cost and the replacement energy cost. The column labeled "Extraordinary Cost" is the difference between the total cost for a given option and the cost of the equilibrium, or no shutdown, case. The case marked with a * is the equilibrium, or no shutdown, case, and thus, there is no Extraordinary Cost given for that option.

## No Recycle Option

In the first recycling option, calculations were made with the assumption that no spent commercial power reactor fuel reprocessing would be available at the time of reactor decommissioning. The results of the calculations for this option are listed in Table 5. Figure 2 graphically shows the results excluding replacement energy costs, and Figure 3 shows the results if replacement energy costs are included.

The extrapolated cost calculations for this option, which were used as a base for computing the extraordinary fuel costs, were found to be $178.5 million. The costs which would result if the reactor were shut down for decommissioning were $255.1 million. This gives us an extraordinary fuel cost of $76.5 million for the baseline case. Of this,

TABLE 5

EXTRAORDINARY FUEL COSTS ASSOCIATED WITH THE NO RECYCLE OPTION

| COASTDOWN POWER LEVEL | | COST IN MILLIONS OF DOLLARS | | | |
|---|---|---|---|---|---|
| Next To Last Cycle | Last Cycle | Fuel Cycle Cost | Replacement Energy Cost | Total Cost | Extra-Ordinary Cost |
| 100 | 100* | 178.5 | 0.0 | 178.5 | 0.0 |
| 100 | 100 | 188.7 | 66.4 | 255.1 | 76.5 |
| 100 | 70 | 188.7 | 42.6 | 269.3 | 52.7 |
| 100 | 50 | 188.6 | 55.1 | 243.7 | 65.1 |
| 100 | 30 | 188.5 | 84.4 | 239.7 | 94.3 |
| 70 | 70 | 188.7 | 18.8 | 207.5 | 28.9 |
| 70 | 50 | 188.7 | 31.3 | 220.0 | 41.4 |
| 70 | 30 | 188.5 | 60.5 | 249.1 | 70.5 |
| 50 | 70 | 188.8 | 31.3 | 220.1 | 41.5 |
| 50 | 50 | 188.7 | 43.8 | 232.5 | 53.9 |
| 50 | 30 | 188.6 | 73.1 | 261.7 | 83.1 |
| 30 | 70 | 188.8 | 60.5 | 249.4 | 70.8 |
| 30 | 50 | 188.8 | 73.1 | 261.9 | 83.3 |
| 30 | 30 | 188.6 | 102.3 | 291.1 | 112.4 |

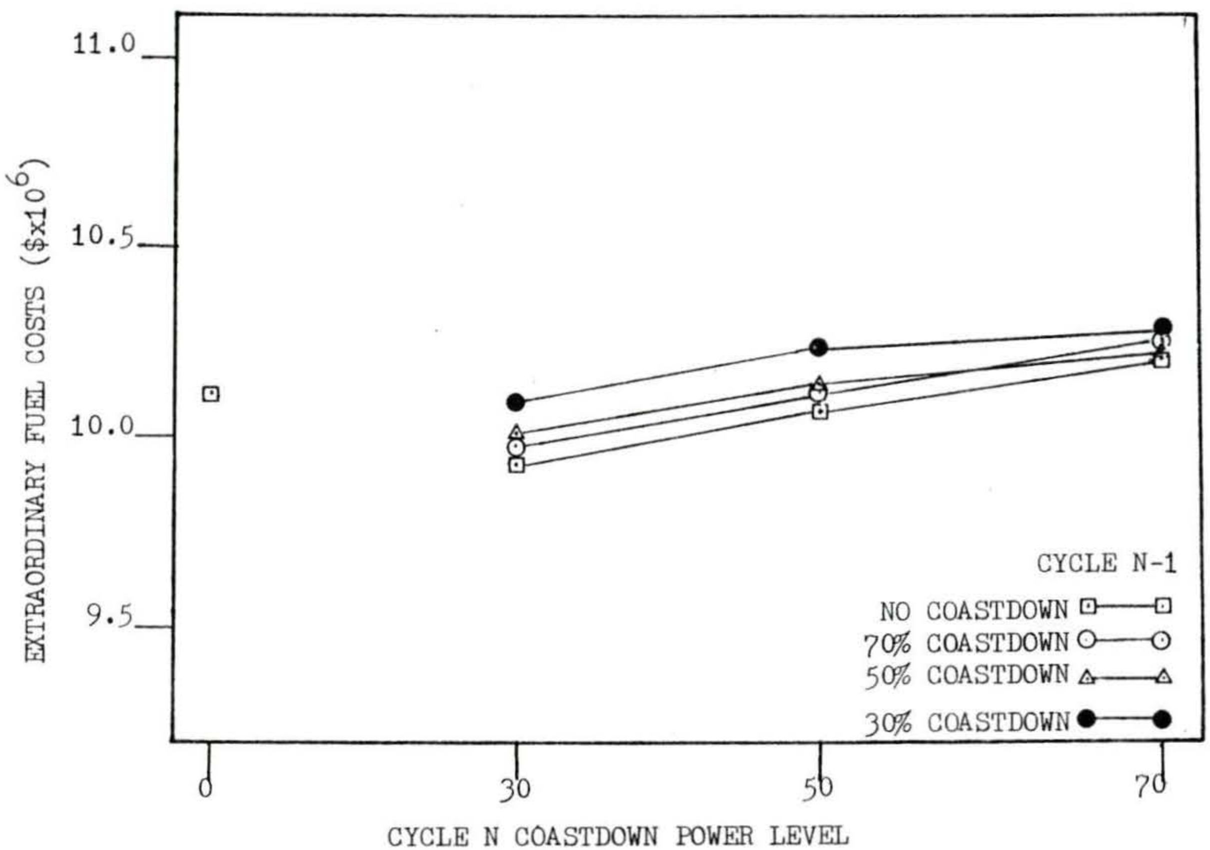


FIGURE 2

EXTRAORDINARY FUEL CYCLE COSTS FOR THE NO RECYCLE OPTION,
WITH REPLACEMENT ENERGY COSTS EXCLUDED

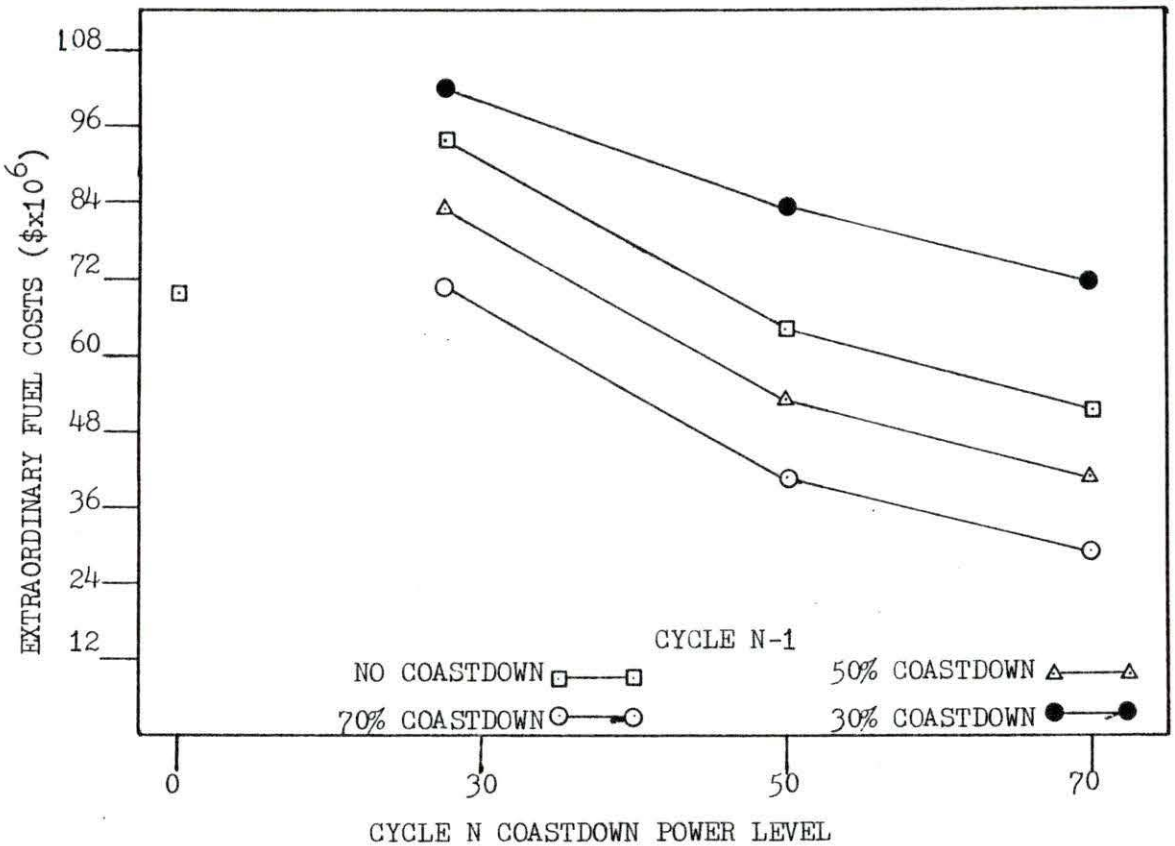


FIGURE 3

EXTRAORDINARY FUEL CYCLE COSTS FOR THE NO RECYCLE OPTION
INCLUDING REPLACEMENT ENERGY COSTS

$66.4 million was in replacement energy costs.

The highest extraordinary fuel costs for the single cycle coastdown cases were associated with the 30% final cycle coastdown. These extraordinary fuel costs were $94.3 million, of which $10.0 million was in higher fuel costs and $84.4 million was in replacement energy costs. The lowest extraordinary fuel costs for the single cycle coastdown cases were those of the 70% final cycle coastdown case. These costs amounted to $52.7 million, of which $10.1 million was for additional fuel costs, and $42.6 million was for replacement energy costs.

For the two cycle coastdown cases, the highest extraordinary fuel costs were for the 30% next to last, 30% last cycle coastdown combination. The extraordinary fuel costs for this option were calculated to be $112.4 million, of which $10.1 million was in fuel costs and $102.3 million was for replacement energy during coastdown. The lowest extraordinary fuel costs for the two cycle coastdown cases were found to be those for a combination of coastdown power levels of 70% in the next to last cycle and 70% in the final cycle of operation. These costs were calculated to be $28.9 million, of which $10.1 million was in fuel costs, and $18.8 million was for the purchase of replacement energy during coastdown.

## Uranium Recycle Option

The computer code used for these calculations did not explicitly calculate the fuel costs for an uranium recycle only fuel cycle. Rather, when calculating the levelized batch cost for energy produced by a given batch of fuel in the core, a credit for the value of recycled uranium and plutonium is subtracted from the fuel costs during the calculations. The plutonium and uranium credits, in dollars, were also supplied for each cycle as part of the output. Thus, by calculating the fuel costs at the end of a given cycle in a manner identical to that described at the beginning of this chapter, and then subtracting the value of the plutonium credit for that cycle, we have the fuel costs of that cycle under a fuel cycle involving only uranium recycle. The results of the calculations for the uranium recycle option are presented in Table 6.

The extrapolated fuel costs for the final cycles, which were used as a basis for calculating the extraordinary fuel costs associated with the uranium recycle option were found to be \$148.0 million. By assuming reactor shutdown instead of making an extrapolation, we get a fuel cost of \$220.0 million. This gives us an extraordinary fuel cost of \$76.5 million for the baseline case of the uranium recycle option. As in the no recycle option, \$66.4 million was in replacement energy costs.

For the single cycle coastdown cases, the highest extraordinary fuel costs were found to be those for the case with an average coastdown power level during the final cycle of 30%. The extraordinary fuel costs for this case were \$97.0 million, of which \$12.6 million was in fuel costs and \$84.4 million was for replacement energy costs. The lowest extraordinary fuel costs for the single cycle coastdown cases was for a 70% coastdown in the final cycle. These extraordinary fuel costs were found to be \$53.2 million, of which \$10.6 million was in fuel costs and \$42.6

TABLE 6

EXTRAORDINARY FUEL COSTS ASSOCIATED WITH THE URANIUM RECYCLE OPTION

| COASTDOWN POWER LEVEL | | COST IN MILLIONS OF DOLLARS | | | |
|---|---|---|---|---|---|
| Next To Last Cycle | Last Cycle | Fuel Cycle Cost | Replacement Energy Cost | Total Cost | Extra-Ordinary Cost |
| 100 | 100* | 148.0 | 0.0 | 148.0 | 0.0 |
| 100 | 100 | 153.6 | 66.4 | 220.0 | 76.5 |
| 100 | 70 | 158.6 | 42.6 | 199.2 | 53.2 |
| 100 | 50 | 159.2 | 55.1 | 214.3 | 66.3 |
| 100 | 30 | 160.6 | 84.4 | 245.0 | 97.0 |
| 70 | 70 | 159.1 | 18.8 | 177.9 | 29.8 |
| 70 | 50 | 159.7 | 31.3 | 191.0 | 43.0 |
| 70 | 30 | 161.1 | 60.5 | 221.7 | 73.7 |
| 50 | 70 | 159.4 | 31.3 | 190.7 | 42.7 |
| 50 | 50 | 160.1 | 43.8 | 203.8 | 55.8 |
| 50 | 30 | 161.4 | 73.1 | 220.8 | 72.7 |
| 30 | 70 | 160.2 | 60.5 | 220.8 | 72.8 |
| 30 | 50 | 160.8 | 73.1 | 233.9 | 85.8 |
| 30 | 30 | 162.1 | 102.3 | 264.5 | 116.5 |

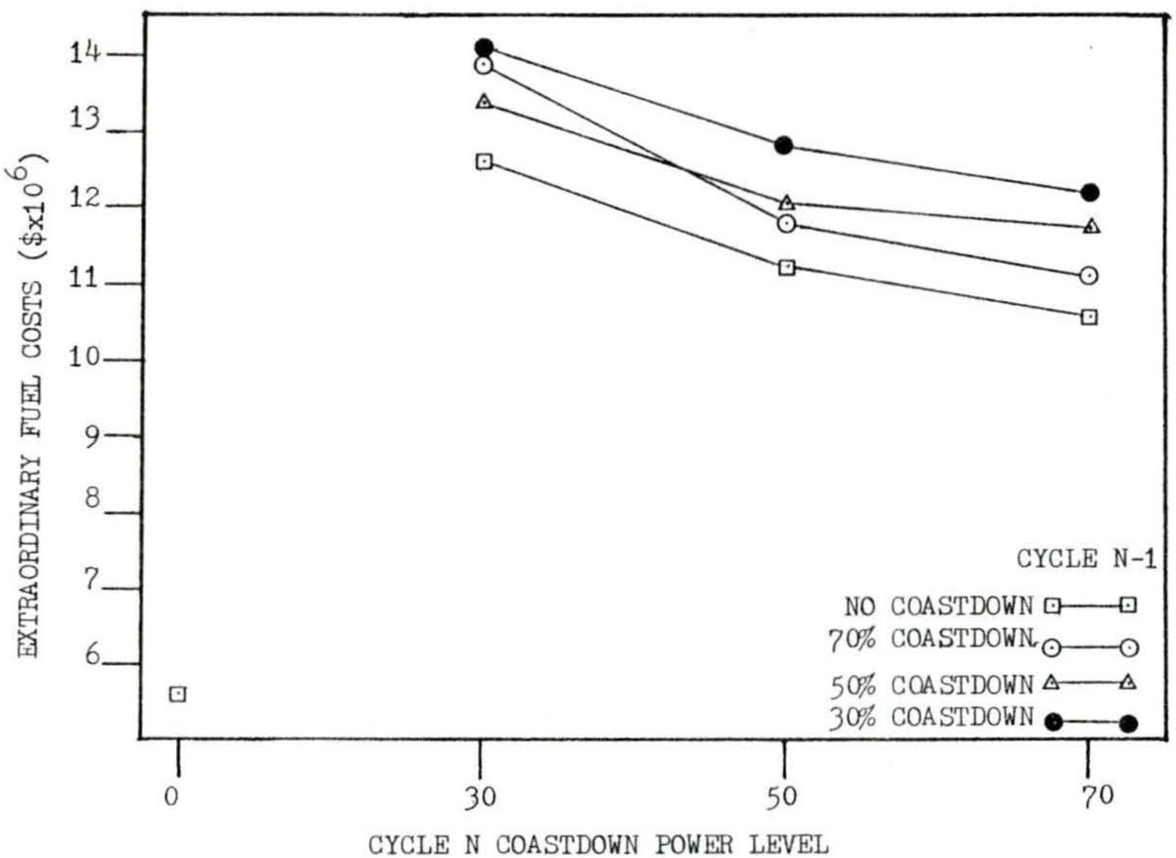


FIGURE 4

EXTRAORDINARY FUEL CYCLE COSTS FOR THE URANIUM RECYCLE OPTION,
WITH REPLACEMENT ENERGY COSTS EXCLUDED

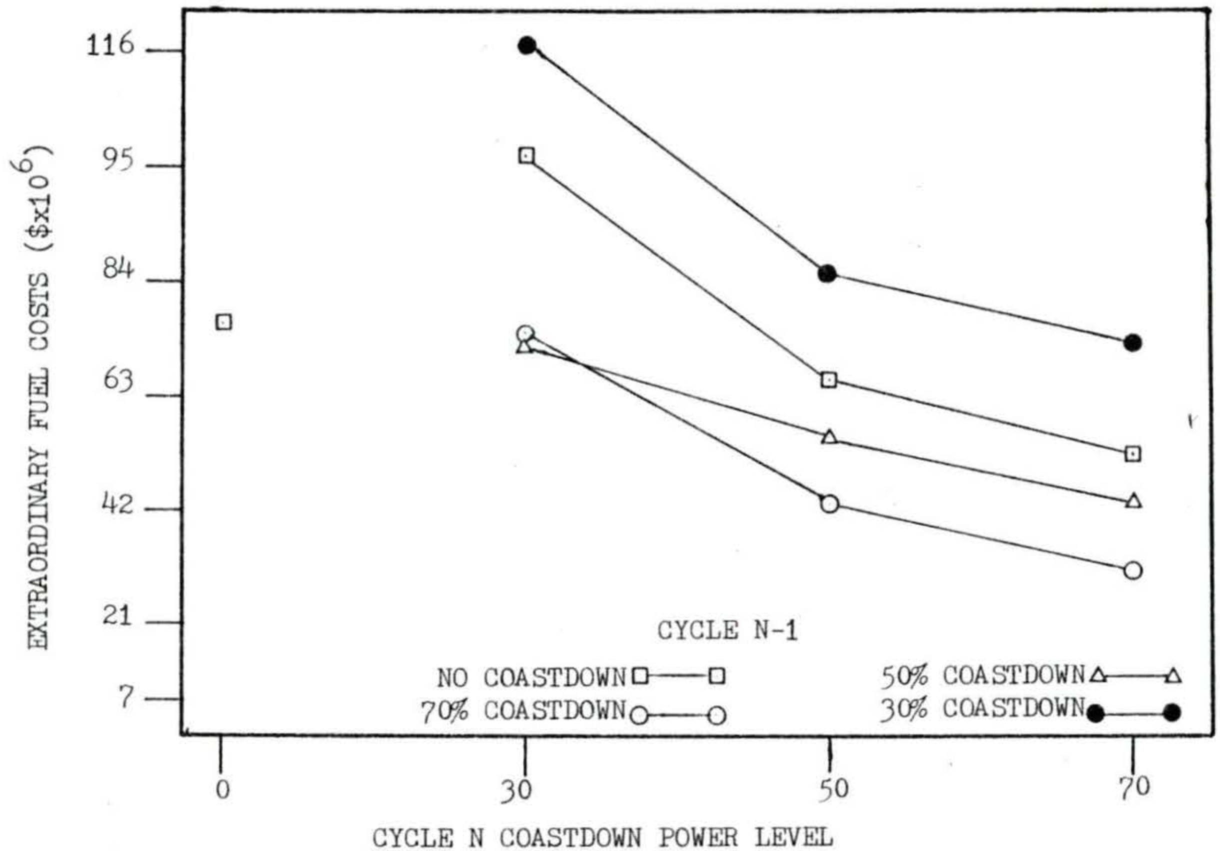


FIGURE 5

EXTRAORDINARY FUEL CYCLE COSTS FOR THE URANIUM RECYCLE OPTION, INCLUDING REPLACEMENT ENERGY COSTS million was for replacement of energy during coastdown.

For the two cycle coastdown cases, the highest extraordinary fuel costs were those associated with the combination of 30% coastdown in the next to last cycle, followed by a coastdown of 30% in the final cycle. These extraordinary fuel costs were calculated to be $116.5 million, of which $14.1 million was in additional fuel costs and $102.3 million was for replacement energy during coastdown operations. The lowest extraordinary fuel costs of any of the two cycle coastdown cases for the uranium recycle option was that of the combination of 70% coastdown in the next to last cycle and 70% coastdown in the final cycle. These extraordinary fuel costs were $29.8 million, of which $11.0 million was for increased fuel costs and $18.8 million was for replacement energy costs.

Uranium and Plutonium Recycle Option

Because the computer code used in these calculations took into account the credit for sale of recycled uranium and plutonium when calculating the cost per kilowatt hour of energy produced by a given batch of fuel, the calculations for the plutonium and uranium recycle option are identical to those of the no recycle option, although the results are quite different. The results of these calculations are presented in Table 7.

The extrapolated fuel costs show that the cycles in question would have yielded a fuel cost of $111.6 million had the reactor not shut down for decommissioning. Because the reactor is shut down for decommissioning, these fuel costs increase to $183.7 million. This gives an extraordinary fuel cost of $72.0 million for the baseline case. As with this

TABLE 7

EXTRAORDINARY FUEL COSTS ASSOCIATED WITH THE URANIUM AND PLUTONIUM RECYCLE OPTION

| COASTDOWN POWER LEVEL | | COST IN MILLIONS OF DOLLARS | | | |
|---|---|---|---|---|---|
| Next To Last Cycle | Last Cycle | Fuel Cycle Cost | Replacement Energy Cost | Total Cost | Extra-Ordinary Cost |
| 100 | 100* | 111.6 | 0.0 | 111.6 | 0.0 |
| 100 | 100 | 117.3 | 66.4 | 183.7 | 72.0 |
| 100 | 70 | 112.6 | 42.6 | 155.3 | 53.6 |
| 100 | 50 | 124.0 | 55.1 | 179.1 | 67.4 |
| 100 | 30 | 127.0 | 84.4 | 211.4 | 99.8 |
| 70 | 70 | 123.9 | 18.8 | 142.7 | 31.0 |
| 70 | 50 | 125.2 | 31.3 | 156.5 | 44.9 |
| 70 | 30 | 128.2 | 60.5 | 188.8 | 77.2 |
| 50 | 70 | 124.8 | 31.3 | 156.1 | 44.5 |
| 50 | 50 | 126.1 | 43.8 | 170.0 | 58.3 |
| 50 | 30 | 129.1 | 73.1 | 202.2 | 90.6 |
| 30 | 70 | 126.9 | 60.5 | 187.5 | 75.9 |
| 30 | 50 | 128.2 | 73.1 | 201.3 | 89.7 |
| 30 | 30 | 131.1 | 102.3 | 233.5 | 121.8 |

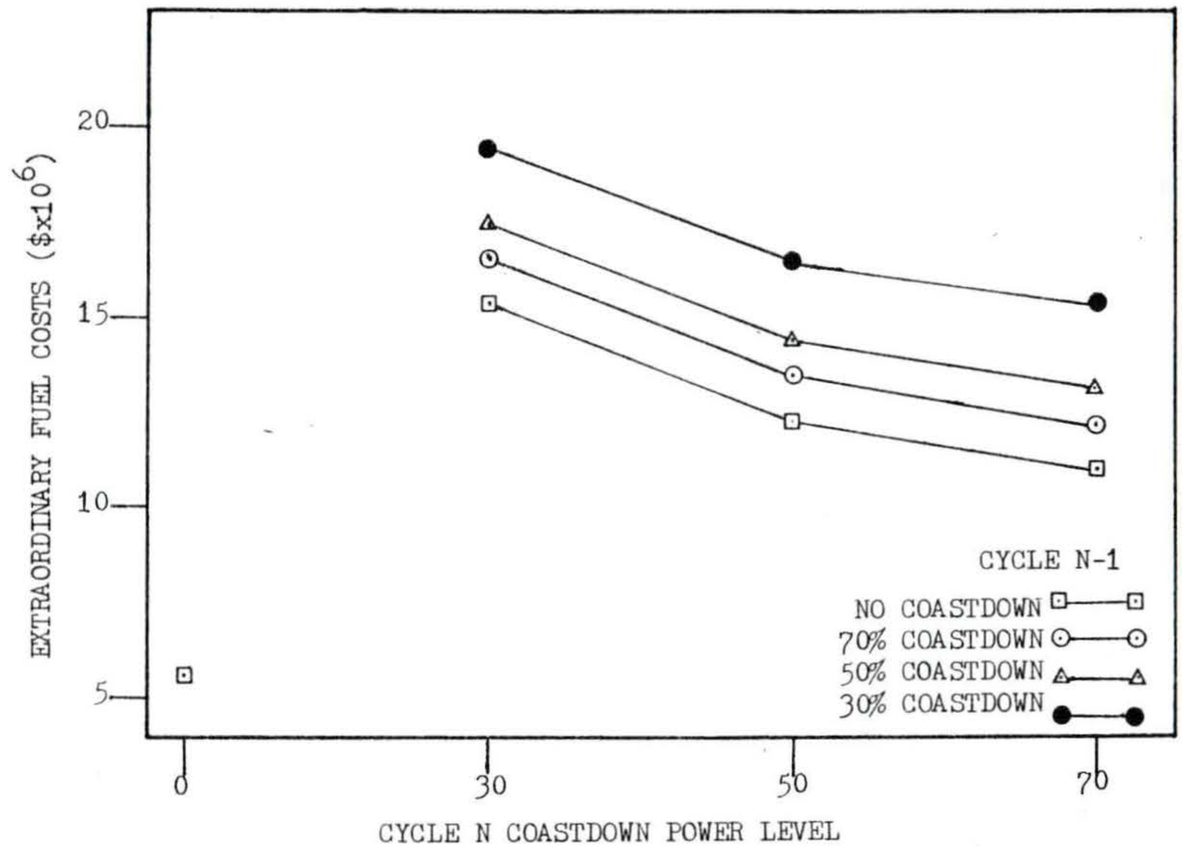


FIGURE 6

EXTRAORDINARY FUEL CYCLE COSTS FOR THE URANIUM AND PLUTONIUM RECYCLE OPTION, WITH REPLACEMENT ENERGY COSTS EXCLUDED

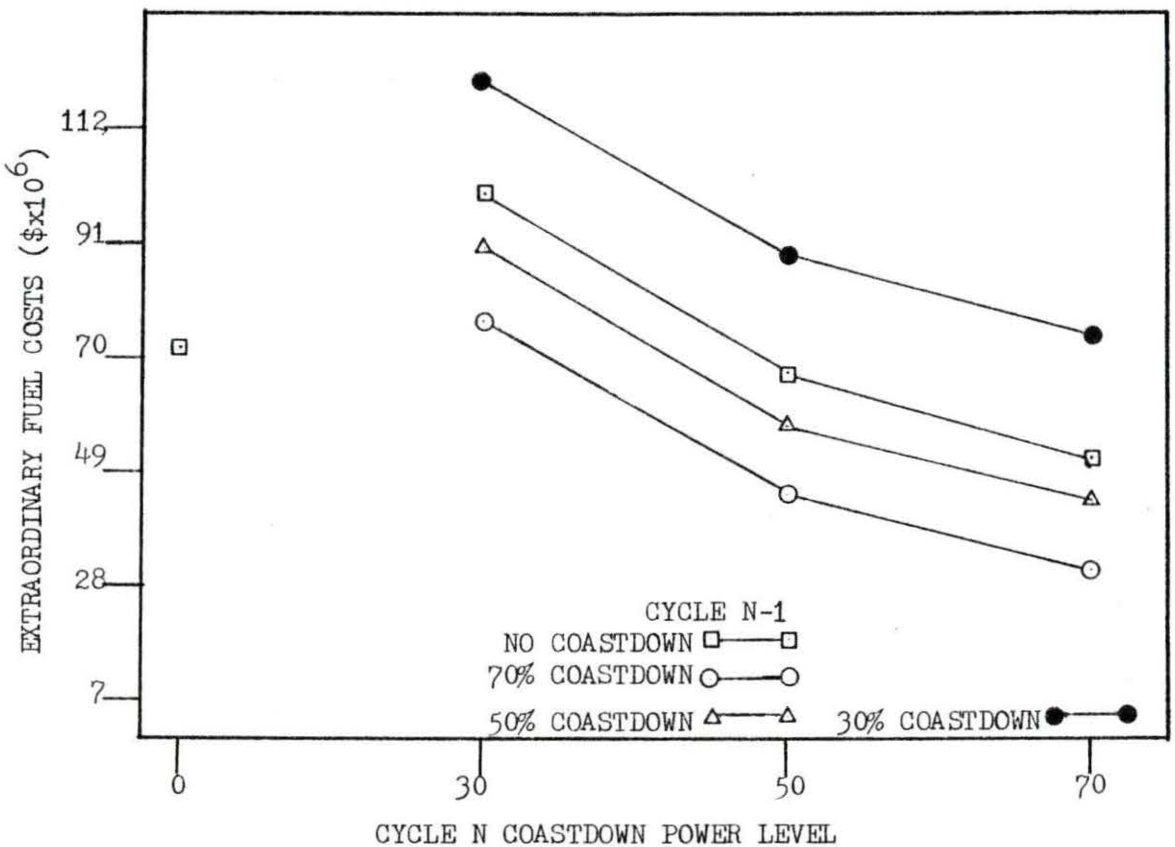


FIGURE 7

EXTRAORDINARY FUEL CYCLE COSTS FOR THE URANIUM AND PLUTONIUM RECYCLE OPTION, INCLUDING REPLACEMENT ENERGY COSTS case in the other two options, $66.4 million is for replacement energy costs.

For the single cycle coastdown cases, the highest extraordinary fuel costs resulted from the 30% final cycle coastdown case. These costs totaled $99.8 million, of which $84.4 million was for replacement energy and $15.4 million was in additional fuel costs. The lowest extraordinary fuel costs for these cases occurred in the 70% final cycle coastdown case. The extraordinary fuel costs for this case amounted to $53.6 million, of which $11.0 million was in additional fuel costs and $42.6 million was for replacement energy during coastdown.

For the cases involving coastdown in the final two cycles of operation, the highest extraordinary fuel costs were found for a combination of a 30% coastdown in the next to last cycle, followed by a 30% coastdown in the final cycle. Extraordinary costs for this case were found to be $121.8 million. Of this, $19.5 million was due to increased fuel costs and $102.3 million was for replacement energy during coastdown. The lowest extraordinary fuel costs for the two cycle coastdown scenario were for a combination of a 70% coastdown in the final cycle, preceded by a coastdown of 70% in the next to last cycle. Extraordinary costs for this case were found to be $31.0 million, of which $12.2 million was associated with increased fuel costs and $9.4 million was in replacement energy costs.

The results from the calculations involving the variation of the cost of yellowcake, enrichment, and permanent storage are presented in Tables 8, 9, and 10, respectively. The extraordinary fuel costs of these calculations are presented in Figures 8, 9, and 10. The replacement energy costs for

TABLE 8

EFFECTS OF VARIANCE OF COST OF YELLOWCAKE
ON EXTRAORDINARY FUEL COSTS

| COST | COASTDOWN OPTION | | | |
|---|---|---|---|---|
| $/kgU | Extrap. | 100-100 | 100-30 | 70-70 |
| 55 | 164.2 | 173.6 | 173.3 | 173.5 |
| 65 | 178.5 | 188.7 | 188.5 | 188.7 |
| 75 | | | | |
| 85 | 207.2 | 218.9 | 218.9 | 219.4 |
| 95 | 221.5 | 234.0 | 234.1 | 234.3 |
| 105 | 236.3 | 249.1 | 249.4 | 249.5 |

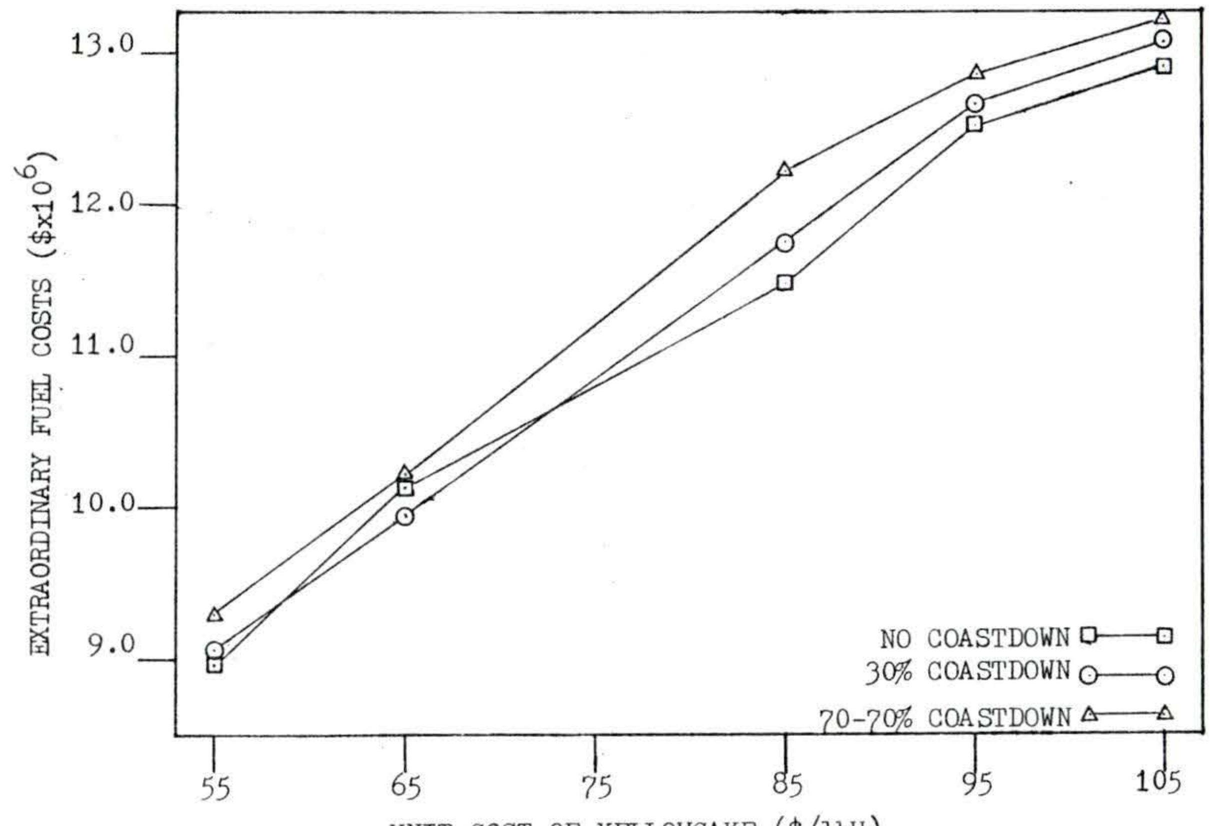


FIGURE 8

EFFECTS OF VARIANCE OF COST OF YELLOWCAKE
ON EXTRAORDINARY FUEL COSTS

TABLE 9

EFFECTS OF VARIANCE OF ENRICHMENT COSTS
ON EXTRAORDINARY FUEL COSTS

| COST | COASTDOWN OPTION | | | |
|---|---|---|---|---|
| $/SWU | Extrap. | 100-100 | 100-30 | 70-70 |
| 100 | 166.8 | 176.3 | 176.0 | 176.2 |
| 125 | 178.5 | 188.7 | 188.5 | 188.7 |
| 150 | 190.3 | 201.1 | 201.0 | 201.2 |
| 175 | | | 213.5 | 213.7 |
| 200 | 213.8 | 226.0 | 226.0 | 226.2 |
| 225 | 225.5 | 238.4 | 238.5 | 238.7 |

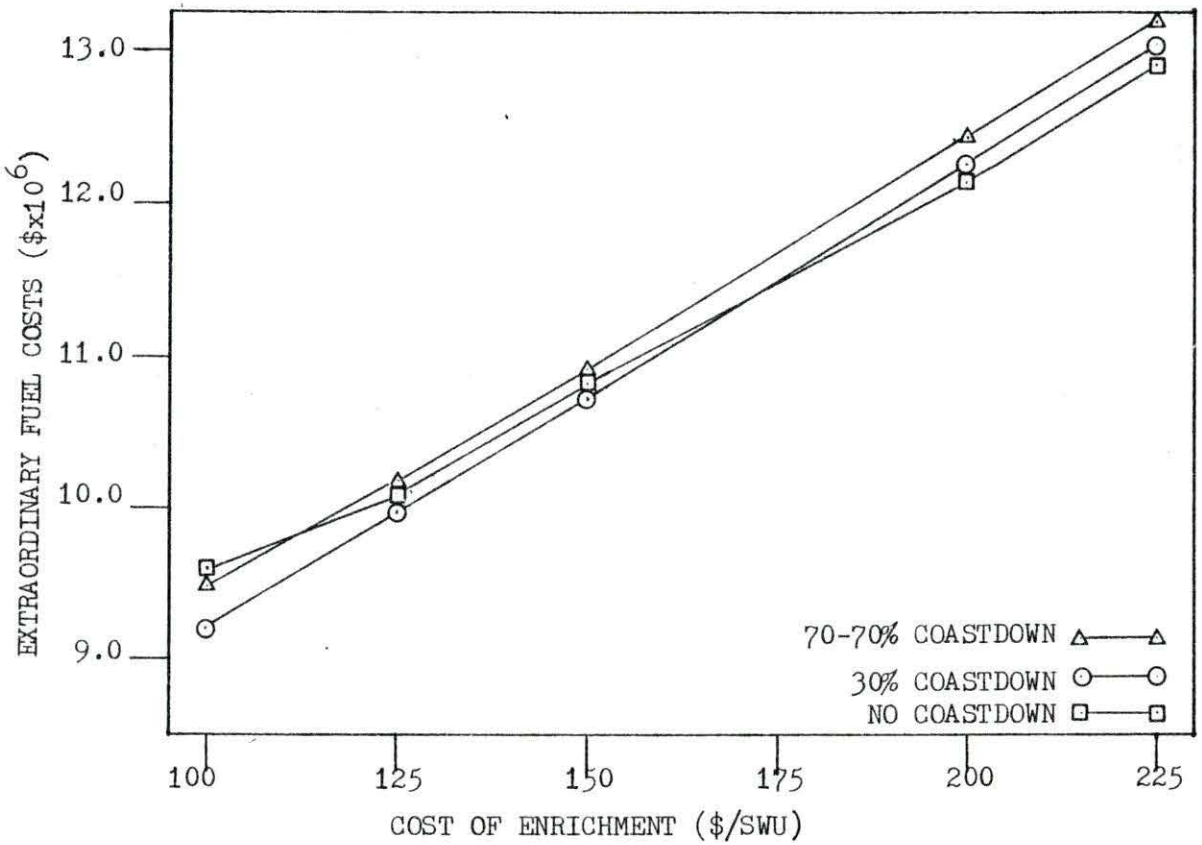


FIGURE 9

EFFECT OF VARIANCE OF COST OF ENRICHMENT
ON EXTRAORDINARY FUEL COSTS

TABLE 10

EFFECTS OF VARIANCE OF COST OF PERMANENT STORAGE
ON EXTRAORDINARY FUEL COSTS

| COST | COASTDOWN OPTION | | | |
|---|---|---|---|---|
| $/kgU | Extrap. | 100-100 | 100-30 | 70-70 |
| 350 | 178.595 | 188.733 | 188.557 | 188.774 |
| 375 | 178.595 | 188.733 | 188.557 | 188.774 |
| 400 | 178.595 | 188.733 | 188.557 | 188.774 |
| 425 | 178.595 | 188.733 | 188.557 | 188.774 |
| 450 | 178.595 | 188.733 | 188.557 | 188.774 |
| 475 | 178.595 | 188.733 | 188.557 | 188.774 |

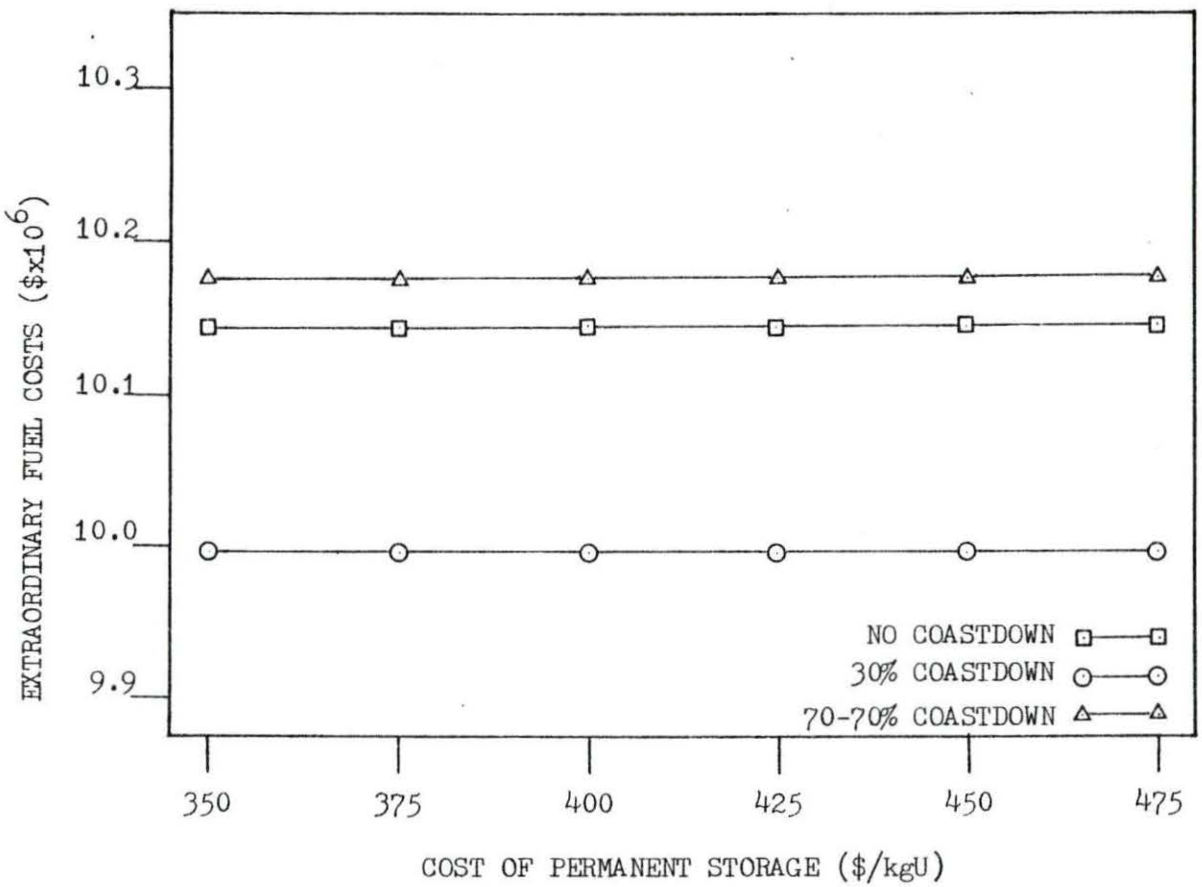


FIGURE 10

EFFECT OF VARIANCE OF COST OF PERMANENT STORAGE
ON EXTRAORDINARY FUEL COSTS

coastdown operations are not included in the tables or figures, but can easily be added from Table 5. The results of these calculations are discussed further in the next chapter.

# CONCLUSIONS

The results obtained from the calculations performed for this research show that coastdown operations can result in a lowering of the extraordinary fuel costs associated with decommissioning. The calculations further show that the extraordinary fuel costs are not dependent on the cost of permanent storage. This was most likely due to an error in the computer code. They are, however, highly dependent on the cost of yellowcake, although the difference between the costs of the different options remains relatively constant. They are also dependent, to a somewhat lesser extent, on the cost of enrichment, although the differences in cost of the various options also remain relatively constant.

Because the differences in cost between the various coastdown cases remain relatively constant, a utility need not repeat its calculations every time one of the costs upon which its calculations are based changes. The utility could make its basic calculations at the time of the initial decommissioning cost calculations, and then it could make its final studies just before shutdown.

The results presented in the previous chapter were all made with a coastdown burnup step of 3000 MWD/MTU. Additional calculations made for some of the coastdown cases for the no-recycle option show that, as the coastdown burnup step is increased, the difference between the extraordinary fuel costs of the various options also increases. Therefore, a utility making calculations similar to those presented in this thesis would probably wish to repeat the calculations for several different coastdown burnup steps in order to find the most economical coastdown option possible.

The lowest overall extraordinary fuel costs for the no recycle option were found to be those of the 70%-70% scenario, with an extraordinary fuel cost of $28.9 million. For both of the recycling options, the lowest extraordinary costs were also for the 70%-70% coastdown case. These costs were $29.8 million for uranium recycle option and $31.0 million for the uranium and plutonium recycle option. The highest extraordinary fuel costs also occurred for the same case in all of the recycling options. Therefore, a utility need consider only one of the two options in its preliminary studies and save detailed studies until the time of decommissioning actually approaches.

It is also quite likely that the nuclear facility to be decommissioned will be replaced by another facility at the time of decommissioning. If this facility becomes available before the end of the coastdown during the final cycle of operation, then all or part of the energy produced during that coastdown may be surplus. Should this be the case, some of the coastdown scenarios then become viable. Should the facility be available during coastdown operations during the next to last cycle of operation, then all of the coastdown scenarios become financially attractive.

In summation, then, it has been shown that utilities have the potential to reduce the fuel costs associated with the decommissioning of their nuclear facilities, which in turn will lead to decreased decommissioning costs. These reductions can be achieved in a rather simple manner using coastdown during the final few cycles of plant operation. By reducing the decommissioning costs of a nuclear facility, a utility will reduce the amount of funds which must be secured well in advance of decommissioning, which will, in turn, reduce the cost of electricity to the consumer.

# SUGGESTIONS FOR FUTURE WORK

The results of this study were obtained by assuming that the method of fuel shuffling used during refueling outages during normal operation was continued through the final cycles. It is possible, however, that alternative fuel shuffling schemes for the last few cycles could be developed which would, either by themselves or coupled with a coastdown scheme, result in even further reductions in the extraordinary fuel costs associated with decommissioning. These possibilities warrant further study.

Since the reactor used in this study is a pressurized water reactor, it may safely be assumed that the results are applicable to any pressurized water reactor, and, with adjustments made for reactor size, similar reductions in the extraordinary fuel costs associated with decommissioning could be achieved. About one third of the reactors in operation in the United States, however, are boiling water water reactors, and the results presented here would not be expected to be applicable. In a pressurized water reactor, coastdown may be achieved by reducing reactor power or coolant temperature. In a boiling water reactor, however, because the effects of reducing reactor power and coolant temperature on the functioning of the reactor are somewhat different, results could vary significantly. This area also merits further study.

A third area which, although not directly related to decommissioning fuel costs, still needs attention is the area of cost comparison of various decommissioning alternatives. A recent study by the Atomic

Industrial Forum[7] concluded that, since no two decommissioning studies take into account the same factors, it is virtually impossible to estimate the costs of decommissioning a nuclear power plant, short of actually completing a plant specific decommissioning study. They suggest, as a research project of some value, the development of a computer code which would estimate decommissioning costs. Not only would such a program help standardize the computation of decommissioning costs, but would also allow a utility to easily observe the effects of varying the costs of labor, money or other factors on the decommissioning costs.

# ACKNOWLEDGMENTS

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