DECISION MODELS FOR OPTIMIZING FUEL ENRICHMENT SERVICES UNDER LONG-TERM FIXED-COMMITMENT CONTRACTS

by

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The author wishes to express his deepest appreciation to his wife, , who so patiently typed the final and many preliminary drafts. Also thanks and appreciation are due to and for their support and assistance in developing the work presented here. I dedicate this report to my wife and my parents.

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I. INTRODUCTION

A. Background and Motivation

Utilities that operate light water nuclear power reactors face a variety of decision problems in interacting with the nuclear fuel cycle to procure reactor fuel. Perhaps the most complex and important of the decision problems faced by the utility companies occurs in the contracting for fuel enrichment services.

Presently the Energy Research Development Administration (ERDA) holds enrichment services contracts that cover 320,000 electrical megawatts of nuclear power. Of that total, 213,100 megawatts represent domestic nuclear power plants and 107,100 megawatts represent foreign plants.[1] Independent of customer identity, different contract types also exist. The two standard types of contracts are the long term fixed-commitment contract and the customer requirements contract.

The customer requirements contract is a contract originally offered by the Atomic Energy Commission. As the name implies, the contract stipulates that enrichment services will be supplied based upon the actual requirements of an individual reactor. If a reactor is delayed in starting up or requires less enriched uranium, the corresponding requirement for enrichment services is also delayed or reduced. The contract holder must provide ERDA with a firm schedule 180 days prior to obtaining enrichment services. For planning purposes only, the contract holder provides ERDA with an estimate of annual requirements for the next five years and a month-by-month estimate of annual requirements for the next two years.[2]

In 1973, the government discontinued the practice of accepting customer requirements contracts for newly constructed reactors. Utilities still holding these contracts were encouraged to convert them to equivalent fixed-commitment contracts.[3]

Under a long term fixed-commitment contract, utilities must provide ERDA with a firm, rolling, ten year schedule in that as the enrichment services of one year are used, another year is added to the schedule. Ten years prior to fuel delivery the utility specifies to the enrichment plant the amount of enriching services by estimating the the number of separative work units (SWU) needed at the enrichment plant to produce the required fuel for the reactor. This estimation of SWU is based upon the amount of enriched product required, the quantity of natural uranium feed sent to the enrichment plant, and the product and tails enrichments needed. Once the SWU requirement is estimated it must remain fixed during the contracting period.[4]

The crucial decision point in the fixed-commitment contracting process occurs 18 months prior to fuel delivery. At the 18 month point, the utility must identify how the fixed-contracted SWU is to be used by specifying the quantities and assays of product to be delivered. The 18 month point in the contracting process is subject to substantial decision flexibility. This decision can be influenced by SWU requirements, inventories of enriched fuel, reactor fuel demand constraints, previous and future contracts, SWU and uranium feed costs, and sudden changes in fuel demand. Decision errors are potentially very costly.[5]

B. The Problem and Objective

The most serious problem today in contracting for nuclear fuel enrichment services is caused by the application of the fixed-commitment contract. The enriching customer has less flexibility with the fixed-commitment contract since the amount of enriching services, estimated ten years prior to fuel delivery, cannot be changed in the event of a fuel demand variation or the occurrance of a reactor schedule slippage. As a result of this ten year inflexibility, utilities overestimate the quantity of enrichment services to assure themselves of having sufficient fuel to satisfy reactor fuel needs. The practice of over-estimating enrichment services has led to the accumulation of inventories of enriched fuel or natural uranium.[6] Due to the fuel inventories, an additional holding cost for fuel storage has increased the total cost for enriching services.

Another important reason for rising costs in enrichment services is attributed to the split-tails mode of operation of the enrichment plant. According to the fixed-commitment contract, ERDA operates the enrichment plants at an operating tails assay of .25% U-235. The utilities, however, base their estimations of SWU on the transaction tails assay of .2% U-235.[7] The main problem with the split-tails mode is that the utility cannot choose the optimum operating tails assay which will adequately represent the most economical operation of the enrichment plant. As a result of this split-tails mode of operation, utility costs for fuel enrichment services increase.

Due to inventory costs, the split-tails mode, and the uncertainty in ten year SWU projections, severe mismatches between contract commitments and the actual needs of the utility may be induced. The combination of these problems have also contributed to the skyrocketing of uranium prices. Since the fixed-commitment contracts were signed in 1973, uranium spot prices have increased from \$6.50/lb.-U_3O_8 in July, 1973 to \$41.00/lb.-U_3O_8 in September, 1976.[8]

The application of the fixed-commitment contract has developed rising costs in the nuclear industry. In order to reduce these rising costs it is imperative that the fixed-commitment contracting process is improved and utilized more efficiently so fuel needs of a utility are satisfied.

The objective of this effort is to improve utility interaction with the fixed-commitment contracting process by determining decision strategies for satisfying utility requirements most economically. Specifically, the objective is to determine an optimum decision strategy that can be used to analyze the 18 month decision point of the fixed-commitment contract from both a static and a dynamic perspective. The models that address this problem are developed separately and are presented for the static and the dynamic cases. In the development of the models, a variable tails concept is introduced in place of the current split-tails method to further optimize the results of the decision models. Justification for using the variable-tails method is presented. Results from analyzing and solving the decision models are presented and the resulting specific optimum decision strategies are identified. In order to indicate the improvement developed by the optimum decision strategies, the results of the decision models are also analyzed with respect to the current method of utilyzing fixed-commitment contracts.

C. Approach

Three models are formulated to analyze the 18 month decision point of the fixed-commitment contract. In each of the models, an optimum decision policy is generated for acquiring nuclear fuel enrichment services. For a given fixed quantity of enrichment services and a reactor fuel demand, this optimum decision policy indicates to a utility the amount of uranium feed sent to the enrichment plant, the amount of enriched product produced, the tails assay, and the total cost for enrichment services. The priniciple descriptions of the three models are presented below:

1. This model describes the current ERDA process for enrichment contracting. The development of the modeling equations is based upon the split-tails concept and all existing regulations of the fixed-commitment contract. The optimum decision policies are generated for a ten year contracting period.

2. In this model, the variable-tails concept is used in place of the split-tails method in order to minimize the total costs of enriching services. In order to understand the simple behavior of the modeling equations, the results of the model are only generated for one contracting year. A detailed analysis of this behavior is

identified to help formulate the dynamic model. This second model is referred to as the static decision model.

3. In this model a ten year dynamic inventory level system is developed to determine the optimum decision policy for enrichment contracting. This dynamic inventory model is designed to permit an analysis of the consequences of manipulating fuel inventories and variable tails enrichments at the 18 month decision points over ten years. In each year, the optimum decision policy for contracting enrichment services is developed using the equations of the second model. The results from this dynamic model are analyzed with respect to the results of the first model to indicate the improvements produced in the fixed-commitment contracting process. In order to examine the transient behavior of the dynamic model, a sensivity analysis on specific parameters is also performed.

The measure of effectiveness for all three decision models is the total cost for enrichment services. The main objective of the models is to minimize total costs while satisfying the fuel demand of the utility. The uranium feed is another important variable that is examined carefully in the analysis of the model results. The usage of the uranium feed should be kept to a minimum in order to deplete the uranium resources in the United States at a lower rate.[9]

The application of the three decision models is done by using data from a typical ten year fuel contract for a 1000 Mwe reactor. This typical ten year contract information is referred to as the base case data. For each contracting year the base case data includes the total number of SWU estimated, the amount of fuel needed, the product enrichments, and the SWU and feed costs per kilogram of fuel. A computer code is constructed to solve the decision models for the optimum decision policies.

D. Chapter Summaries

The thesis is comprised of seven chapters. Following the introductory remarks, additional material on the nuclear fuel cycle and on the description of the enrichment contracting process is found in Chapter Two. Also included in the second chapter are examinations of the current status of enrichment contracting and of the present contracting problems affecting the nuclear industry. Chapter Three presents the derivation of the three decision models. Chapter Four describes the application of the proposed models to a typical fuel contract. The results and the optimum decision policies are presented in Chapter Five. Also in Chapter Five, a sensitivity analysis on certain parameters of the decision models is performed. Conclusions follow in Chapter Six with recommendations discussed in Chapter Seven. Tables describing the results are indicated in Appendix I and the rules and regulations of the fixed-commtment contract are included in Appendix II.

E. Summary of Results

The split-tails model and the dynamic inventory model were developed and applied to a typical ten year fuel contract. The results indicated that there were significant potential penalties in using ERDA's current split-tails model. In using the split-tails model high utility costs and large uranium feed requirements were incurred when fuel requirements were under or overestimated at the ten year point.

The dynamic model appeared to provide an opportunity for utility companies to analyze the enrichment contracting process and thereby use it efficiently. In using the dynamic model there was a significant amount of savings in utility costs and uranium feed, especially during an overcommitment fuel demand case. The variable tails concept used in the dynamic model allowed the utility to choose the optimal tails enrichment that would reflect the minimum cost and the minimum amount of uranium feed needed to satisfy fuel demand. In the split-tails model this flexibility in the tails enrichment does not exist. Therefore the application of the variable tails concept proved to be more economical than the split-tails method.

The manipulation of fuel inventories in the dynamic model also helped to minimize costs and uranium feed. The dynamic inventory model appeared to be an appropriate vehicle for improving the fixed-commitment contract.

II. DESCRIPTION OF THE ENRICHMENT CONTRACTING PROBLEM

A. An Explanation of the Enrichment Contracting Process

To further clarify the contracting problem, some background information explaining the details of the enrichment contracting process is presented here. The nuclear fuel cycle is the sequence of production stages, that transforms uranium bearing ore into reactor fuel and returns it back to the earth in the form of solid waste. These stages are shown in Figure 2.1. One of the most important of the decision situations faced by the utility companies in their interaction with the nuclear fuel cycle occurs in the enrichment stage. In this stage a utility signs an enrichment contract ten years before the resulting fuel is delivered.[10] Many decision problems are usually created in the contracting process because of the ten year lead time.

According to the contract the enrichment plant provides the utility the amounts of fuel demanded at required enrichments. The fuel is enriched to the required enrichments by an enrichment process. The purpose of the enrichment process is to increase the proportion of the fissile U-235 isotope in the fuel from its natural .711% to typically between 2% and 4%, depending upon reactor requirements. The gaseous diffusion process is presently

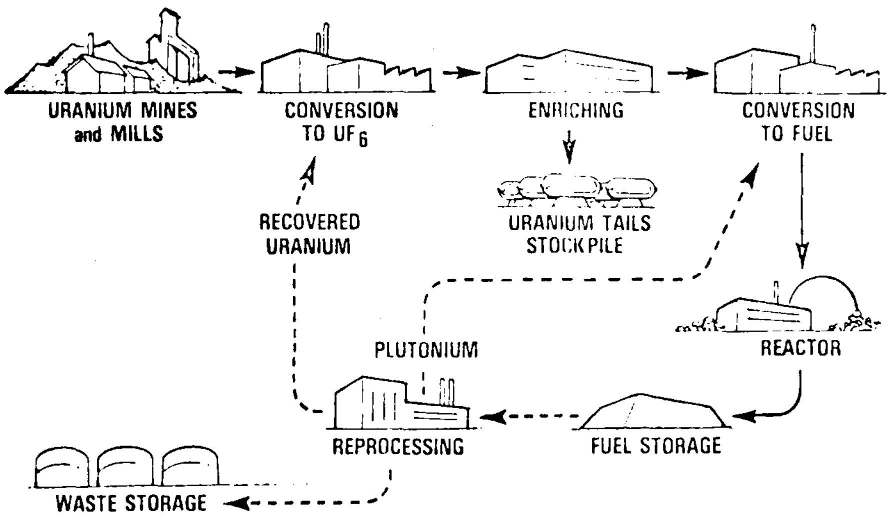


Figure 2.1. The Light Water Reactor Nuclear Fuel Cycle

used to accomplish this enrichment. However, other methods such as the laser and gas centrifuge processes are being considered for the future.

Enrichment plant processing is measured in terms of separative work units (SWU), which are a measure of the performance of the enrichment facility required to separate the UF_6 input into the enriched product and depleted waste (tails) streams and is dimensioned in the units of material quantity (e.g.,kg).

Given the definitions that:

X_p = enrichment of the product material,

X_w = enrichment of the waste material (tails),

X_f = enrichment of the feed material (.711%),

P = quantity of product material generated,

W = quantity of waste material produced,

F = quantity of feed material input,

the material flow balance of the enrichment plant is defined by:

$$F = P + W \qquad (2.1)$$

and the enriched uranium material flow balance is given by:

$$\frac{F}{P} = \frac{X_p - X_w}{X_f - X_w} . \qquad (2.2)$$

The amount of enrichment plant processing required to accomplish the enrichment in terms of SWU is given by:

$$SWU = P\left[V(X_p) - V(X_w)\right] - F\left[V(X_f) - V(X_w)\right] \qquad (2.3)$$

where the function V(X) is called the value function and is defined as:

$$V(X) = (2X-1)\ln(X/1-X).^{11} \qquad (2.4)$$

It can be seen that there is a strong relationship between uranium feed requirements, separative work utilization, and the tails enrichment (X_w). Thus, it is not sufficient merely to select the number of SWU. There is substantial flexibility to manipulate the feed and product quantities, product enrichments, and the tails enrichment. Similarly, for a fixed product stream, a variety of alternative combinations of feed streams and SWU will yield the required product. Alternatively, for a given number of SWU, a variety of feed streams and tails enrichments will yield a range of quantities of enriched product. These observations indicate the complexity of managing the fuel enrichment process.[12]

In all cases, the utility company has the option to receive the tails (waste material) from the process. Tails material has been produced with a range of enrichments between .2% and .3%. This indicates a potential, though often overlooked, further supply of fuel material. If the customer so desires, he may acquire an appropriate quantity of tails material at the time of delivery of the enriched product. No charge is imposed for the material other than those for withdrawal, handling, and packaging. If, at this time, the utility chooses not to acquire the tails material, it becomes the property of the government.[13]

The key to efficient use of enrichment processing lies in the contracting activity in which the utility management contracts for separative work. In general, the SWU contracts specify the flows of material, accountability for material quality and quantity, delivery and receipt schedules, liability, costs external to the process (holding, storage, overhead, interests, taxes, etc.), and the cost of service. Government charges for enrichment services are constructed to recover costs rather than to generate profit. These charges are accordingly revised periodically to reflect rising costs of labor and electricity. Nevertheless, the cost increases can be dramatic such as the increase form $26/SWU in 1967 to $69.80/SWU in 1977.[14]

B. Details of the Long Term Fixed-Commitment Contract

In 1973 ERDA introduced the fixed-commitment contract to the electric utilities. This fixed-commitment contract was developed to provide ERDA with a sounder basis for long term planning of gaseous diffusion plant operations.[15]

The most important regulations of the contract are briefly explained in this section. A copy of an actual contract agreement depicting all the rules and regulations of the fixed-commitment contract is included in Appendix I.

If a utility needs enrichment services, a ten year fixed-commitment contract agreement is the vehicle for obtaining this service. According to the contract agreement, the utility develops an enriching schedule that indicates the number of separative work units ERDA furnishes for the first ten years of the contract. After the tenth year of the contract, an additional year of enrichment services is added on to the schedule. The estimation of the required number of SWU is made at least ten years prior to fuel delivery in order to provide ERDA with greater flexibility in controlling future plant operation.

The ten year enrichment schedule developed ten years prior to fuel delivery is referred to as Appendix A in the fixed-commitment contract. Appendix B is included to indicate the estimated material quantities and assays required to meet the reactor fuel demand of the utility. The information in Appendices A and B are referred to as the standard tables of enriching services. A description of Appendices A and B of the fixed-commitment contract is presented in Appendix II of this report.

There are certain time periods and delivery dates that are included in the rules of the fixed-commitment contract. The most important dates and rules are indicated below.

1. The ten year contract is made ten years in advance of the first fiscal year of fuel delivery. The standard table of enriching services are also developed at this point.

2. By January 1 of each year of the ten year fuel contract the utility provides ERDA with an up-to-date written schedule for the subsequent two fiscal year period of its estimated monthly quantities and assays. At this point the information in Appendix A remains the same.

3. At least 315 days prior to the beginning of the month of desired fuel delivery the utility specifies the amount of enriching services required during that month. The amount of enriching services used is constrained by the amount of SWU estimated in Appendix A of the contract.

4. At least 240 days prior to the beginning of the month of desired fuel delivery ERDA notifies the utility the month and day of delivery of enriched material and the associated date of feed material delivery which will be within 90 to 180 days prior to the delivery of the enriched material.

5. By 30 days prior to written notice ERDA may require notices in excess of 315 days and may require delivery of feed material in excess of 180 days before the desired month of delivery of enriched uranium.

6. At least 180 days prior to the firm delivery dates the customer shall specify the specific quantities and assays of product to the customer and feed material to be delivered to ERDA.

7. In order to acquire the tails material, the utility must deliver a notice to ERDA at least 90 days prior[16] to the date of enriched product fuel delivery.

The chronology of the major dates required by the fixed-commitment contract is shown in Figure 2.2. The most important date of the contract is January 1. At this point, the utility has to decide how the fixed contracted

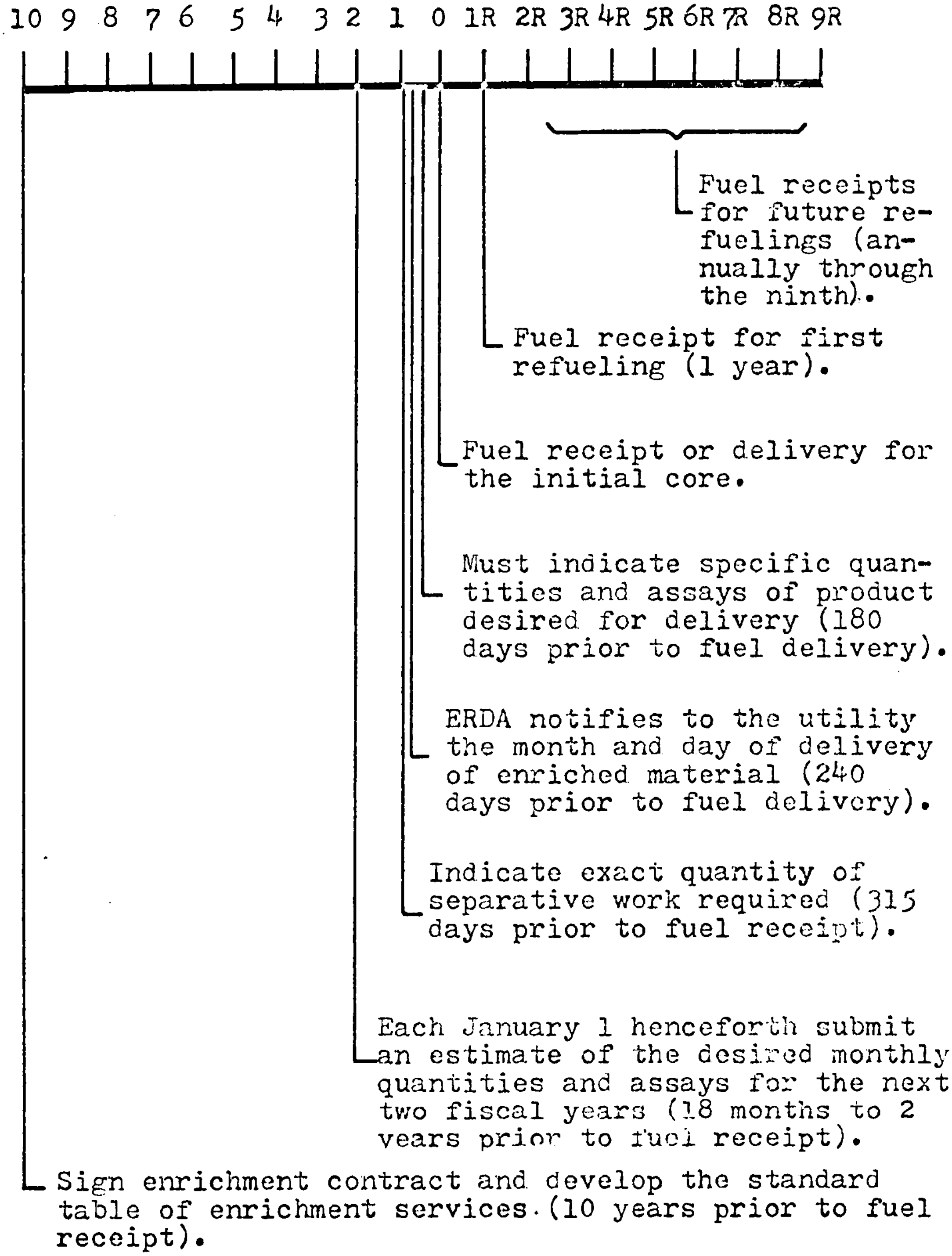


Figure 2.2 Enrichment Contract Chronology[17]

number of SWU are to be utilized by specifying quantities and assays of product to be delivered. This crucial date is sometimes referred to as the 18 month decision point since there is a minimum difference of 18 months between January 1 and the fuel delivery date. This 18 month decision point is analyzed in the decision models of this report in order to determine an optimum decision policy that will incur a minimum cost for fuel enrichment services.

C. Current Status of Enrichment Contracting Activities

1. Current Enrichment Services Contracting

A recent survey of all domestic and foreign utilities with nuclear power plant programs was performed to provide data on the current status of enrichment contracting. This survey was conducted by the Edison Electric Institute (EEI) during March and April of 1977. The survey results include essentially all of the domestic and foreign utility contract commitments and uranium enrichment services to support the domestic nuclear power programs for operating reactors during the period from 1977 to 1990. The data was based on the operation of the enrichment plants at a .2% U-235 tails assay with no recycle of uranium or plutonium from the spent fuel.

The contract information for the survey is compiled for 356 nuclear power plants having a combined capacity of 320,200 Mwe. Of this total 213,100 Mwe represent domestic nuclear power plants and 107,100 Mwe represent foreign plants. In addition to the classification between domestic and foreign plants a further classification in the type of contract also exists. The domestic power plants include 122 units with fixed-commitment contracts, 86 units with requirements type contracts and 8 units that do not have enriching service contracts.[18] In Table 2.1, a classification of the type of contract for the domestic and foreign plants is shown.

According to the survey, the application of the fixed-commitment contract is creating an imbalance between the contract commitments and the current utility needs. To counteract this imbalance contract adjustments of one year or more are desired for sixty-five reactors. Contract terminations are desired for eight of the domestic reactors. Effects of permitting contract adjustments to achieve a balance with current utility schedules include a reduction in the overcommitment on the part of the ERDA enriching facilities, and a decrease in natural uranium procurements of approximately three percent over the thirteen year period. Both the enrichment capacity and uranium supply market are better matched with their capabilities if fixed-commitment contracts are adjusted to current utility

Table 2.1. Uranium Enrichment Services Contracts of April, 1977 [19]

	Thousands of Megawatts			Number of Reactors		
Contract Type	Domestic	Foreign	Total	Domestic	Foreign	Total
Requirements-Type	76	25	101	86	46	132
Fixed-Commitment	130	82	212	122	92	214
Other	7	0	7	8	0	8
Total	213	107	320	216	138	354

schedules. The probable specific result of contract adjustments are the relief of about 12 million SWU of overcommitments for enrichment services and a potential decrease in natural uranium offers of about 12,000 short tons of U_3O_8 for the period from 1977 to 1990.[20] Figures 2.3 and 2.4 indicate this overcommitment in SWU and natural uranium respectively.

2. The Expected Tails Assay Range which ERDA Plans to Transact and Operate

ERDA is presently transacting at a tails assay of .2% U-235. The transaction tails assays specifies the amount of enrichment services a customer purchases from ERDA and the quantity of uranium the customer delivers to ERDA in order to obtain a required amount of enriched uranium. ERDA is presently operating the three gaseous diffusion plants at a tails assay of .25% U-235. Although more natural uranium is required at a higher tails assay, it is possible to operate the plants at a tails assay higher than the transaction tails assay because ERDA has stockpiles of uranium that can be fed to the plants.[23]

Projections of future transaction tails assays for the ERDA Gaseous Diffusion Plants to sustain ERDA's contract commitments were presented in the Uranium Industry Seminar at the Uranium Enrichment Conference in Oak Ridge,

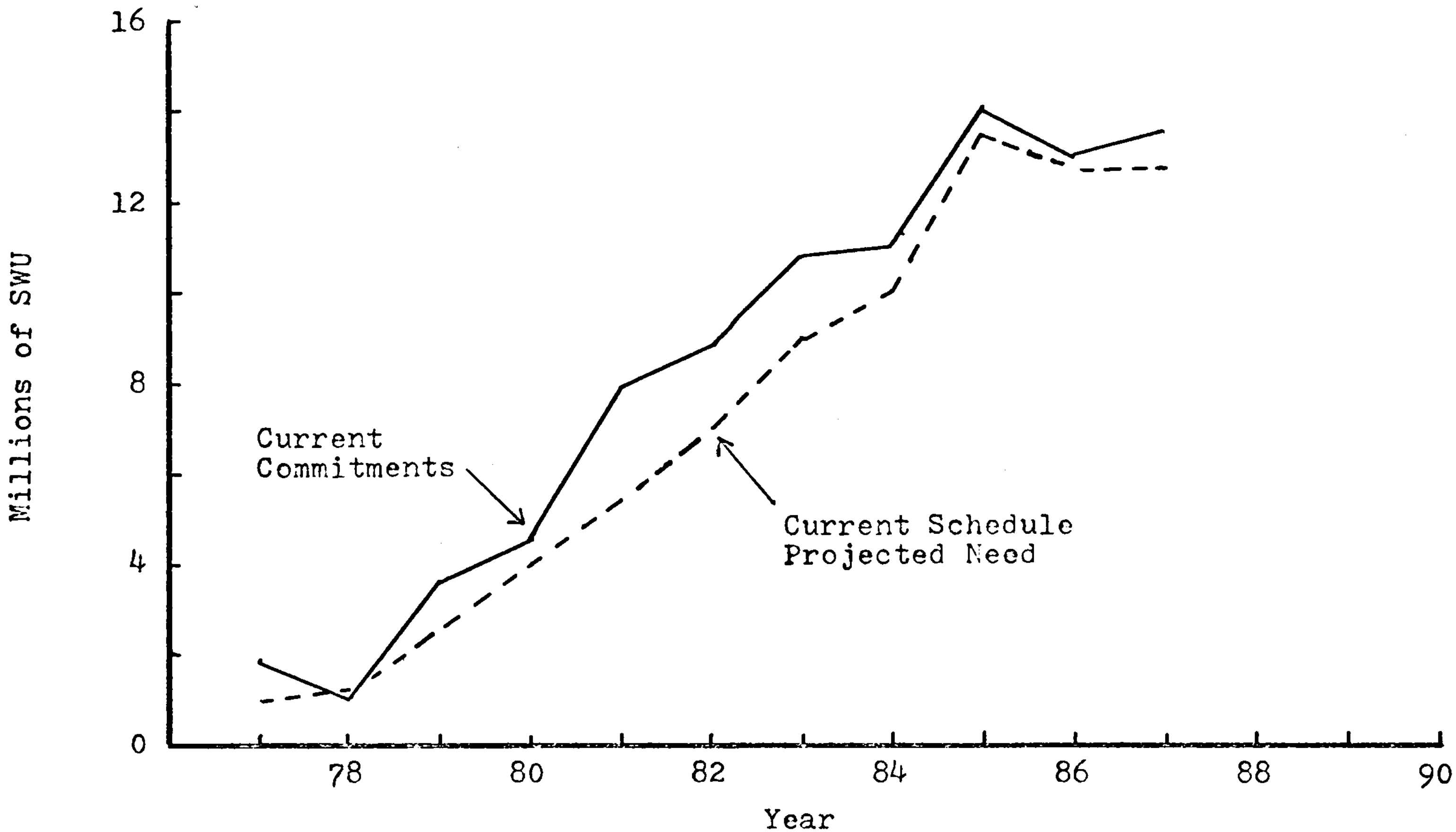


Figure 2.3. Annual Separative Work Requirements Domestic Fixed-Commitment Contracts[21]

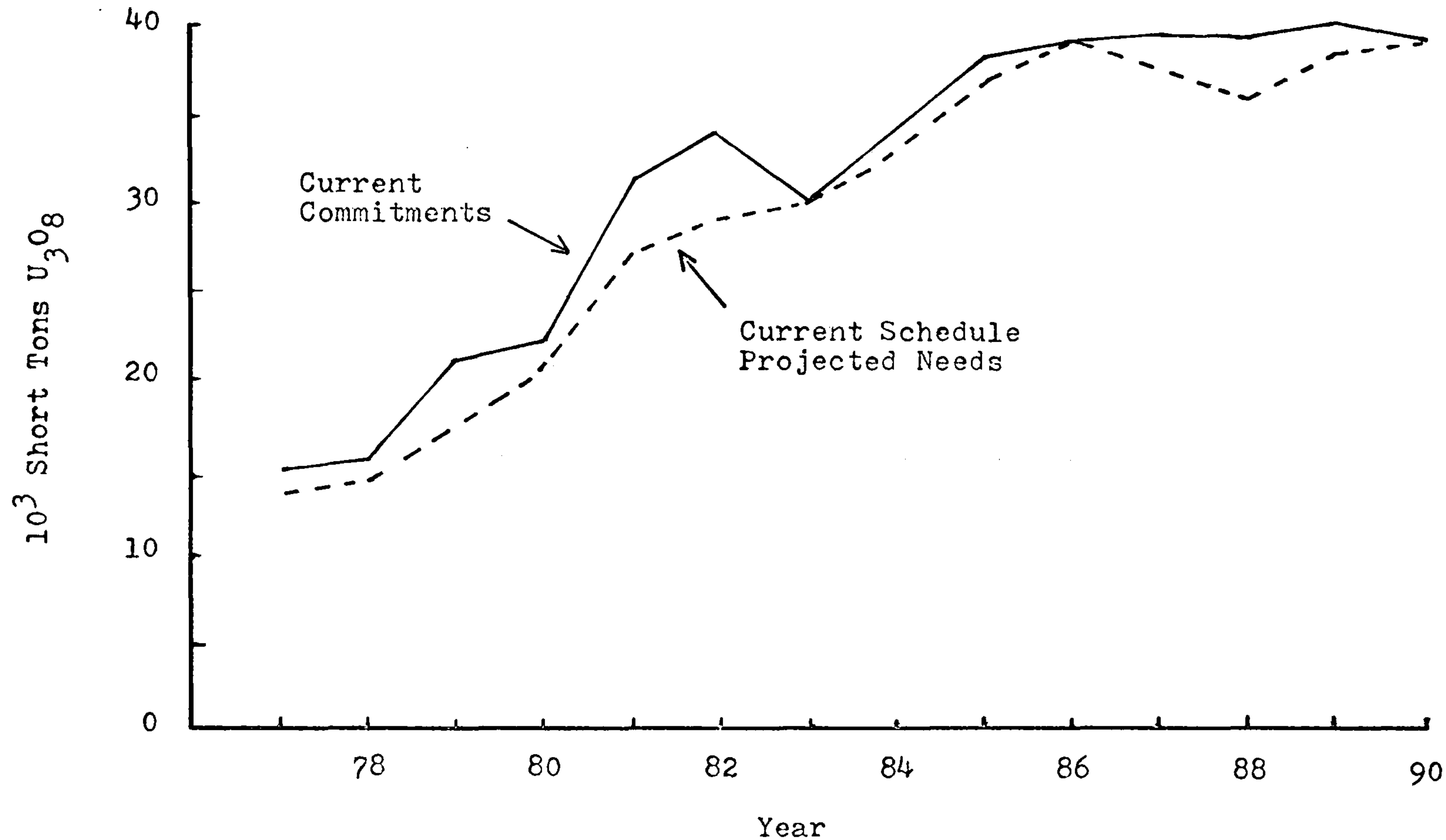


Figure 2.4. Annual Natural Uranium Requirements-All ERDA Domestic Enriching Contracts[22]

Tennessee on November 11, 1975. The major variable influencing the selection of the transaction tails assay is the amount of enriched uranium necessary to fuel the reactors under ERDA contracts. These requirements are directly influenced by the permissibility of using recovered plutonium as a partial substitute for enriched uranium in light water reactors. As shown in the middle column of Table 2.2, the tails assays in the range of .29% U-235 to .37% U-235 are identified as possibilities depending on the degree of plutonium recycle and based on a fixed separative work capacity. In order to supply the enrichment services for 320,000 megawatts under long term contracts with plutonium recycle, ERDA is required to transact and operate at a tails assay of about .29% U-235. This tails assay must be in effect starting in the early to mid-1980's. On the other hand, to supply those same contracts without the reactors recycling plutonium requires ERDA to transact and operate at about .37% U-235. Again, this tails assay must be in effect by the early to mid-1980's.[25]

These high tails assays can be avoided by additional uranium enrichment capacity. Congress has directed ERDA to build an addition to its Portsmouth, Ohio facility, referred to as an "add-on plant".[26] This add-on plant will utilize the centrifuge enrichment process for supplying enrichment services. The plant should be in full operation

Table 2.2. Tails Assays Needed to Sustain 320,000 Megawatts of Nuclear Power[24]

	Tails Assays in Percent U-235	
Generic Approval of PU Recycle	Present Three Plants Producing 28 Million SWU	Present Three Plants Plus Add-On Plant of 8.75 Million SWU
Yes	0.29	0.20
No	0.37	0.25

by 1988.[27] It is currently planned that the additional enrichment capacity from the add-on plant be used to fulfill ERDA's contractual obligations and to supplement the national stockpile of enriched uranium. It is expected that the add-on plant would have a capacity of 8.75 million separative work units (SWU) per year. A plant of this capacity, added to the existing plants, would permit existing ERDA customers to be served at a tails assay of about .2% U-235 assuming recycle of plutonium from spent fuel, or about .25% U-235 assuming no plutonium recycle. This is shown in the last column of Table 2.2.[28]

ERDA plans to develop gas centrifuge plants in the future to help relieve the enrichment capacity problem. ERDA has spent an excessive amount of time and money for the gas centrifuge program because there may be some strong economic advantages to having gas centrifuge plants rather than gaseous diffusion plants. Figure 2.5 indicates ERDA's estimates of the relative economics of uranium enrichment, utilizing a diffusion plant and an equal sized gas centrifuge plant constructed at one of ERDA's existing plant locations. As can be seen in Figure 2.5, the capital cost estimate for the centrifuge plant is about 22% greater than for the Portsmouth Add-On Diffusion Plant, but the unit cost of separation work from a centrifuge plant is projected to be about 30% less than that from the

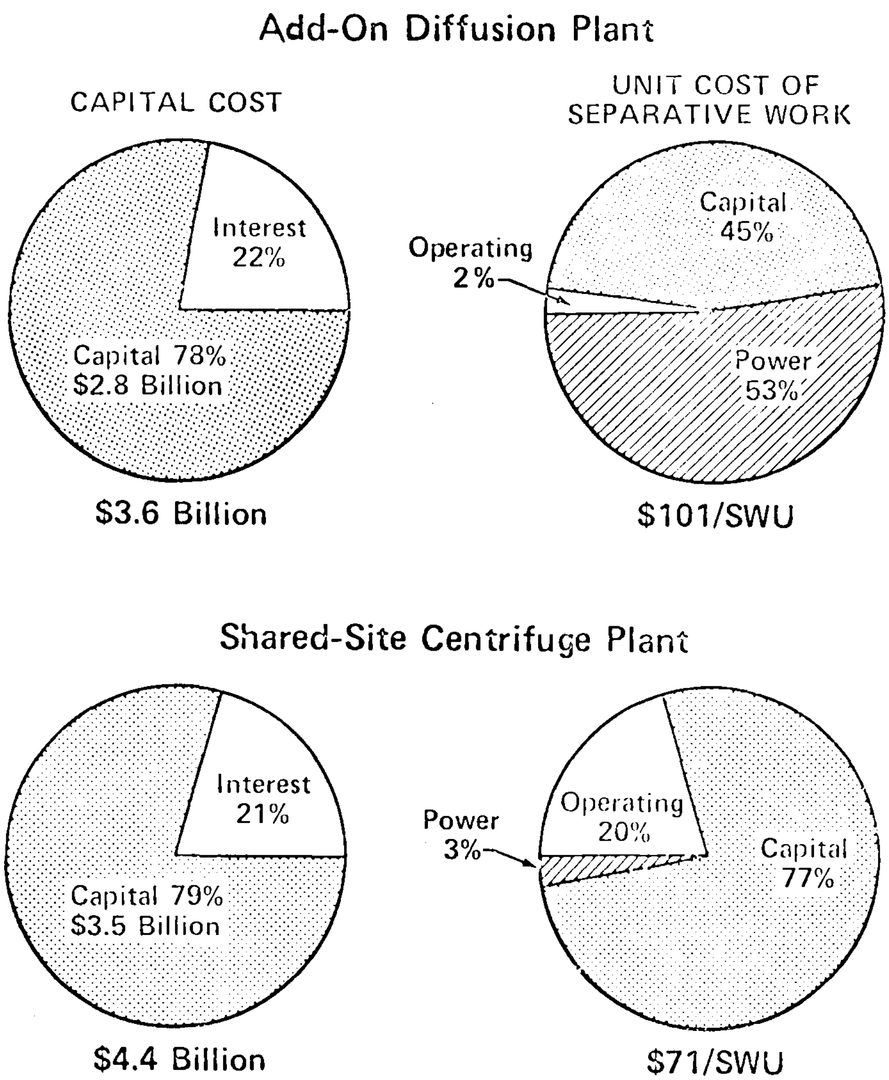


Figure 2.5. Cost Estimates for Gaseous Diffusion and Centrifuge Plants (FY-1977 Dollars)[29]

diffusion plant.[30]

3. The Expected Range in Requirements for Natural Uranium (U_3O_8) and Separative Work Units (SWU)

The lower reactor ordering rate and the uncertain role of nuclear energy in the nation's future suggests that long term uranium requirements may be lower than previously forecast. However, most analysists conclude that the primary sources of electric energy over the next two or three decades will have to be nuclear power and coal. Because of impending strip-mining laws, nuclear power may prove to be more advantageous than coal power. The current commitment to nuclear power is substantial and uranium requirements in the years ahead will be large, requiring a substantial expansion of the U.S. resource position through continued exploration activity along with expansion of production capability.

A comparison of the scheduled uranium deliveries and the projected uranium requirements for domestic reactors is shown in Figure 2.6. The scheduled deliveries are made from domestic primary sources to domestic utilities. The uranium feed requirements are based upon the domestic nuclear reactors that have contracts with ERDA. The curve with the broken line represents ERDA's uranium requirements that are calculated on the basis of .20% U-235 enrichment tails assay until October 1, 1980 and .25%

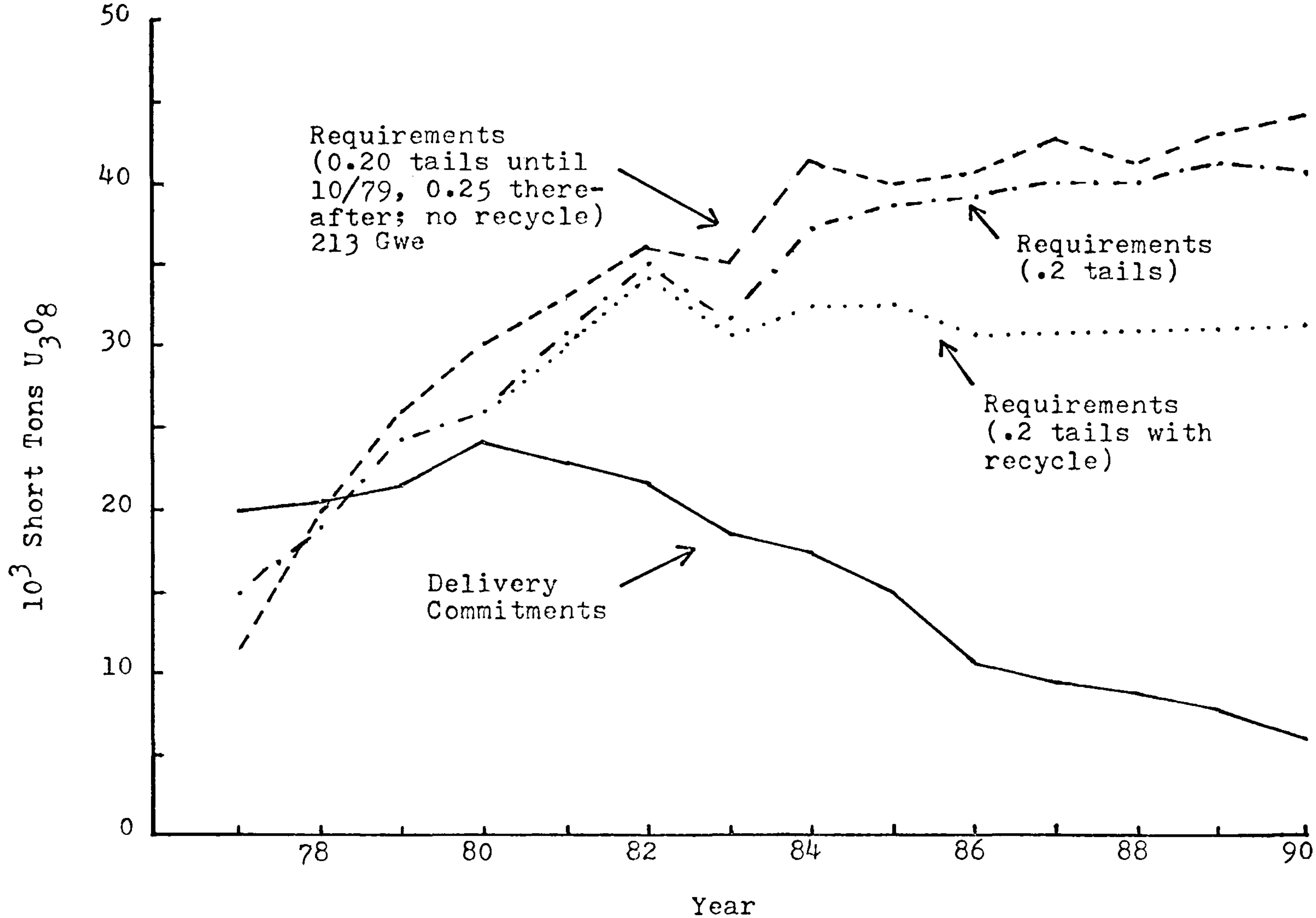


Figure 2.6. Uranium Requirements and Delivery Commitments as of January 1, 1977

thereafter and assuming no recycle of uranium or plutonium.[31] The lined and dotted curve is similar to the previous curve but the uranium requirements are calculated on the basis of a constant .20% tails enrichment assay.[32] The dotted curve represents ERDA's uranium requirements that include the recycle of uranium and plutonium on the basis of a constant .20% tails enrichment assay. The solid line indicates the domestic delivery commitments of uranium feed.[33]

Contrasting these annual requirements against the annual delivery commitments, it can be seen from Figure 2.6 that the contracted deliveries are in excess of the annual requirements until some time in 1979. Fortunately the domestic utilities have inventories of uranium feed that can be added to the supply picture. Figure 2.7 indicates the past level of buyer inventories and the anticipated inventory level growth for the future. The sum of buyer inventories and scheduled deliveries is expected to exceed cumulative demands until around 1984 on the assumption that uranium and plutonium recycling does not occur. After 1984 continuing procurement effort is needed to fill the increasing gap between production procurement and demand.[35]

The annual separative work requirements based upon ERDA contracts, government needs, and a .20% tails assay,

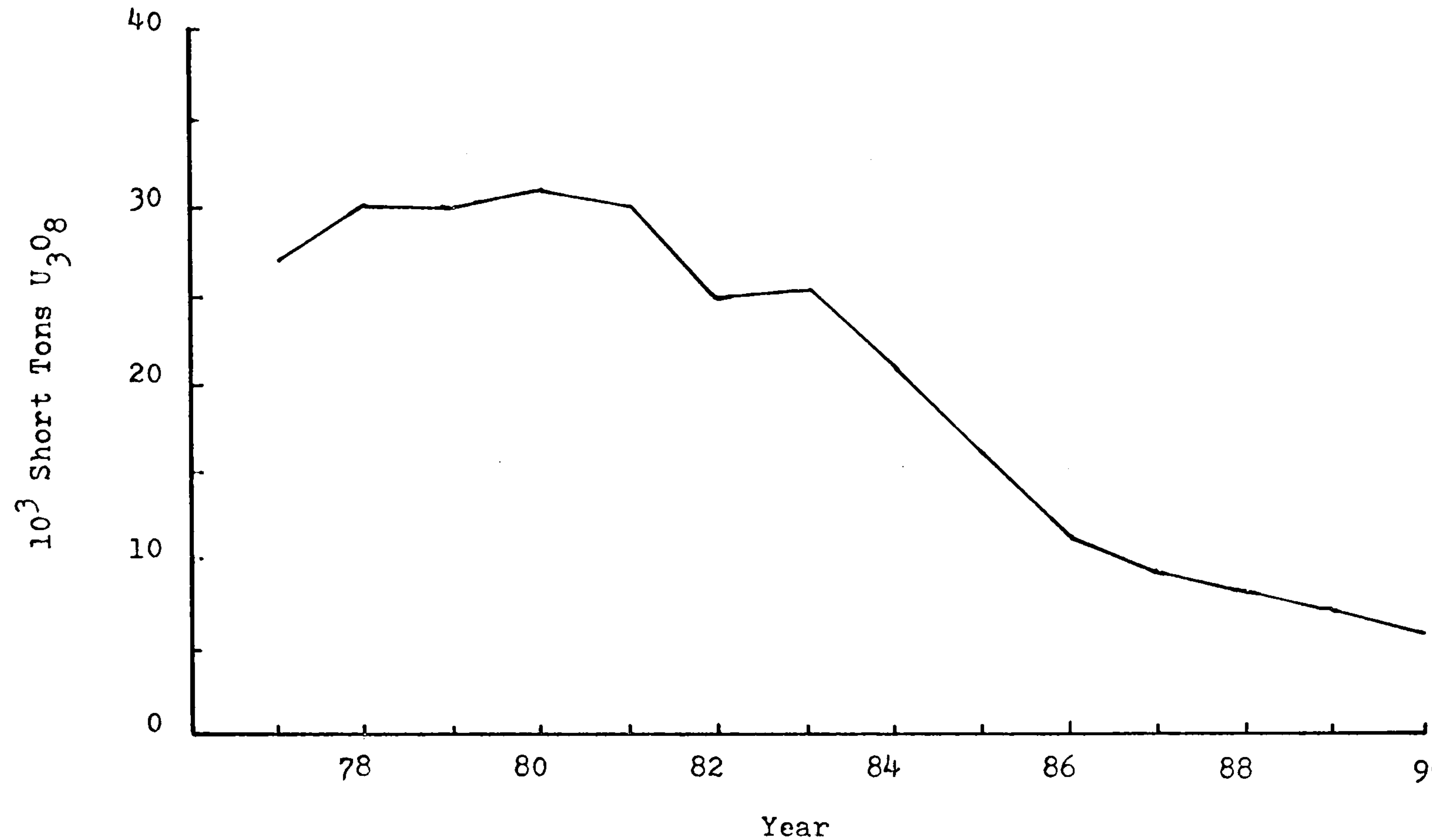


Figure 2.7. Uranium Stockpile Domestic Utilities[34]

are indicated in Figure 2.8. The horizontal lines represent the SWU capacity of the enrichment plants. The current original capacity is approximately 18 x 10^6 SWU/yr. Presently the ERDA diffusion plant complex is expanding and uprating SWU capacity through the Cascade Improvement Program (CIP) and the Cascade Uprating Program (CUP). Upon completion of the CUP and CIP, the SWU capacity is expected to be uprated to 28 x 10^6 SWU/yr. After the Portsmouth Add-On Plant is completed in 1988 the total enrichment capacity is expected to be 36.75 x 10^6 SWU/yr.[37]

When the domestic needs are added to the foreign contracts and to the government requirements to provide the total ERDA SWU demand, it is recognized that the combined demand exceeds the 28 x 10^6 SWU annual capacity of the total planned diffusion enrichment capability including CIP and CUP, in 1983, if plants are operated at the indicated level of .2% U-235 tails assay. Since the Add-On Plant will not be completed until 1988 SWU demand will exceed capacity in 1983 and for each year thereafter until the Add-On Plant is in operation.[38] After 1983 additional SWU capacity will be needed or the tails enrichment assay will be increased in order to reduce the SWU demand. ERDA is considering raising the tails assay to .25% in October 1980.[39]

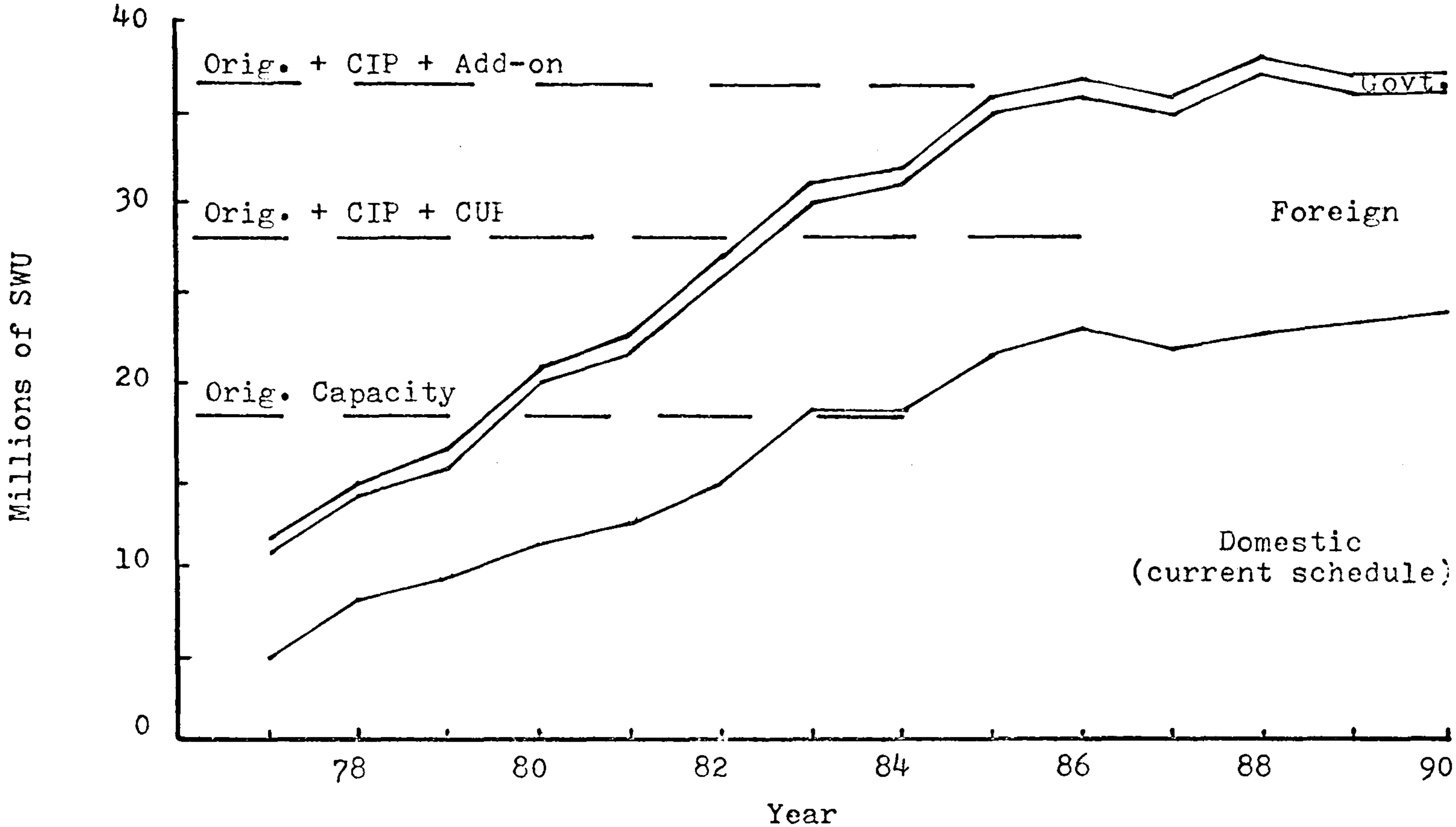


Figure 2.8. Annual Separative Work Requirements ERDA Contracts & Government Needs[36]

4. The Pricing of Uranium Feed and Separative Work Units

In a recently published report surveying 1976 uranium marketing activity within the United States, ERDA has produced two surveys indicating the average delivery prices for uranium under contract. One survey was taken in January 1, 1976 and the other in January 1, 1977.[40]

A description of the average prices reported in 1976 and 1977 is presented in Figure 2.9. Actual deliveries in 1976 averaged $16.10 per pound of U_3O_8, a substantial increase over the $10.70 reported at the beginning of 1976. Price increases in 1976 were a consequence of adjustments to earlier low price contracts, additional procurement at higher spot prices, and settlements for 1976 market price type contracts. Average prices reported for 1977 deliveries were also substantially higher than those reported at the beginning of 1976. Average prices in 1978 and 1979, however, are not expected to increase as much. Average prices in 1981 through 1985 deliveries increase sharply.[42]

The distribution of prices reported for the January 1977 survey is shown in Figure 2.10. This graph shows the percentage of procurement within the five dollar price brackets by year of delivery. Brackets with 15% or more are shaded. It can be seen that comparatively low priced

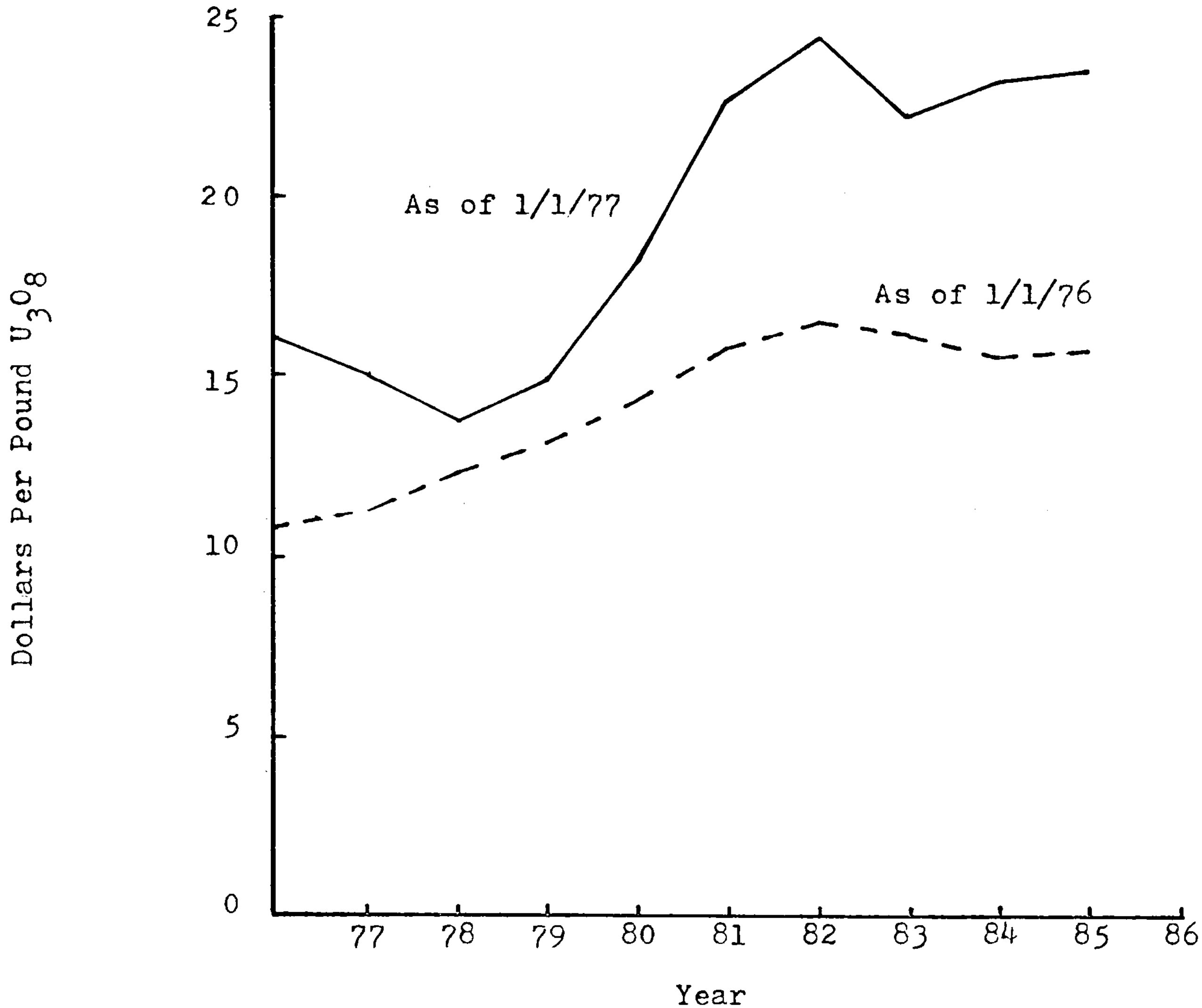


Figure 2.9. Average U_3O_8 Prices Reported in 1/1/76 and 1/1/77 Surveys[41]

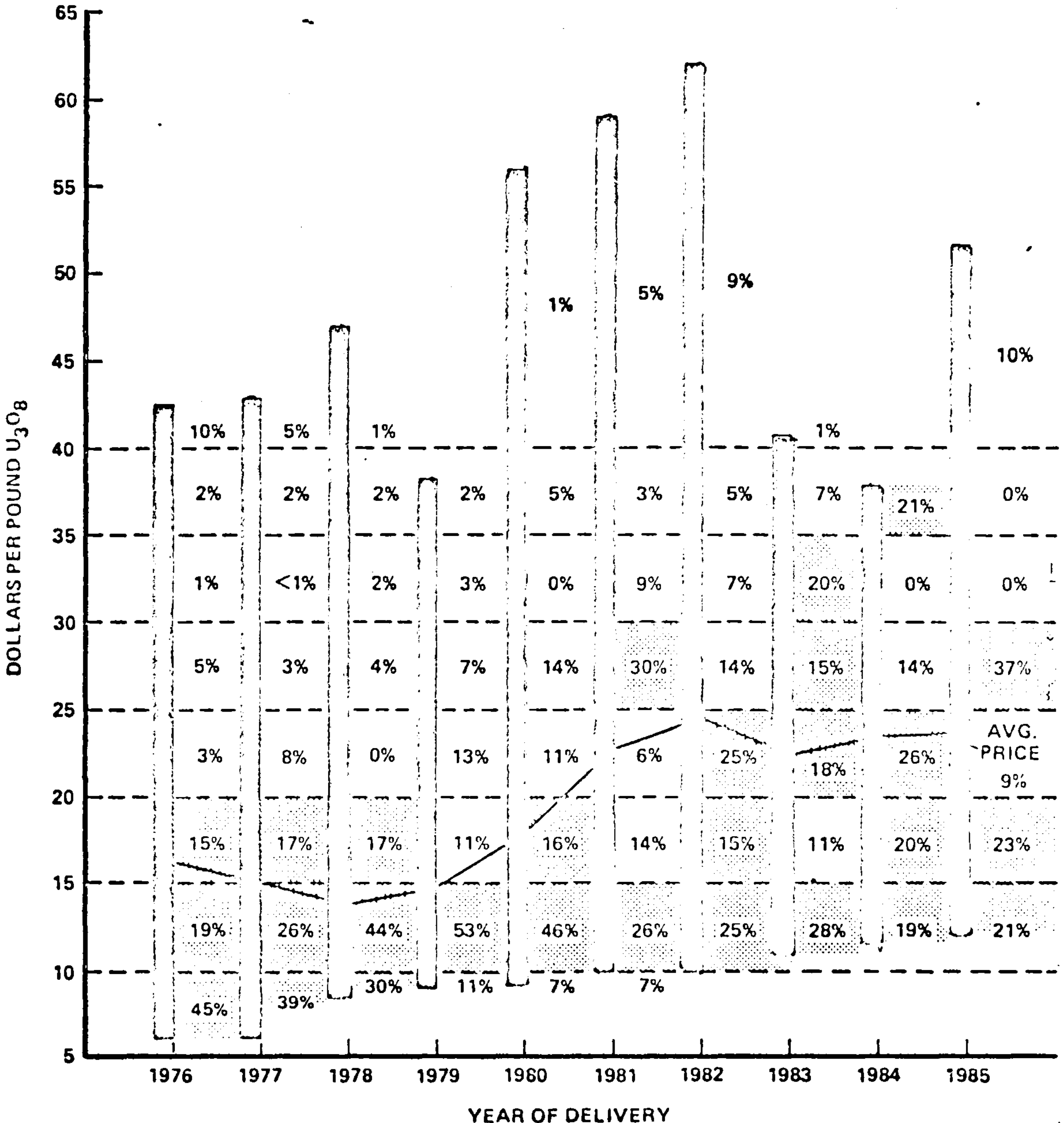


Figure 2.10. Distribution of Reported U_3O_8 Prices, 1/1/77[43]

uranium will dominate deliveries through 1980. Only a small portion of procurement to date has been at spot prices above $40.00 per pound.[44]

The pricing range of Separative Work is indicated in Figure 2.11. This estimate of SWU costs is based upon the 1975 TVA projections.

D. Current Uncertainties in Enrichment Contracting

According to the EEI survey of current enrichment contracting activities, the application of the fixed-commitment contract led to severe mismatches between contract commitments and the actual needs of the utilities. The results of the survey indicate that the fixed-commitment contracts are too one-sided and require the utilities to commit too far into the future thereby leading to unnecessary tying up of large quantities of both enriching services and natural uranium.

In 1975 ERDA allowed some contract relief by declaring an "open season." This open season allowed the utilities to ignore some of the firm fuel delivery dates set by the fixed-commitment contract. In January 1977, ERDA indicated that another open season would be initiated and significant contract relief would be offered to the fixed-commitment contract customers.

Presently, ERDA is still trying to determine the

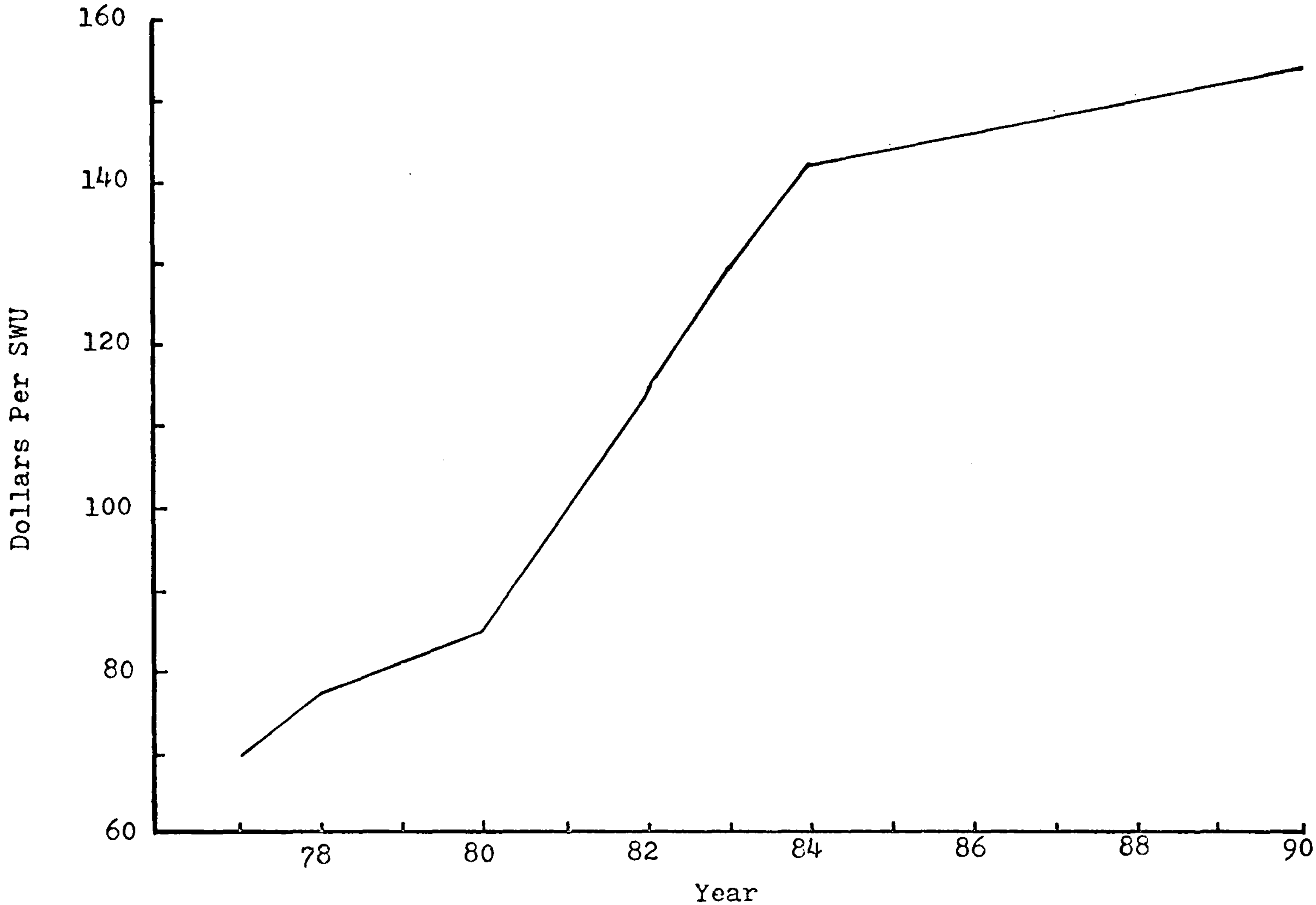


Figure 2.11. Separative Work Cost Projection[45]

nature and the extent of the contract relief desired by its customers before establishing the criteria under which such relief will be granted. ERDA has stressed that the contract modifications will be determined on a case-by-case basis in those instances where a utility is facing severe consequences from contractual obligations because of schedule slippages and other reasons. ERDA has also indicated that it expects to complete such modifications by the end of October 1977.[46]

In order to complete the modifications in the fixed-commitment contract, ERDA has requested all utilities to produce specific suggestions and comments on how various existing contract provisions or concepts might be changed in order to make the contracts more reasonable. In the EEI survey all the domestic utilities have indicated the most important suggestions for improving the fixed-commitment contract.

These suggestions are listed below:

1. Reasonable Price Basis:
   It is important to recognize in responding to ERDA that the utility industry is willing to pay a reasonable price for reasonable enriching services and that the utilities are willing to pay a reasonable additional cost if that is necessary to obtain a greater degree of quantity and schedule flexibility than now exists.

2. Separative Work Quantity Flexibility:
   Some ability to vary the amounts of the enriching service to be furnished is needed by the utility. A simple provision allowing ± 15% variation in

the annual quantity of enriching service until 180 days before delivery is desirable.

3. Time Schedule for Delivery:
The Initial Firm period (10 contract years of the fixed-commitment contract) is simply too long and a shorter period is desired, especially since the production facilities either already exist, are now funded or are included in the budget process. An initial firm period of five years, with year-by-year rolling extension five years in advance seems reasonable.
A second aspect of the time schedule problem relates to setting the beginning of the initial firm period. It is suggested that the beginning of the initial firm period be subject to change by the utility until the construction permit for the nuclear power plant is issued. Similarily, the standard table of enriching services for the initial core fueling should not be required until the construction permit is issued and the operating license is issued.

4. Variable Tails Assay:
The utility's option to select the tails assay (within reasonable limits) is desired for each individual transaction with reasonable advance notice. This feature should be available to the customer, both for optimization of cost purposes and also to provide additional quantity flexibility. This notice could be provided 180 cays in advance of delivery. Tails material should continue to be returnable to the customer.

5. Low Tails Assay:
ERDA should provide its customers with reasonable assurances that customer can indeed plan on a low tails assay in both short and long term. This is very important to utilities in planning their natural uranium supply programs and making firm commitments.

6. Split-Tails Assay:
ERDA should eliminate the split-tails assay mode of operation since it is resulting in depleting the ERDA feed stockpile.

7. Full Termination:
Customers who no longer need their enrichment contract should be allowed to terminate with full

refund of advance payments. Termination costs, if any, should be based on actual costs to ERDA caused by such termination.

8. Enriched Uranium Stockpile:
ERDA should create and publish a set of proposed program objectives in this area for comment by the industry prior to finalizing the policy. It is recognized that time and quantity flexibility create a need for certain stockpiles.

9. Plutonium Recycle:
In view of the administration's position on plutonium, it is suggested that the "plutonium appendices of the fixed-commitment contract" either be eliminated from all contracts at this time or be considered to be an option to be elected by the utility; and that when plutonium recycle becomes feasible, contract commitments will be appropriately adjusted to reflect the capability of the industry at that time.

10. Reprocessing:
In view of the administration's position on reprocessing, ERDA should allow changes in contract appendix data to reflect the lack of reprocessing services, and that when reprocessing is feasible, contract commitments be appropriately modified to reflect the capability of the industry at that time.[47]

These suggestions presented in the EEI survey will hopefully influence ERDA to improve the current enrichment contracting process. In this report, six of the suggestions from the survey are utilized in the development of the decision models in order to improve the contracting process. These six suggestions are the variable tails method, the elimination of the split-tails method, the low tails assay approach, the elimination of plutonium recycle and reprocessing, and a proposed plan for controlling the enriched uranium stockpiles.

III. DERIVATION OF THE DECISION MODELS

A. System Description

Three decision models are developed to analyze the 18 month decision point of the fixed-commitment contract and to determine an optimum decision policy in contracting for fuel enrichment services. The first model indicates the current method for acquiring enrichment services assuming maintenance of the split-tails mode of enrichment plant operation. The second model, referred to as the static decision model, utilizes the variable-tails concept at a single 18 month decision point. The third model uses the basic equations of the second model to develop a dynamic inventory system that is designed to manipulate the fuel inventories and the variable tails enrichments at the 18 month decision points over ten years.

B. Assumptions

The restrictions and contraints placed upon the system to facilitate the creation of the decision models are listed below:

1. The development of the decision models are based upon most of the rules set by the long term fixed-commitment contract.

2. The data for the decision models are based upon a

fuel contract for a typical 1000 Mwe reactor.

3. The reactor fuel demand is deterministic at the 18 month decision point. This deterministic quantity is calculated by the in-core fuel management group of the utility.

4. For the calculation of the SWU and feed requirements in the models, the irrecoverable losses in conversion of U_3O_8 to UF_6 are ignored. These losses increase the SWU and feed requirements approximately .5%.[48] Since the increase is quite small the losses in conversion of U_3O_8 to UF_6 are ignored in order to simplify the calculations in the model.

5. In the formulation of the static and dynamic models the mathematical quantity which represents fuel inventory production is limited to one fuel enrichment in order to simplify the implementation of the decision models. A multiple enrichment inventory could prove to be more economical to the utility, however, the implementation of such a problem is beyond the scope of this report.

6. The form of the fuel in the inventory is the same as that of the enriched uranium product that is produced at the enrichment plant. The form of this fuel is a uranium hexafloride solid. The optimum location for the inventory storage facility is assumed to be near the enrichment plant since transportation of nuclear fuel is very

expensive.

7. There are no space constraints for the fuel inventory. This simply implies that the inventory storage is large enough to handle the undetermined amount of excess fuel. Application of this constraint allows the storage portion of the holding inventory cost to be constant by eliminating the penalty cost associated with the acquisition of additional warehouse space.

8. In case of fuel shortages the utility must pay a multitude of severe costs. Among these are the loss of revenue, interest of capital investment, cost of replacement of the shortage of fuel, and the cost of the reactor being inoperative. The constraints of the static and dynamic decision models indicate a restriction for fuel shortages. In the split-tails model a fuel shortage cost is developed by only taking into consideration the fuel replacement costs at the uranium spot prices. The other severe costs are ignored on the assumption that the additional fuel can be purchased before the deadline dates set by the contract.

9. The total utility costs for enrichment services are based upon SWU and feed costs, fuel replacement costs, interest costs, and inventory costs. Fabrication costs and transportation costs are ignored since they are not related to enrichment services. The interest costs are

based upon the SWU and feed payments made seven months prior to fuel delivery. During the seven months lead time interest costs are incurred on the quantity of money being payed. Interest costs are ignored in the cost calculations of the decision models in order to simplify the analysis of the cost parameters. The uranium feed and SWU costs are determined from current information received from the utilities.[49]

10. The holding inventory costs are developed by multiplying an inventory cost factor with the current fuel value of the inventory. This inventory cost factor takes into consideration interest costs, and all costs incurred in maintaining the storage facility for one year.

11. The uranium and plutonium recycling are ignored in the decision models. This is a reasonable assumption since presently President Carter has delayed reprocessing.[50]

12. The range of the tails assay for the variable tails concept is arbitrarily chosen between .15% and .25%. The determination of this range is based upon ERDA's current transaction tails of .20%.[51] In the application of the decision models the tails assay range can be varied if required.

These assumptions and constraints are the result of an effort to limit the system under study to a very basic form in order to obtain solutions that may be interpreted in a straight forward fashion. The limitations, therefore, have been applied as an aid to analysis rather than a burden to be overcome. The models that are developed deter- an optimum decision policy in contracting for nuclear fuel enrichments services. It is intended that future work might allow the system to expand toward the goal of application to specific nuclear fuel problems.

C. Terminology

In order to introduce the terminology used in the development of the important modeling equations, a list of parameters, variables, and their definitions are presented below:

SWU = the number of separative work units that represents a measure of performance of the enrichment facility,

SWUT = the total SWU requirements for one contracting year,

R = the amount of enriched uranium required for reactor fuel demand, kg-UF_6

Io = the amount of enriched uranium which represents the initial inventory at the storage facility before contracting for fuel, kg-UF_6

I = the amount of enriched uranium which represents the final inventory level of the storage facility after the fuel product is sent to the utility, kg-UF_6

P = the amount of enriched product that is produced at the enrichment plant, kg-UF_6

F = the amount of natural uranium feed sent to the enrichment plant, kg-UF_6

FT = the total uranium feed requirements for one contracting year, kg-UF_6

FA = the amount of excess uranium feed needed to satisfy fuel demand requirements in the event of a fuel shortage,

X_f = the assay enrichment of Uranium-235 in the feed material,

X_w = the assay enrichment of Uranium-235 in the diffusion plant tails material,

X_p = the assay enrichment of Uranium-235 in the product material,

$V(X_f)$, $V(X_w)$, and $V(X_p)$ = the value functions for the feed, tails, and product enrichments respectively,

H = the holding inventory cost factor which is a fraction of the economic value of the fuel in the inventory,

C_s = the unit cost of separative work, $/SWU

C_f = the unit cost of uranium feed, \$/kg-UF_6

C_p = the unit cost of enriched product, \$/kg-UF_6

C_{sh} = the fuel shortage factor that is added on to the cost of feed to represent the total fuel shortage costs, \$/kg-UF_6

Z = the total utility costs for enrichment services, \$

ZT = the total utility costs for ten contracting years, \$

N = the total amount of product enrichments for each contracting year,

n = the subscript which represents the index number of each product enrichment, n = (1,2,3,..N)

t = the subscript which represents the index number of each contracting year, t = (1,2,3,...10).

The results of the decision models indicate the optimum choice of the unknown variables which will minimize total utility costs and satisfy reactor demand. The term (Z) which represents the total utility costs for enrichment services, is the measure of effectiveness for the decision models. Specifically the cost term (Z) is the sum of the fuel enrichment costs and the inventory holding costs.

D. Mathematical Development of the Three Decision Models

1. Split-Tails Model

This model indicates ERDA's present method for enrichment contracting. The modeling equations are constrained by the regulations of the fixed-commitment contract. The equations modeling the operation of the enrichment plant are:[52]

$$SWU_{n,t} = P_{n,t}\left[V(Xp_{n,t})-V(Xw_t)\right] - F_{n,t}\left[V(Xf)-V(Xw_t)\right] \quad (3.1)$$

$$F_{n,t} = \left[\frac{Xp_{n,t} - Xw_t}{Xf - Xw_t}\right] P_{n,t} \quad (3.2)$$

$$FT_t = \sum_{n=1}^{N}\left[P_{n,t}\left(\frac{F}{P}\right)_{n,t}\right] \quad (3.3)$$

$$SWUT_{t(calculated)} = \sum_{n=1}^{N}\left[P_{n,t}\left(\frac{SWU}{P}\right)_{n,t}\right] \quad (3.4)$$

$$V(X) = (2(X) - 1)\,Ln(X/1-X) \quad . \quad (3.5)$$

Equations (3.1), (3.2), and (3.5) were explained previously in Chapter Two of this report. Equations (3.3) and (3.4) indicate the relationships for calculating the total feed and SWU requirements for one contracting year.

The cost of product equation that determines the fuel enrichment costs per kilogram of fuel is:[53]

$$Cp_{n,t} = \left[\left[V(Xp_{n,t}) - V(Xf) \right] - (Xp_{n,t} - Xf) \left[\frac{V(Xf) - V(Xw_t)}{Xf - Xw_t} \right] \right] Cs_t + \left[\frac{Xp_{n,t} - Xw_t}{Xf - Xw_t} \right] Cf_t \quad . \tag{3.6}$$

In this model fuel inventories and fuel shortages can be induced, if the amount of (SWUT) calculated does not agree with the amount of (SWUT) estimated in the fixed-commitment contract. If the ratio

$$\frac{\text{SWUT (contracted)}}{\text{SWUT (calculated)}} \tag{3.7}$$

is greater than one, enriched product inventories are produced. The following equations indicate how the amounts of enriched product and fuel inventory are calculated:[54]

$$P_{n,t} = R_{n,t}\left[\frac{SWUT_t(\text{cont.})}{SWUT_t(\text{calc.})}\right] \qquad (3.8)$$

$$I_{n,t} = P_{n,t}\left[\frac{SWUT_t(\text{cont.})}{SWUT_t(\text{calc.})} - 1\right] \quad . \qquad (3.9)$$

If the ratio in equation (3.7) is less than one, a fuel shortage occurs. In the event of a fuel shortage, the fuel inventory becomes zero and the enriched product equals the reactor demanded. The equations used during a fuel shortage are defined below:

$$P_{n,t} = R_{n,t} \quad , \qquad (3.10)$$

$$I_{n,t} = 0 \quad . \qquad (3.11)$$

During a fuel shortage, the utility must also provide additional uranium feed to the enrichment plant in order to meet the fuel demand requirements. According to Appendix C of the fixed-commitment contract, ERDA has formulated a set of equations that indicate the amount of additional uranium feed needed to meet demand. These equations are based upon the split-tails method of operation of the enrichment plant.

As indicated by the fixed-commitment contract, the split-tails method implies that the utility must base its calculations of fuel enrichment service requirements on the transaction tails of .2% while the enrichment plant operates at .25%. In the event of a fuel shortage, the enrichment plant revises the operating tails enrichment to a higher enrichment so fuel demand requirements are met for the utility. The utility then supplies the additional uranium feed needed to operate at the revised tails. The equations that are developed in Appendix C of the fixed-commitment contract indicate the method for calculating the revised operating tails assay and the amount of additional feed needed to meet demand requirements. These equations are indicated below:[55]

$$\sum_{n=1}^{N}\left[P_{n,t}\left(\frac{SWU}{P}\right)_{n,t(Xw_t \text{unknown revised tails})}\right]$$

$$= \sum_{n=1}^{N}\left[P_{n,t}\,\frac{SWUT_t(\text{cont.})}{SWUT_t(\text{calc.})}\left(\frac{SWU}{P}\right)_{n,t(Xw_t=.25\%)}\right] . \quad (3.12)$$

Equation (3.12) is a transcendental equation that is used for finding the revised operating tails assay. Once the revised operating tails assay is found, the additional uranium feed requirement is calculated by the following equation:

$$FA = \sum_{n=1}^{N}\left[P_{n,t}\left(\frac{F}{P}\right)_{n,t(Xw = \text{revised operating tails})}\right]$$

$$- \sum_{n=1}^{N}\left[P_{n,t}\,\frac{SWUT_t(\text{cont.})}{SWUT_t(\text{calc.})}\left(\frac{SWU}{P}\right)_{n,t(Xw_t=.25\%)}\right] . \quad (3.13)$$

The equations introduced thus far can be simplified and combined into this next equation:

$$Z_t = \sum_{n=1}^{N} \left[(P_{n,t}\, Cp_{n,t} + I_{n,t}\, Cp_{n,t}\, H) \right] + FA_t(Cf_t + Csh) \quad (3.14)$$

where t = 1,2,.....10 years.
This equation calculates the total utility costs for fuel enrichment services. Using equation (3.14) and the previous equations defined in this model the unknown variables $F_{n,t}$, FT_t, $I_{n,t}$, $Cp_{n,t}$, Z_t, $SWUT_{t(calc.)}$, $V(Xw_t)$, $V(Xp_{n,t})$, $V(Xf)$, FA_t, Xw_t, can be determined. All other parameters in the model are deterministic. The optimum decision policy for this model is defined by the solution values of these variables.

2. The Static Decision Model

In this model, the variable tails concept is introduced in place of the split-tails method in order to examine its impact on utility costs for enrichment services. The tails assay (Xw_t) is treated as a decision variable in this model.

As indicated previously, the equations (3.1), (3.2), (3.3), and (3.5) model the operation of the enrichment plant. Equation (3.6) is again utilized to identify the costs of enriched product. The inventory level equation representing the material balance of the storage facility is now:

$$I_{n,t} = P_{n,t} + Io_{n,t} - R_{n,t} \, , \qquad (3.15)$$

where n = 1.
The subscript (n) is equal to one to indicate that the fuel inventory production is limited to one fuel enrichment in order to simplify the implementation of the model. Multiple enrichment inventories produces a very complicated model to solve.

The equations introduced thus far are combined into a minimization problem. The objective equation is expressed as:

$$\text{MINIMIZE } Z_t = \sum_{n=1}^{N} (P_{n,t}\ Cp_{n,t}) + I_{1,t}\ Cp_{1,t}\ H \qquad (3.16)$$

where t = (1,2,.....10 years)
Subject to the constraints:

$$\sum_{n=1}^{N}\left[P_{n,t}\left(\frac{SWU}{P}\right)_{n,t}\right] = SWUT_{t\ (contracted)} \qquad (3.17)$$

$$.0015 \leq Xw_t \leq .0025 \qquad (3.18)$$

$$P_{n,t} + IO_{n,t} \geq R_{n,t} \qquad (3.19)$$

where n = 1,

$$P_{n,t} = R_{n,t} \qquad (3.20)$$

where n = (2,.....N).

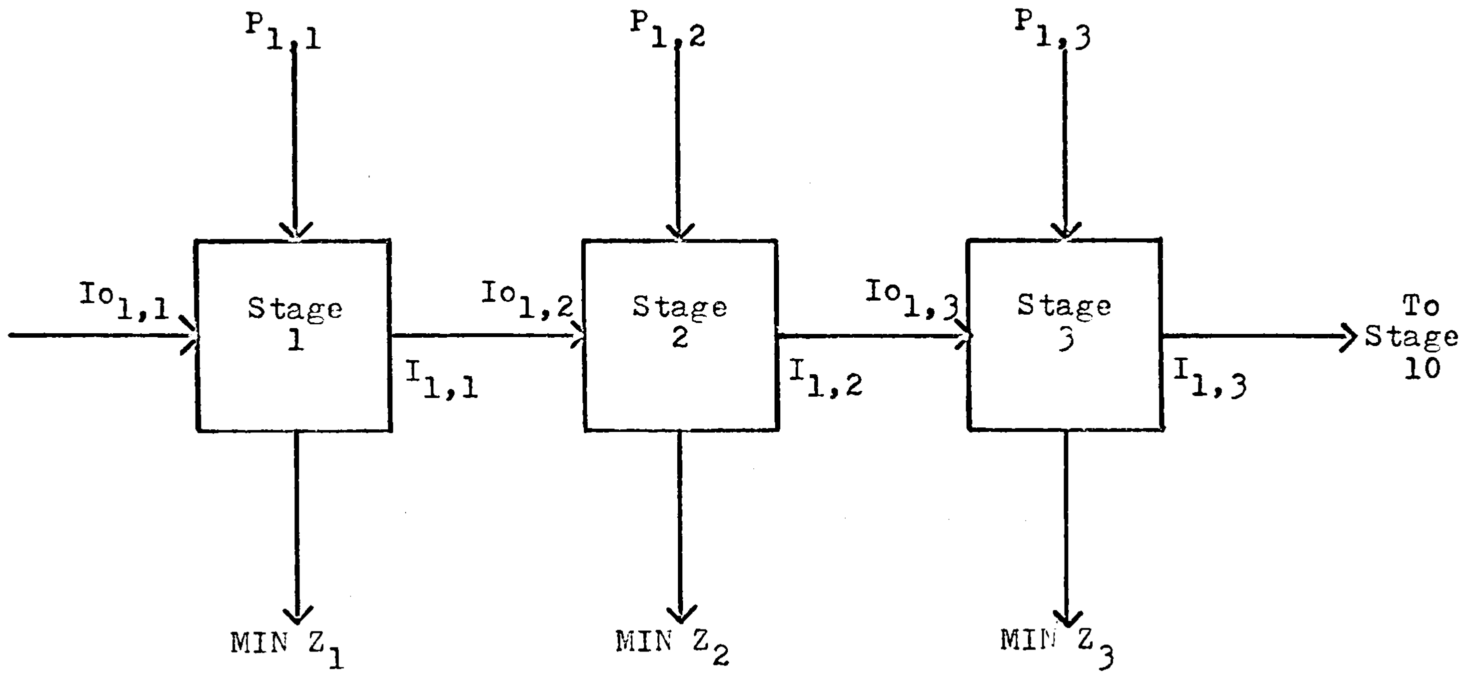
Equation (3.16) identifies the minimum total utility costs for fuel enrichment services in the feasibility region of the four constraints. Equation (3.17) is the constraint that restricts the SWU demand requirements to the SWU limits estimated in the fixed-commitment contract. Equation (3.16) restricts the tails assay to be within a certain range in order to allow the enrichment plant to operate within reasonable tails enrichment limits. Equation (3.19) designates the fuel supply to be greater than or equal to the reactor demand for the fuel enrichment chosen for inventory production. Equation (3.20) implies that the enriched product is equal to the reactor demand for all enrichments not chosen for fuel inventory production. The main objectives of these four contraints are to eliminate the possibility of fuel shortages and to meet the fuel demand requirements of the utility.

This model is a constrained nonlinear optimization problem in which the equations are coupled and which includes a transcendental value function. It must be solved numerically to determine the optimal values of $P_{n,t}$, Xw_t, and $F_{n,t}$. The remaining unknown variables which are calculated in the model are $I_{1,t}$, FT_t, $Cp_{n,t}$, $V(Xw_t)$, $V(Xp_{n,t})$, $V(Xf)$, and Z_t. The optimal selection of these variables defines the optimum decision policy for enrichment contracting. The results of this model are produced for one contracting year only in order to understand the simple behavior of the model's objective equation. The knowledge of this static decision model behavior will aide in the development of the dynamic model.

3. The Ten Year Dynamic Inventory Decision Model

All of the equations included in the static decision model are used in this dynamic model to produce a system that minimizes total utility costs for ten contracting years. The dynamic inventory model is designed to permit an analysis of the consequences of manipulating fuel inventories and variable tails enrichments at the 18 month decision points over ten years. The static modeling equations are applied at each year of the dynamic model. Each of the ten contracting years represents a stage of the dynamic model. The ten sequential stages are coupled together by the inventory level ($Io_{1,t}$). The inventory level ($Io_{1,t}$) is referred to as the state variable. As indicated previously in the static model, the decision variable at each stage of the dynamic model is the amount of enriched product ($P_{1,t}$) generated. From the optimum choice of the enriched product the optimum tails enrichment is also determined at each stage. The return in each stage is the minimum total utility costs (Z_t). In Figure 3.1 a flow diagram demonstrating the basic layout of the ten stage sequential decision model is presented.[56]

The stage transformation equation that defines the inventory level of each stage of the model is:



$P_{1,t}$ = Decision Variable

$Io_{1,t}$ = Input State

$I_{1,t}$ = Output State

Z_t = Total Return Costs

Figure 3.1. Decision Model Flow Diagram

$$I_{1,t} = Io_{1,t} = P_{1,t} + Io_{1,t} - R_{1,t} \qquad (3.21)$$

The overall objective equation for the ten stage model is:

$$ZT = \text{MINIMIZE} \sum_{t=1}^{10} Z_t \qquad (3.22)$$

where Z_t is defined by equation (3.16).

The contraints of the dynamic model are equivalent to the constraints of the static model. From equation (3.22), the optimum decision policy is defined by choosing the optimum amount of enriched product and the inventory level for each stage of the model. The measure of effectiveness of the model is expressed by the total minimum costs for ten contracting years (ZT).

IV. APPLICATION OF THE DECISION MODELS

A. Data Summary

In order to apply the methodology described in the previous chapters and to show its utility it is necessary to set up a representative or base case for analysis. It is desired that this base case would be representative of a potentially real situation and would, therefore, have credibility with people in the nuclear power industry. Any other base case could have been constructed and examined just as easily. Consequently, the results of this study are specific to the base case and no claim is made that they are absolute results. However, in order to understand the analysis and results, it is essential that the case upon which they are based is understood.

The base case data is categorized into two components. The first component, referred to as the benchmark case, represents the data values of a typical ten year fuel contract for a 1000 Mwe reactor. This is the fuel contract that is calculated by the utility ten years prior to fuel delivery. The second component of the base case indicates the data values of the ten year fuel contract at the 18 month decision point. These data values are based upon the utility's fuel needs at the 18 month decision point. This second component is referred to as the 18 month case. In addition to the contract data of the base case, there are many other basic pieces of relevant data which are inputed into the model. This information includes the SWU and uranium feed costs,fuel replacement costs, and holding inventory costs. A brief description of all the data and how they were determined is presented here.

The data for the benchmark case is taken from a typical ten year fuel contract for a 1000 Mwe boiling water reactor (BWR) in the Tennessee Valley Power System (TVA).[57] This contract data is presented in Table 4.1. A BWR fuel contract is chosen instead of a PWR fuel contract since the BWR contract is more complicated to utilize in the application of the decision models. The BWR fuel contract is more intricate to implement since a BWR refueling requires several different assays of product. The PWR contract usually requires only one or two assays of product during a refueling. The decision models are developed with a resonable amount of flexibility to allow the data input of a BWR or a PWR fuel contract.

The information in Table 4.1 includes the ten year SWU requirements, the fiscal years of product delivery, product material quantities, and the respective assays of product desired by the utility. This information is based on the transaction tails of .2% U-235. According to the fixed-commitment contract the information in Table 4.1 is referred

Table 4.1. Standard Table of Enriching Services Benchmark Case Data[58]

Fiscal Year of Reload	Reactor Fuel Demand ($R_{n,t}$) KgU	Enriched Product Assay ($Xp_{n,t}$) U-235 %	SWU Requirements ($SWUT_t$)
First Core 1980	56,165 36,250 14,495 7,250	2.3 1.8 1.6 1.4	250,966.42
Reload 1 1981	17,800 11,485 4,595 2,300	3.2 2.4 2.2 1.8	135,229.82
Reload 2 1982	17,190 11,090 4,440 2,215	3.2 2.4 2.2 1.8	130,586.59
Reload 3 1983	13,810 8,915 3,565 1,785	3.2 2.4 2.2 1.8	104,931.50
Reload 4 1984	15,655 10,100 4,040 2,020	3.2 2.4 2.2 1.8	118,922.45
Reload 5 1985	14,545 9,385 3,750 1,880	3.2 2.4 2.2 1.8	110,490.36
Reload 6 1986	14,545 9,385 3,750 1,880	3.2 2.4 2.2 1.8	110,490.36
Reload 7 1987	14,545 9,385 3,750 1,880	3.2 2.4 2.2 1.8	110,490.36
Reload 8 1988	14,545 9,385 3,750 1,880	3.2 2.4 2.2 1.8	110,490.36
Reload 9 1989	14,545 9,385 3,750 1,880	3.2 2.4 2.2 1.8	110,490.36

to as the standard table of enriching services. This table of enriching services is produced for the enrichment plant ten years prior to the first fuel delivery date indicated in the table.

At the 18 month decision point of the contract the material quantities in Table 4.1 can be changed, however, the SWU estimations must remain constant. To apply the decision models at the 18 month point, the material quantities in Table 4.1 are arbitrarily changed plus or minus ten percent in order to represent the possible fuel demand changes of a utility. These fuel demand changes may be due to fuel assembly damage, reactor schedule slippages, changes in burnup, changes in load factor, and many other possibilities. These changes in material quantities are indicated in Table 4.2.

As indicated in Table 4.1, the assays of product for every reload are the same after the initial fueling of the first core. These assays are referred to as the equilibrium enrichments. Since the equilibrium enrichments remain constant after the initial fueling, enriched product inventories can be produced at these enrichments in order to help supply enriched uranium for future reloads. In the event of a fuel shortage these enriched product inventories can save a utility a reasonable amount of money. The main questions are how much fuel inventory should be

Table 4.2. Standard Table of Enriching Services-
18 Month Decision Point Data

Fiscal Year of Reload	Reactor Fuel Demand ($R_{n,t}$) KgU	Enriched Product Assay ($Xp_{n,t}$)U-235 %	SWU Requirements ($SWUT_t$)
First Core 1980	56,165 36,250 14,495 7,250	2.3 1.8 1.6 1.4	250,966.42
Reload 1 1981	16,020 10,336 4,135 2,070	3.2 2.4 2.2 1.8	135,229.82
Reload 2 1982	17,190 11,090 4,440 2,215	3.2 2.4 2.2 1.8	130,586.59
Reload 3 1983	15,191 9,806 3,921 1,963	3.2 2.4 2.2 1.8	104,931.50
Reload 4 1984	17,220 11,110 4,444 2,222	3.2 2.4 2.2 1.8	118,922.45
Reload 5 1985	15,999 10,323 4,125 2,068	3.2 2.4 2.2 1.8	110,490.36
Reload 6 1986	14,545 9,385 3,750 1,880	3.2 2.4 2.2 1.8	110.490.36
Reload 7 1987	13,091 8,447 3,375 1,692	3.2 2.4 2.2 1.8	110,490.36
Reload 8 1988	15,999 10,323 4,125 2,068	3.2 2.4 2.2 1.8	110,490.36
Reload 9 1989	15,999 10,323 4,125 2,068	3.2 2.4 2.2 1.8	110,490.36

created and which of the equilibrium enrichments should be utilized in the inventory production. The dynamic inventory model determines the optimum amount of inventory produced for one of the equilibrium enrichments. As indicated in Table 4.1 the four equilibrium enrichments are 3.2%, 2.4%, 2.2%, and 1.8% U-235. In the dynamic model the enrichment 3.2% is used for inventory production. In the parametric analysis section of the report each of the equilibrium enrichments are tested to identify the optimum enrichment for inventory production.

The prices of uranium feed and separative work units for the ten year fuel contract are indicated in Tables 4.3 and 4.4 respectively. These cost projections developed by TVA in 1975, are utilized in the decision models within the ten year contracting period from 1980 to 1989.

The fuel shortage cost factor (Csh) in the split-tails model is developed in order indicate an unfavorable financial penalty for purchasing uranium feed during a fuel shortage. The determination of this fuel shortage cost factor is estimated on the basis of the average uranium spot prices in the current uranium market. Figure 2.10 identifies the distribution of the uranium spot prices in the current uranium market. From Figure 2.10 the shortage factor is determined by taking the average difference between the uranium spot prices and the average uranium

Table 4.3. Estimate of Feed Cost[59]

Year	\$/lb U as UF_6
1975	\$ 25.00
1976	28.00
1977	31.00
1978	35.00
1979	40.00
1980	45.00
1981	48.00
1982	51.00
1983	52.00
1984	54.00
1985	57.00
1986	59.00
1987	64.00
1988	70.00
1989	77.00
1990	87.00
1991	98.00
1992	107.00
1993	114.00
1994	119.00
1995	124.00
1996	129.00
1997	134.00
1998	140.00
1999	146.00
2000	152.00

Table 4.4. Estimate of Enrichment Costs[60]

Year	$/SWU
1976	$ 63.00
1977	70.00
1978	77.00
1979	81.00
1980	85.00
1981	99.00
1982	114.00
1983	129.00
1984	143.00
1985	145.00
1986	147.00
1987	149.00
1988	151.00
1989	153.00
1990	155.00
1991	157.00
1992	160.00
1993	162.00
1994	164.00
1995	167.00
1996	169.00
1997	172.00
1998	175.00
1999	177.00
2000	175.00

delivery prices through the contract years 1976-1985. This shortage factor is added to the cost of feed for that specific contracting year to indicate the total shortage costs. If a utility cannot acquire the additional feed material at the current uranium spot prices, severe costs can occur. The consequential impact of a single day delay in fuel delivery can lead to a tremendous loss of money for a utility. A single day's outage of a 1000 Mwe nuclear unit produces a loss of revenue in the range of a quarter to one million dollars depending on the local fuel situations.[61]

The inventory holding costs are controlled by the value of the fuel in the inventory. The holding inventory cost factor (H) is a fraction of the economic value of the fuel in the inventory. The cost factor (H) time the value of the fuel in the inventory is equal to the inventory holding costs. This cost factor (H) is arbitrarily chosen to be .15 for the initial application of the decision models. In the parametric analysis section of this report the cost factor is varied in the dynamic model to examine the transient behavior of the model.

B. Implementation of the Decision Models

In order to determine the relative importance of this data, many analytical calculations had to be made. A computer program "ECONTI" (Enrichment Contract Improvement) was written to incorporate the given numerical data into the models and perform the calculations required to determine the optimum decision policies.[62] A simple flow diagram explaining the basic structure of the computer code is presented in Figure 4.1.

As shown in Figure 4.1, the computer program receives the benchmark case data, the 18 month decision point data, and all cost parameters of the ten year fuel contract as input. The output of the code contains the optimum decision policy results for the benchmark case information, the split-tails model, and the dynamic inventory model.

The benchmark case results are formulated using the data in Table 4.1. The equations of the split-tails model for enrichment contracting are directly utilized in the computer program to develop the benchmark case results for ten contracting years.

The equations of the split-tails model are again utilized for the application of the 18 month decision point data. This data reflects the current utility needs for enriched uranium. The optimum decision policy is determined for ten contracting years by the computer code.

The dynamic inventory model results are developed by solving the static model equations over a ten year contracting period. These static model equations are coupled together by the inventory level at each stage of the model.

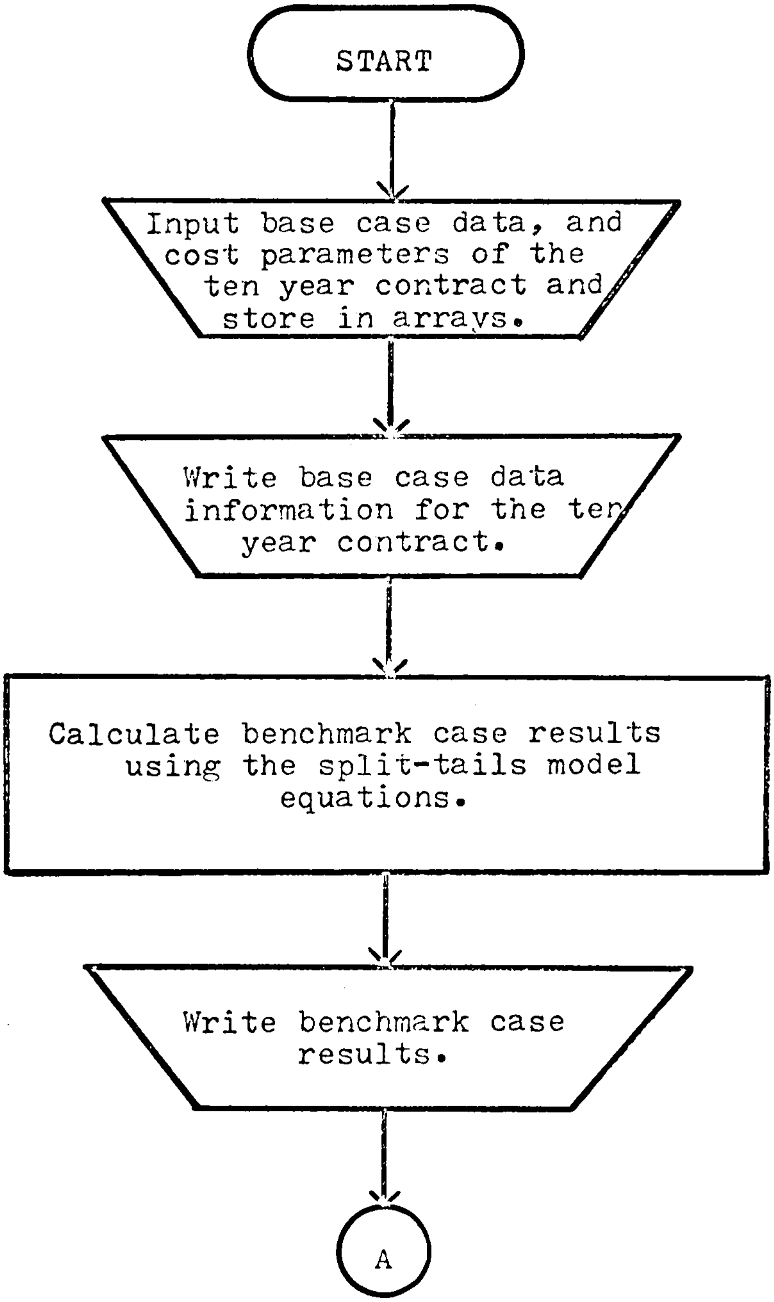
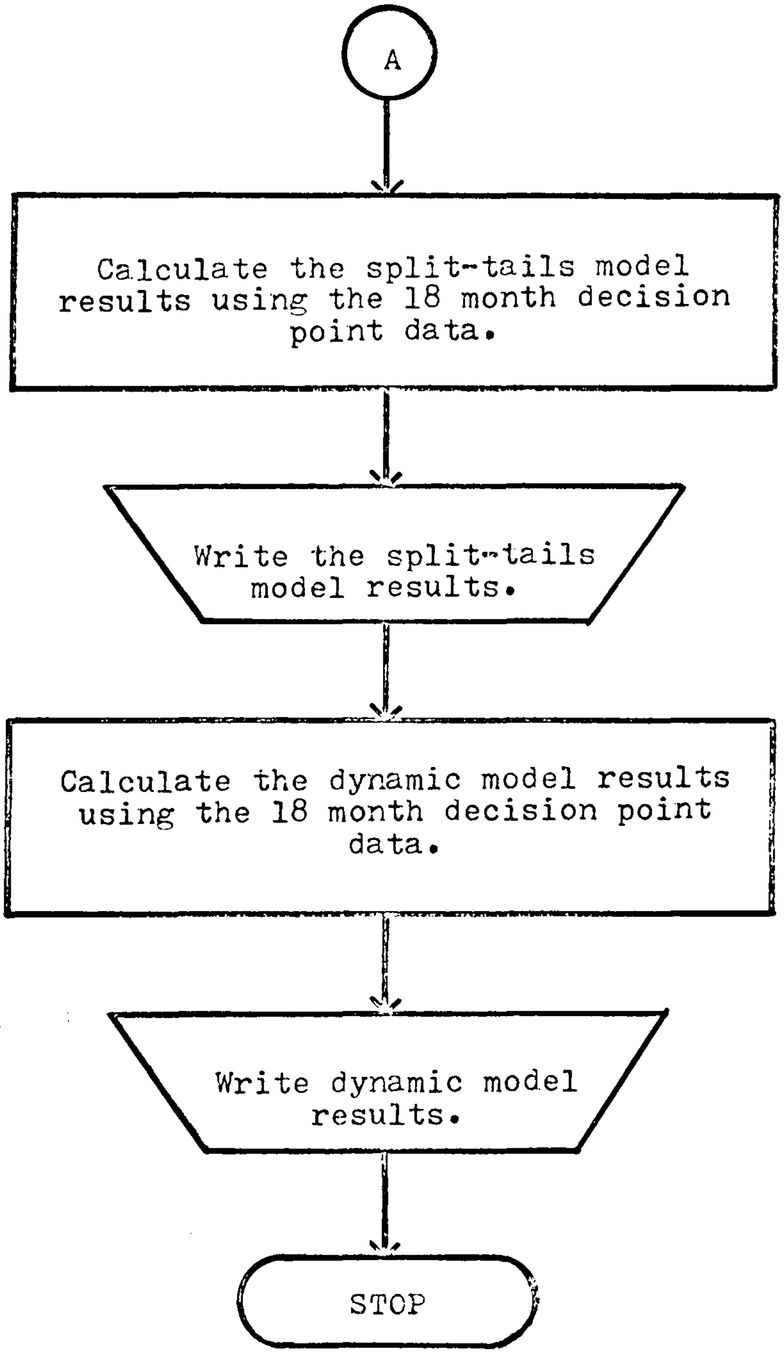


Figure 4.1. Basic Structure of Computer Code

Figure 4.1 continued



The 18 month decision point data is used in the application of the modeling equations. The optimum decision policy is calculated in the computer code by using various dynamic programming techniques. These techniques are explained in the following section.

C. Dynamic Programming Application

As indicated previously in Figure 3.1, the dynamic inventory model is a ten stage sequential decision model which minimizes the utility costs for all ten stages. The return in each stage is the utility cost (Z_t). The decision variable and state variable for each stage are the enriched product ($P_{1,t}$) and the initial inventory level ($Io_{1,t}$) respectively. The return function $r(Io_{1,t}, P_{1,t})$ is expressed in terms of the decision variable and the state variable in the following equation:

$$r(Io_{1,t}, P_{1,t}) = Z_t = \sum_{n=1}^{N} P_{n,t}\, Cp_{n,t}$$

$$+ (P_{1,t} + Io_{1,t} - R_{1,t}) Cp_{1,t}\, H \qquad (4.1)$$

where t = (1,.....10) years,

subject to the same constraints in the static model. Equation (4.1) is equivalent to the static model objective equation (3.14). In equation (4.1), the expression within the brackets simply represents the stage transformation equation that defines the inventory level of each stage. In the static model objective equation the stage transformation equation is substituted by the inventory level quantity ($I_{1,t}$).

The return functions and the stage transformation equations are incorporated into a dynamic programming system which calculated the optimum decision policy for the model. This dynamic programming system utilizes a tabular search technique for finding the optimum decision and state variables of the system. Tables are developed for each stage of the model to indicate the possible range of returns as a function of the enriched product and inventory level. A search technique is then applied to all ten tables in order to locate the optimum choice of enriched product and the inventory level for each stage. The optimum choice of these two variables are selected on the basis of the associated minimum return of the stage. The recursive equations used to implement the tabular search technique of the dynamic programming system are indicated below:[63]

$$Q_t(Io_{1,t}, P_{1,t}) = r_t(Io_{1,t}, P_{1,t}) \qquad (4.2)$$

where t = 10

$$Q_t(Io_{1,t}, P_{1,t}) = r_t(Io_{1,t} P_{1,t}) + F_{t+1}(Io_{t+1}) \qquad (4.3)$$

where t = (1,.....9)

$$F_t(Io_{1,t}) = \text{MINIMIZE } Q_t(Io_{1,t}, P_{1,t}) \qquad (4.4)$$

where t = (1,.....10)

$$Io_{1,t+1} = P_{1,t} + Io_{1,t} - R_{1,t} \qquad (4.5)$$

These recursive equations are used in the dynamic model to develop an optimum decision policy for enrichment contracting. A general schematic of how these recursive equations are implemented in the computer code is illustrated in the flow chart of Figure 4.2.[64]

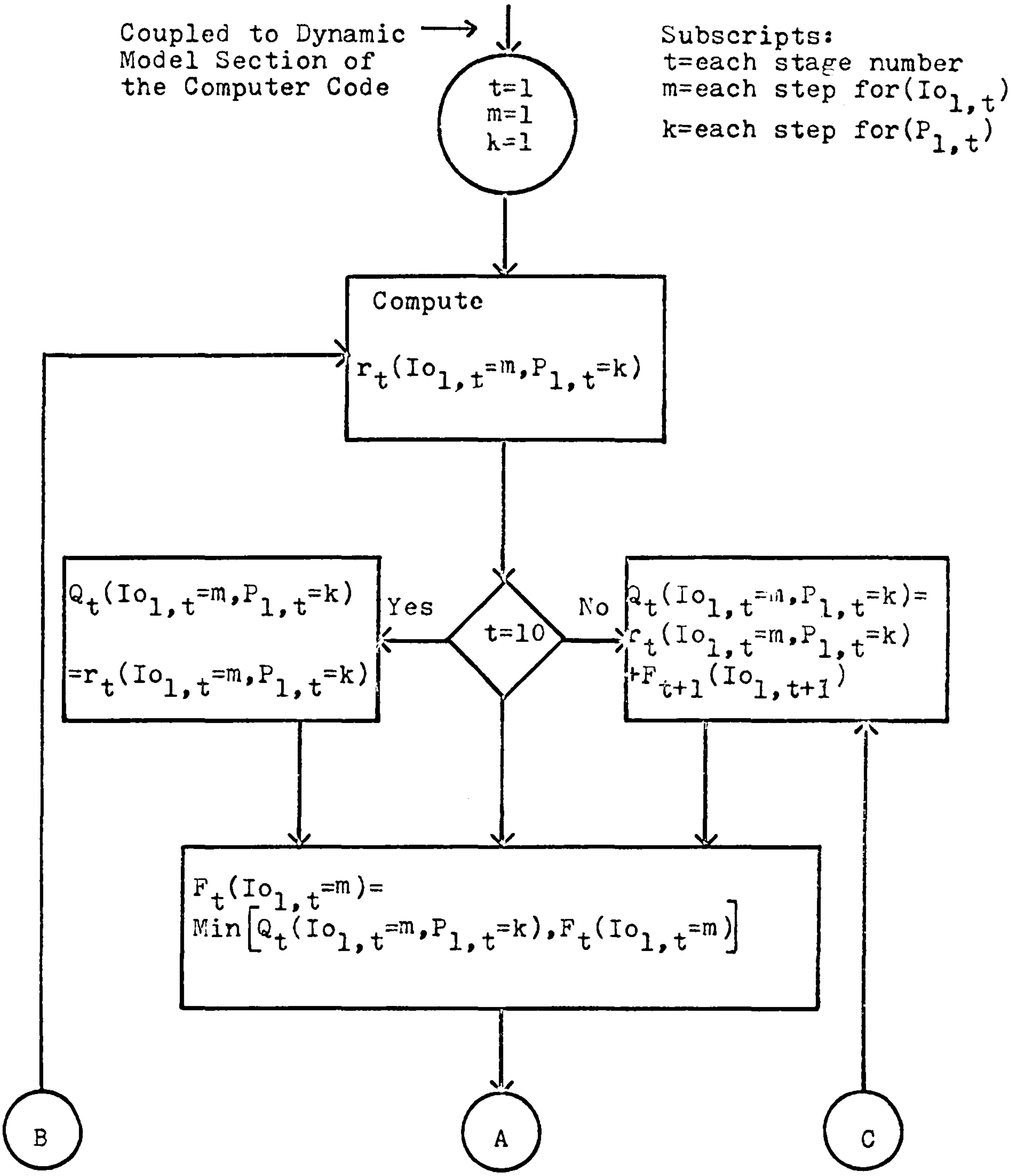


Figure 4.2. Dynamic Programming Flow Chart

Figure 4.2. continued

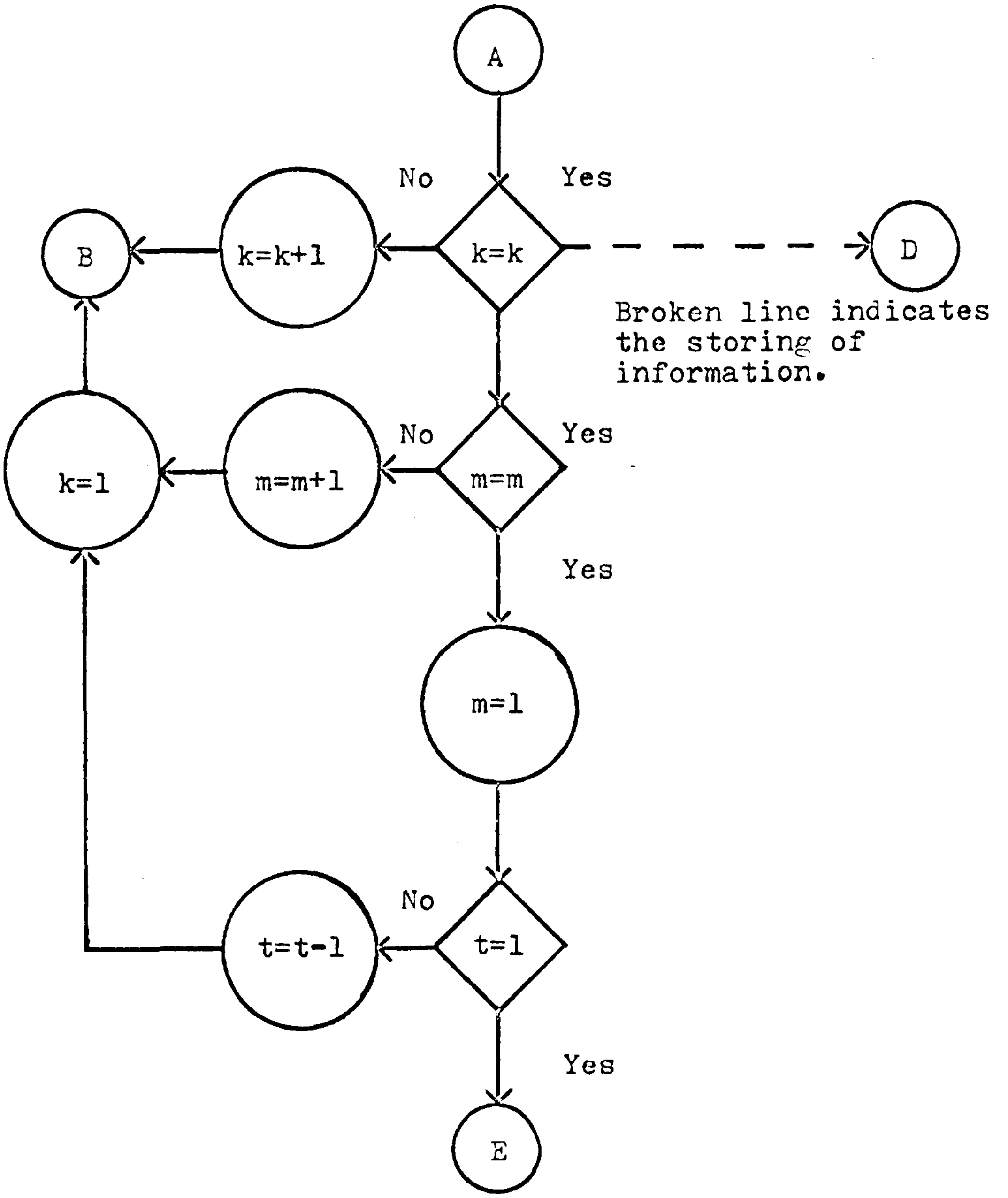


Figure 4.2. continued

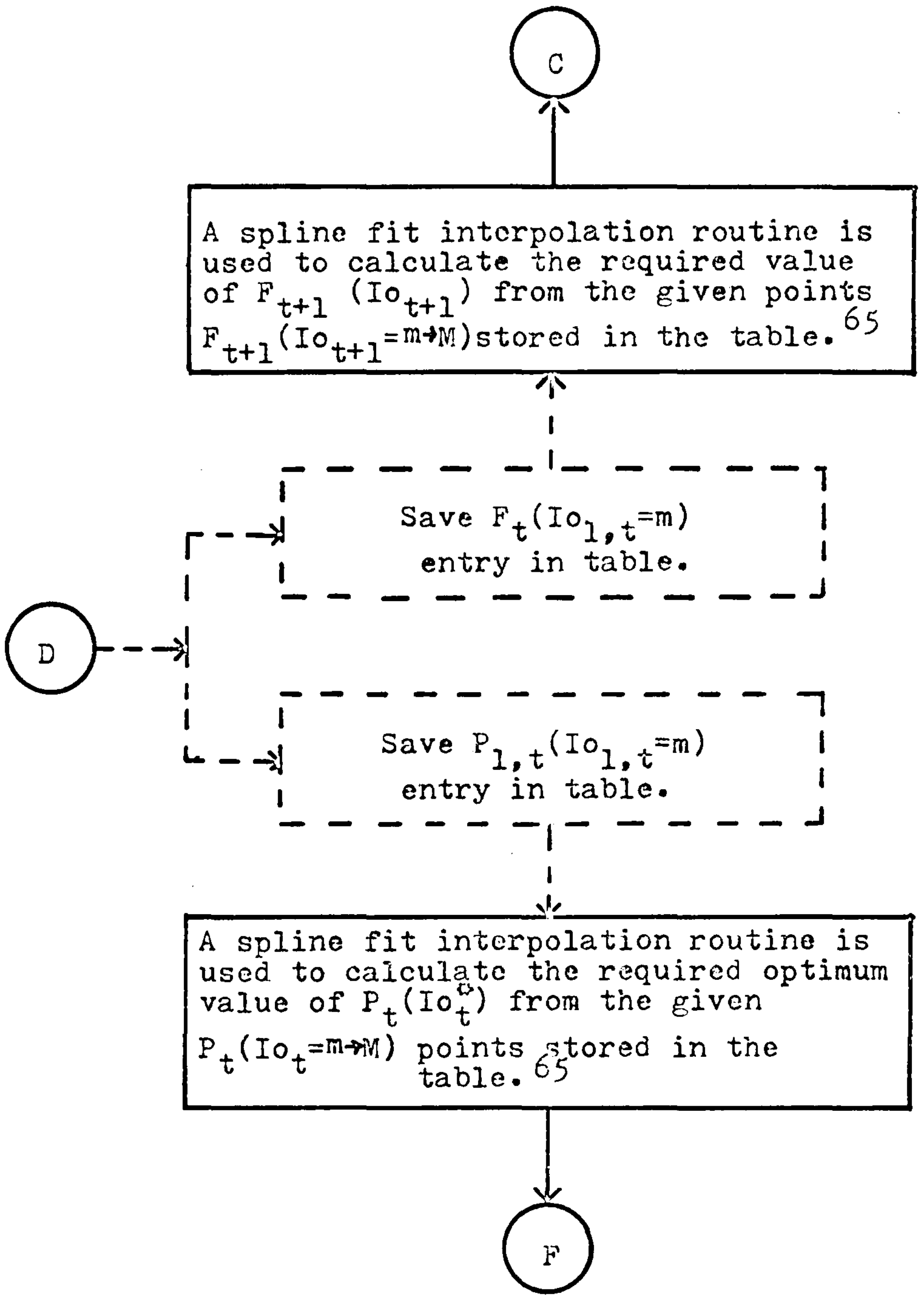
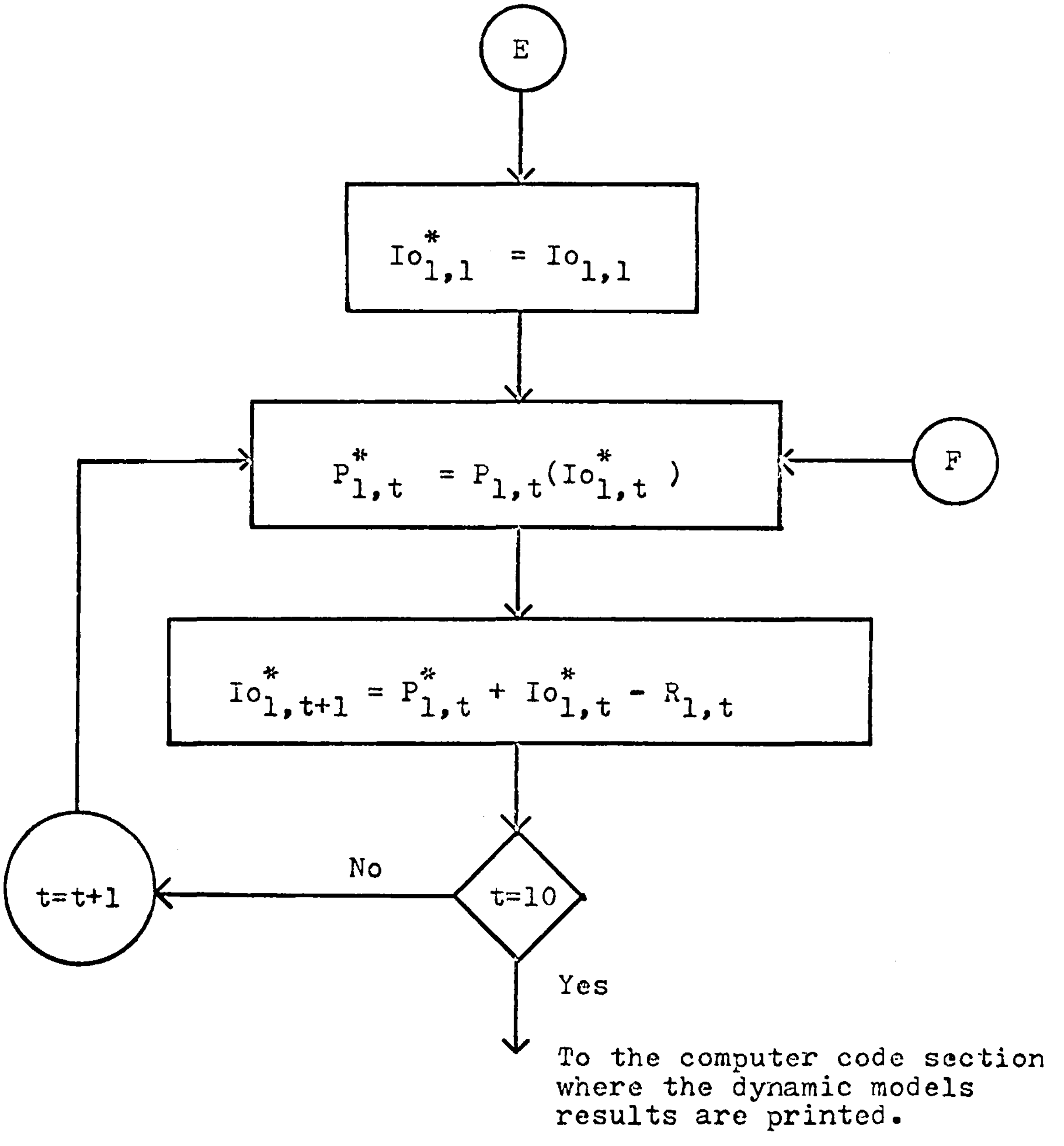


Figure 4.2. continued



V. RESULTS

A. Decision Model Results

The base case data described in Chapter Four is used as input in the computer code to determine the initial results of the decision models. Specifically the base case data is divided into two components. One component is the benchmark case data and the other is the 18 month case data. The benchmark case data is incorporated into the split-tails model equations to determine the benchmark results for the ten year point of the contract. The 18 month case data is incorporated into the split-tails model and the dynamic model equations to determine the optimal results for for the 18 month decision point of the contract. The results of the benchmark case are considered as a reference to the decision model results applied at the 18 month decision point. The results for the benchmark case, the split-tails model and the dynamic model are presented in this chapter. A parametric analysis of the decision models is also included.

1. Benchmark Case Results

The benchmark case results are indicated in Table 5.1. The results specify the total utility costs and the uranium feed required in each fiscal year of the contract on the

Table 5.1. Benchmark Case Results

Fiscal Year of Fuel Delivery	Transaction Tails	Total Utility Costs ($)	Total Uranium Feed (KgU)
1980	.002	61,122,480.0	401,055.6
1981	.002	32,345,520.0	179.132.9
1982	.002	34,336,980.0	172,978.4
1983	.002	29,473,070.0	138,999.9
1984	.002	35,760,530.0	157,528.3
1985	.002	34,415,020.0	146,359.9
1986	.002	35,281,470.0	146,359.9
1987	.002	37,115,380.0	146,359.9
1988	.002	39,272,740.0	146,359.9
1989	.002	41,752,080.0	146,359.9

basis of a .2% transaction tails. The total utility costs and the amount of uranium feed are the highest during the first fiscal year because of the initial fueling of the core. In the next nine years of the contract, the utility costs and the amounts of uranium feed are lower since only a portion of the fuel in the core is replaced during each refueling. Specifically, the utility costs and the amounts of uranium feed are different between each refueling year due to changes in separative work units, SWU and feed prices, and fuel demands.

In the first four refueling years the uranium feed requirements are different from each other. These differences are mainly due to changes in fuel demands and separative work units for each refueling year. As indicated in Table 4.1 of Chapter Four the fuel demands and the SWU requirements do vary considerably during the first four refueling years. After the fourth refueling year the fuel demands and SWU requirements approach an equilibrium level which is shown in Table 4.1. Therefore, the feed requirements in Table 5.1 approach a constant value after the fourth refueling year. During the first four refueling years, different fuel demands are required at each refueling to maintain the reactor at the correct power and fuel burnup levels. However, after the fourth refueling year, the reactor can be maintained at the correct levels by using the same amount of fuel for each refueling.

The utility costs in Table 5.1 appear to vary appreciably between each refueling year. In the first four refueling years the variations in utility costs are due to changes in SWU and feed prices, separative work units, and fuel demands. Specifically, in the fiscal year of 1983 the fuel requirements and separative work units are low, therefore producing a large change in utility costs. After the fourth refueling year the differences in utility costs are mainly due to changes in SWU and feed prices, because the fuel requirements are constant at each refueling year. The changes in SWU and feed prices are indicated in Tables 4.3 and 4.4 (Chapter Four). During the years 1980 to 1989, the SWU and feed prices indicated in Table 4.3 and 4.4, increase in a more random pattern instead of a constant rate. These random increases in SWU and feed prices cause the total utility costs in Table 5.1 to also increase in a random manner. The choice of the SWU and feed prices directly influences the total utility costs figures in Table 5.1. It appears that the TVA cost projections are quite irregular and further analysis should be provided to examine these projections and change them to the most current forecast projections. If a utility decides to use these decision models it is important that the cost projections are estimated as accurate as possible in order to reveal the best strategy for contracting enrichment services.

2. Split-Tails Model Results at the 18 Month Decision Point

If a utility does not have to make any fuel demand changes at the 18 month decision point, then the results in Table 5.1 will signify the optimal decision policy for contracting fuel. However, in the event of a fuel demand change the split-tails model is reapplied with different fuel demand requirements. These demand requirements should reflect the current fuel needs of the utility. In Table 4.2 of Chapter Four an example of a current hypothetical fuel demand case is used in the split-tails model in order to notice the behavior of the model results at the 18 month decision point. This data is input to the computer code and analyzed using the split-tails model equations to determine the new optimal results. These results are presented in Tables 5.2, 5.3, and 5.4.

Table 5.2 indicates the total utility costs, the uranium feed requirements and the operating tails enrichment for each fiscal year of the contract. The operating tails enrichment in Table 5.2 represents the tails assay used to operate the enrichment plant. ERDA presently operates the enrichment plant at the tails assay of .0025. However, in the event of a fuel shortage, ERDA revises the operating tails enrichment to a higher enrichment so

Table 5.2. Results of the Split-Tails Model

Fiscal Year of Fuel Delivery	Total Utility Costs ($)	Total Uranium Feed (KgU)	Operating Tails Enrichment
1980	61,122,480.0	401,055.6	.0025
1981	36,414,300.0	179,132.9	.0025
1982	34,336,980.0	172,978.4	.0025
1983	35,149,600.0	168,143.2	.00293368
1984	42,340,660.0	190,564.7	.00293378
1985	40,730,590.0	177,047.6	.00293368
1986	35,281,470.0	146,359.9	.0025
1987	41,781,280.0	146,359.9	.0025
1988	46,468,420.0	177,047.6	.00293368
1989	49,421,600.0	177,047.6	.00293368

that fuel demand requirements are met for the utility. In Table 5.2 the revised operating tails level is identified for the contracting years 1983, 1984, 1985, and 1989. Fuel shortages are produced in these years by the demand increases in Table 4.2. The uranium feed also increases in these fuel shortage years in order to supply the additional uranium feed needed to operate at the revised tails level. Due to the high cost incurred in acquiring additional uranium feed at uranium spot prices, the total utility costs also increase. These increases in utility costs and uranium feed are indicated by the comparison of Table 5.2 with the benchmark case results in Table 5.1.

The amounts of enriched product produced at the required assays are presented in Table 5.3. The enriched product values in Table 5.3 when compared to the reactor demand values in Table 4.2, indicate that there is an excess of enriched product produced in the years 1981 and 1987. The amounts of excess product are identified in Table 5.4 as fuel inventories. Under the split-tails mode of operation these fuel inventories are caused by the fuel demand decreases at the 18 month decision point. Inventories are not created in the remaining years of the ten year contract since the amount of enriched product is forced by the split-tails model equations to equal the amount of fuel demand required at the 18 month decision point.

Table 5.3. The Amounts of Enriched Product Calculated by the Split-Tails Model

Fiscal Year of Fuel Delivery	Enriched Product (KgU) Assay = .032	Enriched Product (KgU) Assay = .024	Enriched Product (KgU) Assay = .022	Enriched Product (KgU) Assay = .018
1980	56,165.0	36,250.0	14,495.0	7,250.0
1981	17,797.8	11,483.0	4,593.8	2,299.7
1982	17,190.0	11,090.0	4,400.0	2,215.0
1983	15,191.0	9,806.0	3,921.0	1,963.0
1984	17,220.0	11,110.0	4,444.0	2,222.0
1985	15,999.0	10,323.0	4,125.0	2,068.0
1986	14,545.0	9,385.0	3,750.0	1,880.0
1987	14,542.8	9,384.8	3,749.3	1,879.6
1988	15,999.0	10,323.0	4,125.0	2,068.0
1989	15,999.0	10,323.0	4,125.0	2,068.0

Table 5.4. The Amounts of Fuel Inventory Calculated by the Split Tails Model

Fiscal Year of Fuel Delivery	Inventory (KgU) Assay = .032	Inventory (KgU) Assay = .024	Inventory (KgU) Assay = .022	Inventory (KgU) Assay = .018
1980	0.0	0.0	0.0	0.0
1981	1,777.8	1,147.0	458.8	229.7
1982	0.0	0.0	0.0	0.0
1983	0.0	0.0	0.0	0.0
1984	0.0	0.0	0.0	0.0
1985	0.0	0.0	0.0	0.0
1986	0.0	0.0	0.0	0.0
1987	1,451.8	936.8	374.3	187.6
1988	0.0	0.0	0.0	0.0
1989	0.0	0.0	0.0	0.0

3. Behavior of the Static Model Objective Function

In preparation for the solution of the dynamic model, the behavior of the static model objective function is analyzed at each stage of the planning horizon to see if the objective function is uniform and solveable within the given constraints of the system. It is found that the static model objective function is solveable and convex at each stage. An example of the static model behavior at one of the stages is indicated in Figure 5.1. Because the objective function is convex, the costs can be minimized at each stage within the variable tails region from .0015 to .0025. The optimum quantity of enriched product is calculated at each stage by choosing the optimal tails enrichment which yields minimum cost for that stage.

The initial inventory level at each stage of the model is also defined as a function of the optimal tails enrichment. An example of this inventory behavior as a function of the optimal tails enrichment is presented in Figure 5.2.

The results shown in Figure 5.1 and 5.2 are calculated using the dynamic programming recursive equations presented in Chapter Four. At each stage of the dynamic model, results similar to Figure 5.1 and 5.2 are computed and stored in tables. A tabular search technique is then used to locate the optimal decisions from the tables.

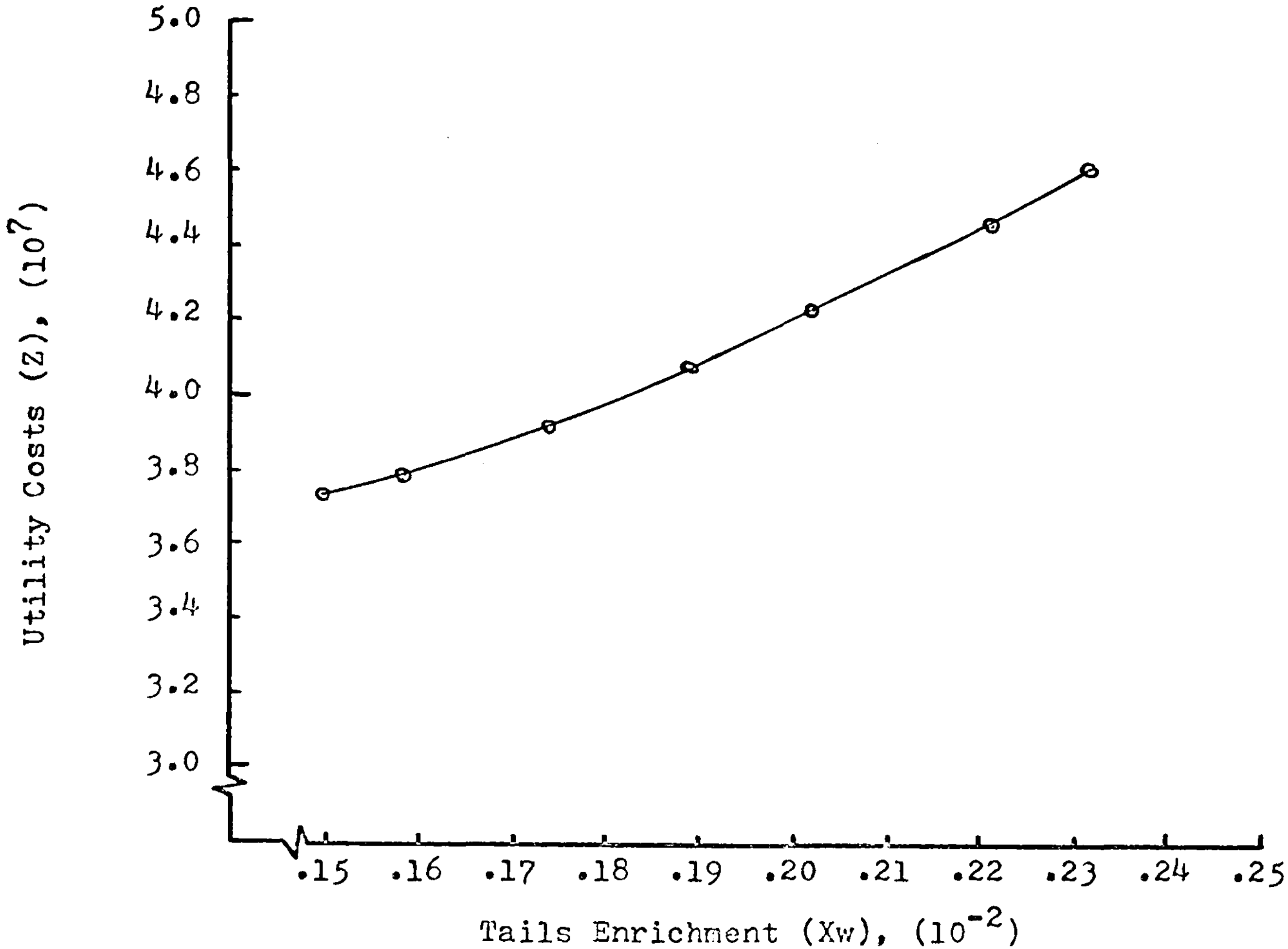


Figure 5.1. The Behavior of the Static Model's Objective Function

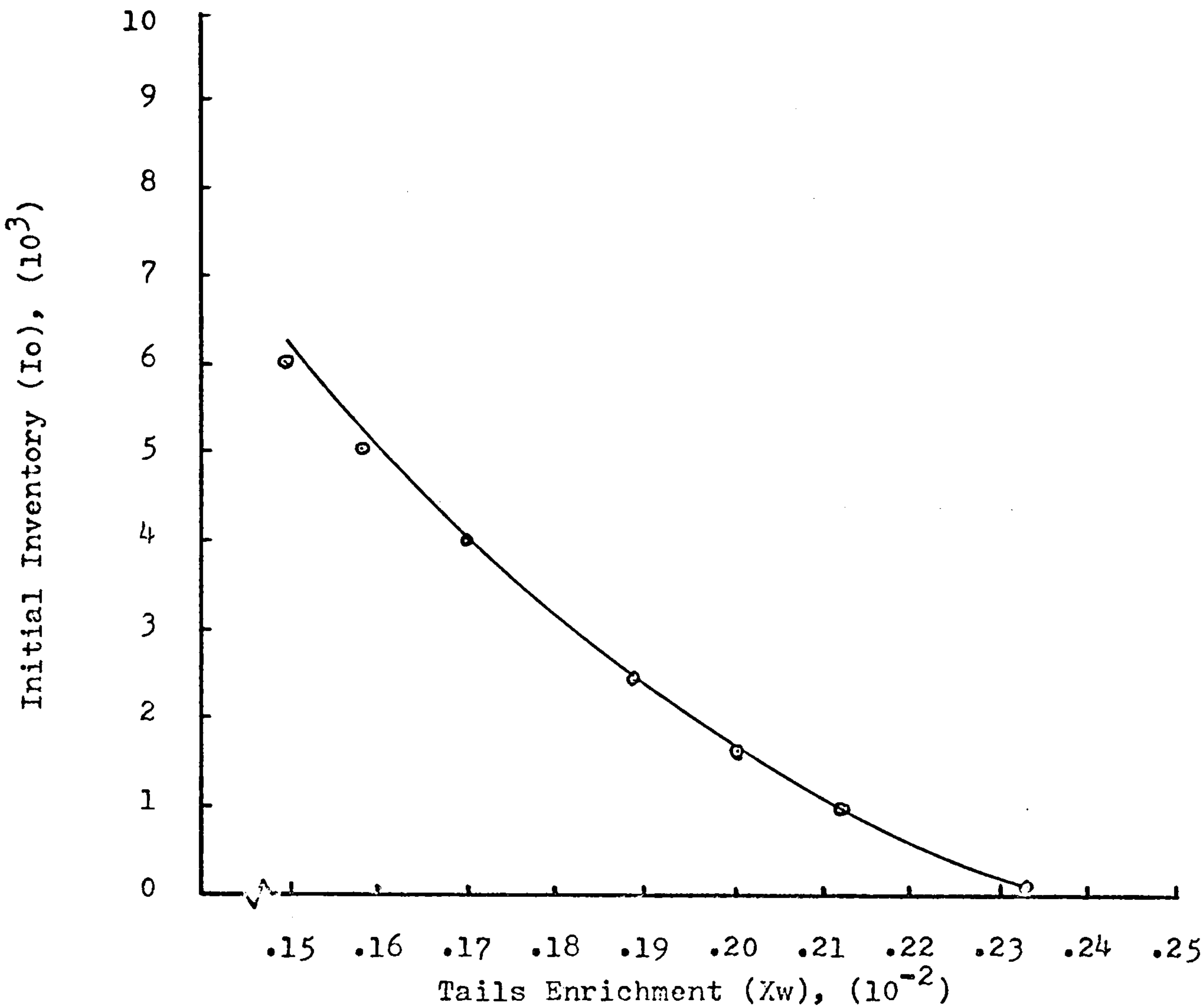


Figure 5.2. Inventory Versus Tails Enrichment in the Static Model

4. Dynamic Model Results

The analysis of the dynamic model considers the 18 month decision point data in Table 4.2. The results of the analysis are presented in Tables 5.5 and 5.6. Table 5.5 displays the minimum utility costs, the uranium feed requirements, and the optimal variable tails enrichment at each year of the contract. The optimal amounts of enriched product and fuel inventory for one product assay are presented in Table 5.6.

The variable tails enrichment is the operating tails assay of the enrichment plant. As indicated in Table 5.5 the variable tails enrichment increases for the contracting years 1983, 1984, 1985, 1986, 1988, and 1989. As the variable tails enrichment increases above the transaction tails value of .002, the uranium feed requirements and utility costs also increase relative to the benchmark case results. When the variable tails enrichment decreases the uranium feed requirements also decrease but the utility costs may increase. During a large fuel inventory production, the utility costs may increase above the benchmark case costs due to the additional costs incurred from maintaining a large inventory. An example of this occurance is indicated in Table 5.5 for the contracting year 1987. The tails enrichment decreases below the transaction tails

Table 5.5. Dynamic Model Results

Fiscal Year of Fuel Delivery	Total Utility Costs ($)	Total Uranium Feed (KgU)	Variable Tails Enrichment
1980	61,122,400.0	401,065.4	.002000174
1981	29,796,320.0	154,669.8	.001663963
1982	34,236,290.0	171,887.8	.001984780
1983	32,015,940.0	161,193.2	.002355166
1984	38,943,310.0	184,285.8	.002377334
1985	37,540,290.0	171,248.6	.002377756
1986	35,283,060.0	146,387.0	.002000795
1987	37,176,020.0	143,353.4	.001965781
1988	41,097,790.0	156,995.1	.002158539
1989	44,568,530.0	162,957.1	.002252016

value of .022 but the utility costs increase above the associated benchmark case costs. The reason for this increase is depicted by the large fuel inventory production in 1987. As indicated in Table 5.6, the amount of fuel inventory produced in 1987 is large.

In Table 5.6, production of fuel inventories are shown to occur in certain years to relieve the enriched fuel production in other contracting years. There are no fuel inventories for the first and last year of the ten year contract. The first year fuel inventory is set to zero because the inventory assay .032 is not included as a demand enrichment at the first stage of the dynamic model. The inventory at the last stage becomes zero because there is no financial benefit of having an inventory without future stages to utilize the inventory. However, after the first contracting year is terminated, another year of enriching services is added on to the tenth year to maintain the rolling ten year contract. As a result there may be a financial benefit in having a tenth year inventory in the old ten year contract in order to further minimize the costs in the new ten year contract. There is a great deal of uncertainty in determining the amount of the final inventory that should be produced at the tenth year because future contracting years are difficult to predict. Further

Table 5.6. The Enriched Product and Inventory Calculated by the Dynamic Model

Fiscal Year of Fuel Delivery	Enriched Product (KgU) Assay = .032	Inventory (KgU) Assay = .032
1980	56,165.0	0.0
1981	16,270.0	250.0
1982	17,073.7	133.8
1983	15,060.3	3.1
1984	17,217.2	0.28
1985	15,999.3	0.58
1986	14,546.5	2.1
1987	15,201.7	2,112.8
1988	14,653.4	767.3
1989	15,231.6	0.0

analysis is needed to understand how the tenth year final inventory requirement can be estimated.

5. Comparison of the Results in the Decision Models

Comparison of the total utility costs and the uranium feed requirements in the decision models are presented in Table 5.7 and 5.8 respectively. In both tables, the split-tails model results, the dynamic model results, and the benchmark case results are listed.

As indicated in Table 5.7, the minimum total ten year costs occur for the benchmark case. The cost for the solution of the dynamic and split-tails models are higher because these models utilize the 18 month decision point data instead of the benchmark case data. Due to the demand situation predicted at the 18 month decision point, the total ten year cost for the split-tails model is 11% greater than the benchmark case costs. This 11% increase represents a difference of approximately 42 million dollars. In the dynamic model the total ten year cost is 3% greater than the benchmark case cost (11 million dollar difference). In using the dynamic model instead of the split-tails model, there is an 8% savings or a 31 million dollar decrease in utility costs.

In Table 5.8 the total ten year uranium feed requirements for the dynamic and split tails models are greater

Table 5.7. Comparison of the Enrichment Costs in the Decision Models

Fiscal Year of Fuel Delivery	Benchmark Model Costs ($)	Split Tails Model Costs ($)	Dynamic Model Costs ($)
1980	61,122,480.0	61,122,480.0	61,122,400.0
1981	32,345,520.0	36,414,300.0	29,796,320.0
1982	34,336,980.0	34,336,980.0	34,236,290.0
1983	29,473,070.0	35,149,600.0	32,015,940.0
1984	35,760,530.0	42,340,660.0	38,943,310.0
1985	34,415,020.0	40,730,590.0	37,540,290.0
1986	35,281,470.0	35,281,470.0	35,283,060.0
1987	37,115,380.0	41,781,280.0	37,176,020.0
1988	39,272,740.0	46,468,420.0	41,097,790.0
1989	41,752,080.0	49,421,600.0	44,568,530.0
Total	380,875,000.0	423,047,200.0	391,779,300.0

Table 5.8. Comparison of the Feed Requirements in the Decision Models

Fiscal Year of Fuel Delivery	Benchmark Uranium Feed (KgU)	Split Tails Uranium Model Feed (KgU)	Dynamic Model Uranium Feed (KgU)
1980	401,055.6	401,055.6	401,065.4
1981	179,132.9	179,132.9	154,669.8
1982	172,978.4	172,978.4	171,887.8
1983	138,999.9	168,143.2	161,193.2
1984	157,528.3	190,564.7	184,285.8
1985	146,359.9	177,047.6	171,248.6
1986	146,359.9	146,359.9	146,387.0
1987	146,359.9	146,359.9	143,353.4
1988	146,359.9	177,047.6	156,995.1
1989	146,359.9	177,047.6	162,957.1
Total	1,781,494.6	1,935,737.5	1,854,043.9

than the benchmark case requirements due to the assumed inaccuracy of the fuel demand predictions at the ten year point. In using the dynamic model instead of the split-tails model, there is a total ten year uranium feed savings of approximately 4½%. The 4½% savings represents a 82,000 (KgU) decrease in natural uranium feed requirements.

On the basis of the results presented in Tables 5.7 and 5.8, the dynamic inventory model appears to create significant savings in the utility costs and the uranium feed. Due to the manipulation of fuel inventories and the tails enrichment, the dynamic model appears to be more flexible than the split-tails model.

B. Parametric Analysis of the Decision Models

The main purpose of this section is to analyze the behavior of the decision models under variations of certain key parameters. The tables that include the results of the parametric analysis are presented in Appendix I of this report.

1. Variation of the Inventory Enrichments in the Dynamic Model

The equilibrium enrichment that is used for inventory production in the dynamic model is arbitrarily chosen in Chapter Four to be .032. In this section, the other equilibrium enrichments .024, .022, and .018 are each utilized in the dynamic model as the inventory enrichment. The same 18 month decision point information (Chapter Four) is used as input data. The dynamic model results for each of the equilibrium enrichments are presented in Tables 5.9 to 5.13.

On the basis of the results in Table 5.9 and 5.10, the total ten year costs and feed requirements are minimum at the .032 inventory enrichment. The optimal enrichment for inventory production is, therefore, .032. In comparing the total ten year costs for all four enrichments, there is a maximum .024% difference in costs. In Table 5.10 a maximum difference in the total ten year feed requirements for all four equilibrium enrichments of .075% is shown. The small differences in the utility costs and the uranium feed requirements indicate that the dynamic model results are somewhat insensitive to the choice of inventory enrichment.

As shown in Table 5.11, the variable tails enrichment also appears to change by a small amount between each inventory enrichment category. Tables 5.12 and 5.13 indicate the amounts of enriched product and fuel inventories produced at each of the four equilibrium enrichments. In Table 5.13, the inventory behavior pattern appears to be similar for all four enrichment categories.

2. Variation of the Inventory Cost Factor in the Decision Models

The inventory holding cost factor (H) represents the fraction of the economic value of the fuel in the inventory. This fraction (discussed in Chapter Four) is arbitrarily chosen to be 15%. In this section, the cost factor is varied between 5% and 35% in order to identify its influence upon the decision model results. The 18 month decision point data (Chapter Four) is again analyzed using the models.

In Tables 5.14 and 5.15, the total utility costs for both the split-tails model and the dynamic model are presented. On the average, the total ten year costs in both tables increases .15% as the inventory cost factor increases 10%. This average increase appears to be quite small compared to a typical ten year cost figure. The total ten year cost is a linear increase in the split-tails model results but in the dynamic model results the cost increase is nonlinear. The total ten year cost for the dynamic model increases in a nonlinear fashion within the lower range of the inventory cost factors. In the higher cost factor range, the total ten year cost increases at a more constant rate.

In Table 5.16, the transient behavior of the total ten year uranium feed requirements in the dynamic model is shown to be similar to the behavior of the dynamic model results of Table 5.15. The results for the uranium feed requirements in the split-tails model are not presented because the inventory cost factor variation does not alter the feed requirements. In the split-tails model, the feed requirements, the inventories, and the enriched product remain the same as the cost factor increases.

In Table 5.17, the variable tails enrichment is not constant in the low cost factor range. At higher cost factors, the tails enrichment seems to become more constant as the cost factor increases.

In Tables 5.18 and 5.19, the changes of the enriched product and fuel inventories are nonlinear within the low cost factor range. The amounts of enriched product and fuel inventories appear to be sensitive to changes in low inventory cost factors.

On the basis of the results in this section a change in the inventory cost factor appears to produce a nonlinear change in the dynamic model results. In the split-tails model a change in the inventory cost factor produces a linear change in the utility costs but no change in the uranium feed, fuel inventories, and the enriched product. As the inventory cost factor changes the magnitude of the differences in utility costs in both models are relatively unchanged for the total ten year figures.

3. Reactor Demand Variations at the 18 Month Decision Point

The 18 month decision point data in Table 4.2 of Chapter Four is a hypothetical example of a fuel demand case predicted by a utility. At the 18 month decision point, there exists an infinite number of possible different demand cases which a utility might face. The utility chooses a demand case that reflects the current fuel needs of the reactor. Since the current needs of a reactor are unattainable in this thesis an effort is made to choose two different demand cases that will help understand the detailed behavior of the decision model results during a demand change at the 18 month decision point. In order to comprehend this detailed behavior of the results, two extreme demand cases are chosen. One demand case indicates all fuel shortages in the ten year contract and the other demand case portrays all overcommitments in fuel demand. These demand changes for the shortage and overcommitment cases are determined by systematically changing the benchmark case demands plus or minus 10%. The data for the demand cases are presented in Table 5.20. The numbers are input into the decision models and the computed optimal results are shown in Tables 5.21 to 5.27.

In Table 5.21, the utility costs are presented for both demand cases. In the shortage case the total ten year cost in the split-tails model is 16% greater than the benchmark case cost. In the dynamic model the ten year cost is 8% greater than the benchmark case cost. There is an 8% savings in using the dynamic model instead of the split-tails model. In the overcommitment case the total ten year cost in the split-tails model is 10½% greater than the benchmark case cost, and in the dynamic model the ten year cost is 7½% smaller than the benchmark case cost. There is an 18% savings in using the dynamic model instead of the split-tails model. In both cases, the application of the dynamic model produces a significant cost savings over the split-tails model.

Comparing the results for both cases, the shortage case is more costly than the overcommitment case. A utility should, therefore, try to prevent fuel shortages. In the overcommitment case, the total ten year costs using the dynamic model are less than the benchmark case costs but in the split-tails model, the costs are much higher. While using the dynamic model in the overcommitment case a utility may save a large amount of money. In the split-tails model the utility loses money in the overcommitment case because of the split-tails mode of operation.

The uranium feed requirements for the different demand cases are presented in Table 5.22. As in the utility cost results, the dynamic model generates a requirement for less uranium feed than that of the split-tails model. Comparing both demand cases, the overcommitment case requires the least amount of uranium feed. A significant amount of feed is saved by using the dynamic model in the overcommitment case.

The tails enrichment comparison for the different demand cases is presented in Table 5.23. In the shortage case, the tails enrichment in the dynamic and split-tails models is increased in each contracting year in order to produce the correct amount of enriched product for meeting demand. For the overcommitment demand case, the operating tails in the split-tails model remains constant because of the split-tails mode of operation. In the dynamic model of the overcommitment case, the tails enrichment decreases in order to minimize utility costs and uranium feed requirements.

Tables 5.24 and 5.25 depict the amount of enriched product and inventory calculated by the split-tails model in the overcommitment demand case. The large inventories shown in Table 5.25 indicate a significant increase in inventory holding costs. This increase in the inventory costs produces a significant increase in the total utility costs. Enriched product and inventory results are not included for the shortage case because the enriched product is forced to equal the fuel demand in the split-tails model.

The enriched product calculated in the dynamic model for both demand cases is presented in Table 5.26. The amounts of enriched product for both demand cases are similar to the fuel demands presented in Table 5.20. Since the amounts of enriched product are approximately equal to the fuel demand, the amounts of fuel inventory in Table 5.27 are small.

4. The Validity and Accuracy of the Computer Code Results

In constructing a computer code to solve the decision models, many errors could be induced in the final results. Several hand calculations were made to verify some of the simple calculations performed in the computer code. However, in the dynamic programming section of the computer code, there were too many calculations to verify. To test the validity of the dynamic program, many tables were printed to analyze some of the numbers calculated at each stage of the program. The basic calculations in the dynamic program appeared to be correct, however, because of the great number of calculations, complete verification of all the numbers is impractical.

Most of the benchmark case results and the split-tails model results are verified by the hand calculator. Assuming that these hand calculations are correct, the dynamic model results can be compared to the benchmark case results by inputing the same benchmark case data into the dynamic model instead of the 18 month decision point data. If the dynamic program is performing accurately, the benchmark case results theoretically should be equivalent to the dynamic model results. In Tables 5.28 to 5.32, the results are compared.

Table 5.28 indicates a comparison of the utility costs. The total ten year costs for the dynamic model is .000735% smaller than the benchmark case costs. In Table 5.29, the total ten year uranium feed requirements for the dynamic model is approximately .0271% greater than the benchmark case transaction tails. The increased tails enrichment explains the feed increase in the dynamic model results. Table 5.31 indicates the enriched product produced in both cases. The enriched product calculated in the dynamic model is smaller than the benchmark case values for many of the contracting years, thus, creating a decrease in the total ten year utility costs of Table 5.28. In Table 5.32, the amount of fuel inventory calculated by the dynamic model is approximately two kilograms for most of the contracting years. Theoretically, the amount of inventory should be zero, according to the benchmark case results.

The errors produced in the dynamic model results appeared to be quite small with respect to the assumed correct benchmark case results. Some of these errors may be due to a few iteration routines and the spline fit interpolation method used in the dynamic program.

The spline fit interpolation method is used to perform many interpolations between numbers in the optimal return tables of the dynamic program. The interpolations are made between the optimal cost values for a specific initial inventory at each stage. An example of a few comparisons between the actual and interpolated return costs at one of the stages is presented in Table 5.33. The actual return costs are calculated by the computer program for one of the stages in order to provide an assumed true reference for the interpolated values. Interpolation errors are calculated by comparing the actual and interpolated return values. On the basis of the assumed actual return costs, the interpolation error was always less than

1%. A few of these interpolation errors are indicated in Table 5.33.

The small discrepancies in the results of Tables 5.28 to 5.32 are probably due to the errors in the spline fit interpolations, iteration routines, and computational error buildup in the computer. Since the errors in the program are small, the computer code results appear to be quite accurate on the basis of the assumptions made in this section.

VI. CONCLUSIONS

After examining the results of the three decision models, five conclusions appear justifiable. First, the models do provide a useful representation of the decision problem at the 18 month point in the enrichment contracting process.

Second, there are significant potential penalties associated with ERDA's current split-tails mode of enrichment plant operation. In using the split-tails model, high utility costs and large uranium feed requirements are incurred when fuel requirements are under or overestimated at the ten year point.

Third, the dynamic inventory model seems to provide an opportunity for utility companies to analyze the enrichment contracting process and thereby use it more efficiently. In the dynamic model, manipulation of fuel inventories and the tails enrichments appears to create significant savings in the utility costs and uranium feed. Specifically, in the overcommitment case, a utility may save a large amount of money and uranium feed by utilizing the dynamic inventory model.

Fourth, the variable tails concept used in the static and dynamic models allows the utility to choose the optimal tails enrichment that will reflect the minimum cost and the minimum amount of uranium feed needed to satisfy fuel demand. In the split-tails model this flexibility in the tails enrichment does not exist. Therefore, the application of the variable tails concept proves to be more economical than the split-tails method.

Fifth, the SWU and feed cost projections used in the dynamic and split-tails models directly influence the optimal results. If a utility decides to use the decision models, the SWU and feed cost projections should be estimated as accurately as possible in order to determine the best strategy in contracting for enrichment services.

The dynamic inventory model appears to be an appropriate vehicle for improving the fixed-commitment contracting process. In the theoretical sense the dynamic model offers to the utility a flexibility in enrichment contracting but in the practical sense ERDA may consider the dynamic model impossible to employ because of certain constraints defined by the operational limits of the enrichment plant. One of the major constraints is the fixed operating tails enrichment. In this thesis the effort is made to help improve the enrichment contracting process by proposing new methods that will help ERDA decide how to solve the enrichment contracting problem. The dynamic inventory model concept may not be the most practical answer to enrichment contracting but further research in this direction may provide insight that ERDA and the utilities will find enlightening.

VII. RECOMMENDATIONS FOR FUTURE WORK

There are many different directions which might be taken in an effort to expand and improve the decision models. These directional efforts may be categorized into two basic groups. These groups might be titled model improvement and model expansion.

In the area of model improvement, there are numerous efforts worthy of pursuit. Relaxation of the many assumptions and constraints introduced in the initial analysis may lead to revised results. Among these are the use of uranium and plutonium recycling in the enrichment contracting strategies, and the more detailed analysis of inventory holding costs, shortage costs, feed costs, interest costs, and SWU costs in the models. Specifically, a more accurate estimation of the SWU feed cost projections will produce more meaningful results from the utility's standpoint. Also of value would be the improvement of the dynamic programming section of the computer code. The dynamic programming may be improved by minimizing the errors produced in the spline fit interpolations and the iteration routines of the program. Perhaps the most important improvement that can be made in the model would be to implement the dynamic model in a more practical perspective. For example, one of the major concepts in the dynamic model is the variable tails principle. ERDA feels that the application of the variable tails concept is somewhat impractical since the operating tails of the enrichment plant cannot be changed readily. The dynamic model should, therefore, utilize a more practical tails enrichment method. ERDA could possibly operate the enrichment plants at several tails enrichments. These several tails enrichments could be incorporated into the dynamic model instead of the variable tails method. Using the several tails enrichment principle, the dynamic model results might not be as favorable as the variable tails results but they will have more meaning and practicality for ERDA. Other improvements may be applied to the dynamic model in order to make the model more useful in the nuclear industry.

In the model expansion group, the dynamic inventory model should be applied to more than one reactor in order to manipulate a larger potential inventory. The dynamic model should also be expanded by incorporating a multiple enrichment inventory instead of the one enrichment inventory. The incorporation of a larger potential inventory with multiple enrichments should further optimize the dynamic model results.

It is recommended by the author that all these approaches be implemented in order to best determine the optimum practical strategy in the decision models.

APPENDIX I TABLES

Table 5.9. Enrichment Cost Comparison for Different Inventory Enrichments Used in the Dynamic Model

Fiscal Year of Fuel Delivery	Total Utility Costs ($) Assay = .032	Total Utility Costs ($) Assay = .024	Total Utility Costs ($) Assay = .022	Total Utility Costs ($) Assay = .018
1980	61,122,480.0	61,122,400.0	61,122,400.0	61,135,250.0
1981	32,345,520.0	29,567,470.0	29,540.530.0	29,537,780.0
1982	34,336,980.0	34,321,790.0	34,332,900.0	34,325,540.0
1983	29,473,070.0	32,161,410.0	32,177,840.0	32,177,440.0
1984	35,760,530.0	38,946,560.0	38,946,450.0	38,946,460.0
1985	34,415,020.0	37,540,460.0	37,540,500.0	37,540,540.0
1986	35,281,470.0	35,283,280.0	35,283,340.0	35,283,620.0
1987	37,115,380.0	37,354,190.0	37,442,140.0	36,538,980.0
1988	39,272,740.0	40,771,040.0	40,751,460.0	41,829,490.0
1989	41,752,080.0	44,735,310.0	44,674,860.0	44,558,270.0
Total	391,779,300.0	391,803,400.0	391,812,100.0	391,872,800.0

Table 5.10. Uranium Feed Comparison for Different Inventory Enrichments in the Dynamic Model

Fiscal Year of Fuel Delivery	Total Uranium Feed (KgU) Assay = .032	Total Uranium Feed (KgU) Assay = .024	Total Uranium Feed (KgU) Assay = .022	Total Uranium Feed (KgU) Assay = .018
1980	401,065.4	401,065.4	401,065.4	401,183.7
1981	154,669.8	152,848.7	152,633.8	152,596.5
1982	171,887.8	172,837.8	172,957.1	172,890.9
1983	161,193.2	162,466.4	162,609.7	162,606.0
1984	184,285.8	184,312.9	184,312.1	184,312.1
1985	171,248.6	171,249.5	171,249.9	171,249.9
1986	146,387.0	146,388.2	146,388.6	146,390.3
1987	143,353.4	144,464.6	145,009.9	139,582.7
1988	156,995.1	155,022.9	154,842.8	161,725.9
1989	162,957.1	163,941.5	163,584.5	162,897.8
Total	1,854,043.9	1,854,597.9	1,854,653.8	1,855,435.8

Table 5.11. Tails Enrichment Comparisons for Different Inventory Enrichments in the Dynamic Model

Fiscal Year of Fuel Delivery	Tails Enrichment Assay = .032	Tails Enrichment Assay = .024	Tails Enrichment Assay = .022	Tails Enrichment Assay = .018
1980	.002000174	.002000174	.002000174	.002000887
1981	.001663963	.001635969	.001632970	.001632450
1982	.001984780	.001998527	.002000095	.001999386
1983	.002355166	.002375317	.002377380	.002377362
1984	.002377334	.002377713	.002377704	.002377708
1985	.002377756	.002377760	.002377763	.002377759
1986	.002000795	.002000786	.002000784	.002000785
1987	.001965781	.001953749	.001950766	.001845591
1988	.002158539	.002147932	.002153013	.002261108
1989	.002252016	.002276310	.002274710	.002275510

Table 5.12. Enriched Product Comparison for Different Inventory Enrichments Used in the Dynamic Model

Fiscal Year of Fuel Delivery	Enriched Product Assay = .032	Enriched Product Assay = .024	Enriched Product Assay = .022	Enriched Product Assay = .018
1980	56,165.0	56,165.0	56,165.0	36,274.9
1981	16,270.0	10,382.2	4,145.6	2,074.6
1982	17,073.7	11,066.5	4,433.8	2,192.3
1983	15,060.3	9,784.1	3,917.6	3,921.0
1984	17,217.2	11,109.4	4,443.2	2,221.0
1985	15,999.3	10,323.5	4,125.7	2,068.9
1986	14,546.5	9,387.3	3,752.7	1,883.9
1987	15,201.7	11,646.1	7,050.6	5,256.1
1988	14,653.4	8,098.0	1,598.9	1,629.9
1989	15,231.6	9,345.4	2,971.5	4,032.2

Table 5.13. Inventory Comparison for Different Inventory Enrichments Used in the Dynamic Model

Fiscal Year of Fuel Delivery	Inventory Assay = .032	Inventory Assay = .024	Inventory Assay = .022	Inventory Assay = .018
1980	0.0	0.0	0.0	24.9
1981	250.[illegible]	46.2	10.6	29.5
1982	13[illegible].[illegible]	22.8	4.5	6.8
1983	3.1	0.93	1.2	1.6
1984	0.25	0.40	0.44	0.71
1985	0.58	0.98	1.16	1.6
1986	2.1	3.37	3.9	5.6
1987	2112.8	3202.5	3679.5	3569.7
1988	767.3	977.6	1153.5	1664.7
1989	0.0	0.0	0.0	0.0

Table 5.14. Enrichment Cost Comparison for Different Inventory Cost Factors in the Split-Tails Model

Fiscal Year of Fuel Delivery	Total Utility Costs ($) H = .05	Total Utility Costs ($) H = .10	Total Utility Costs ($) H = .15	Total Utility Costs ($) H = .25	Total Utility Costs ($) H = .35
1980	61,122,480	61,122,480	61,122,480	61,122,480	61,122,480
1981	36,091,260	36,252,780	36,414,300	36,737,360	37,060,400
1982	34,336,980	34,336,980	34,336,980	34,336,980	34,336,980
1983	35,149,600	35,149,600	35,149,600	35,149,600	35,149,600
1984	42,340,660	42,340,660	42,340,660	42,340,660	42,340,660
1985	40,730,590	40,730,590	40,730,590	40,730,590	40,730,590
1986	35,281,470	35,281,470	35,281,470	35,281,470	35,281,470
1987	41,410,800	41,596,030	41,781,280	42,151,760	42,522,240
1988	46,468,420	46,468,420	46,468,420	46,468,420	46,468,420
1989	49,421,600	49,421,600	49,421,600	49,421,600	49,421,600
Total	422,353,400	422,700,300	423,047,200	423,740,740	424,434,260

Table 5.15. Enrichment Cost Comparison for Different Inventory Cost Factors in the Dynamic Model

Fiscal Year of Fuel Delivery	Total Utility Costs ($) H = .05	Total Utility Costs ($) H = .10	Total Utility Costs ($) H = .15	Total Utility Costs ($) H = .25	Total Utility Costs ($) H = .35
1980	61,122,400	61,122,400	61,122,400	61,122,400	61,122,400
1981	33,015,780	31,045,860	29,796,320	29,540,300	29,540,960
1982	34,958,690	34,172,300	34,236,290	34,333,600	34,333,900
1983	30,749,700	30,829,630	32,015,940	32,178,100	32,178,180
1984	37,418,830	38,844,020	38,943,310	38,946,530	38,946,560
1985	36,017,600	37,541,710	37,540,290	37,540,450	37,540,540
1986	37,166,740	35,283,550	35,283,060	35,283,360	35,283,680
1987	38,621,470	38,213,550	37,176,020	35,534,270	34,057,470
1988	40,184,380	40,825,100	41,097,790	41,568,420	43,105,420
1989	41,246,060	43,524,210	44,568,530	45,973,760	45,972,450
Total	390,501,400	391,402,000	391,779,300	392,020,700	392,081,100

Table 5.16. Uranium Feed Comparison for Different Inventory Cost Factors in the Dynamic Model

Fiscal Year of Fuel Delivery	Total Uranium Feed (KgU) H = .05	Total Uranium Feed (KgU) H = .10	Total Uranium Feed (KgU) H = .15	Total Uranium Feed (KgU) H = .25	Total Uranium Feed (KgU) H = .35
1980	401,065.4	401,065.4	401,065.4	401,065.4	401,065.4
1981	183,712.1	165,334.7	154,669.8	152,626.7	152,626.7
1982	176,496.4	170,258.3	171,887.8	172,961.2	172,961.2
1983	148,760.5	150,764.0	161,193.2	162,611.5	162,611.5
1984	170,776.3	183,453.0	184,285.8	184,312.8	184,312.8
1985	159,085.1	171,260.1	171,248.6	171,249.2	171,249.2
1986	160,058.6	146,391.5	146,387.0	146,387.0	146,387.0
1987	154,497.6	151,005.4	143,353.4	132,612.3	124,688.9
1988	150,841.1	155,004.6	156,995.1	161,252.1	171,209.6
1989	143,386.3	156,806.3	162,957.1	171,236.5	171,229.2
Total	1,848,679.4	1,851,343.3	1,854,043.9	1,856,314.7	1,858,341.5

Table 5.17. Tails Enrichment Comparison for Different Inventory Cost Factors in the Dynamic Model

Fiscal Year of Fuel Delivery	Tails Enrichment H = .05	Tails Enrichment H = .10	Tails Enrichment H = .15	Tails Enrichment H = .25	Tails Enrichment H = .35
1980	.002000174	.002000174	.002000174	.002000174	.002000174
1981	.002078870	.001821927	.001663963	.001632970	.001632970
1982	.002050036	.001961400	.001984780	.002000093	.002000093
1983	.002152832	.002186382	.002355166	.002377371	.002377371
1984	.002185131	.002365851	.002377334	.002377708	.002377708
1985	.002191716	.002377926	.002377756	.002377765	.002377765
1986	.002222846	.002000869	.002000795	.002000795	.002000795
1987	.002150433	.002093706	.001965781	.001777721	.001632690
1988	.002058732	.002126600	.002158539	.002225734	.002377180
1989	.001933387	.002155337	.002252016	.002377387	.002377287

Table 5.18. Enriched Product Comparison for Different Inventory Cost Factors in the Dynamic Model

Fiscal Year of Fuel Delivery	Enriched Product (KgU) H = .05	Enriched Product (KgU) H = .10	Enriched Product (KgU) H = .15	Enriched Product (KgU) H = .25	Enriched Product (KgU) H = .35
1980	56,165.0	56,165.0	56,165.0	56,165.0	56,165.0
1981	19,463.5	17,500.9	16,270.0	16,025.8	16,025.8
1982	17,553.7	16,901.1	17,073.7	17,186.6	17,186.6
1983	13,879.6	14,076.4	15,060.3	15,189.1	15,189.1
1984	15,948.1	17,141.7	17,217.2	17,219.6	17,219.6
1985	14,858.2	16,000.3	15,999.3	15,999.3	15,999.3
1986	15,919.1	14,546.9	14,546.5	14,546.5	14,546.5
1987	16,344.2	15,994.9	15,201.7	14,019.9	13,092.7
1988	14,034.6	14,455.9	14,653.4	15,067.8	15,995.7
1989	13,252.6	14,635.6	15,231.6	15,999.1	15,998.4

Table 5.19. Fuel Inventory Comparison for Different Inventory Cost Factors in the Dynamic Model

Fiscal Year of Fuel Delivery	Inventory (KgU) H = .05	Inventory (KgU) H = .10	Inventory (KgU) H = .15	Inventory (KgU) H = .25	Inventory (KgU) H = .35
1980	0.0	0.0	0.0	0.0	0.0
1981	3,443.5	1,480.9	250.0	5.8	5.8
1982	3,807.3	1,192.1	133.8	2.5	2.5
1983	2,495.9	77.5	3.1	0.62	0.62
1984	1,224.0	0.75	0.28	0.22	0.22
1985	83.3	0.60	0.58	0.58	0.58
1986	1,457.4	2.5	2.1	2.1	2.1
1987	4,710.7	2,906.4	2,112.8	931.1	3.8
1988	2,746.3	1,363.4	767.3	0.0	0.60
1989	0.0	0.0	0.0	0.0	0.0

Table 5.20. Demand Changes at the 18 Month Decision Point

Fiscal Year of Fuel Delivery	Product Enrichment U-235	Benchmark Demands (KgU)	Overcommitment 10% Demand Decrease (KgU)	Shortage 10% Demand Increase (KgU)
1980	.023	56,165	56,165	56,165
	.018	36,250	36,250	36,250
	.016	14,495	14,195	14,195
	.014	7,250	7,250	7,250
1981	.032	17,800	16,020	19,580
	.024	11,485	10,336	12,633
	.022	4,595	4,135	5,054
	.018	2,300	2,070	2,530
1982	.032	17,190	15,471	18,909
	.024	11,090	9,981	12,199
	.022	4,440	3,996	4,884
	.018	2,215	1,993	2,436
1983	.032	13,810	12,429	15,191
	.024	8,915	8,023	9,806
	.022	3,565	3,208	3,921
	.018	1,785	1,606	1,963
1984	.032	15,655	14,089	17,220
	.024	10,100	9,090	11,110
	.022	4,040	3,636	4,444
	.018	2,020	1,818	2,222
1985	.032	14,545	13,090	15,999
	.024	9,385	8,446	10,323
	.022	3,750	3,375	4,125
	.018	1,880	1,692	2,068
1986	.032	14,545	13,090	15,999
	.024	9,385	8,446	10,323
	.022	3,750	3,375	4,125
	.018	1,880	1,692	2,068
1987	.032	14,545	13,090	15,999
	.024	9,385	8,446	10,323
	.022	3,750	3,375	4,125
	.018	1,880	1,692	2,068
1988	.032	14,545	13,090	15,999
	.024	9,385	8,446	10,323
	.022	3,750	3,375	4,125
	.018	1,880	1,692	2,068
1989	.032	14,545	13,090	15,999
	.024	9,385	8,446	10,323
	.022	3,750	3,375	4,125
	.018	1,880	1,692	2,068

Table 5.21. Enrichment Cost Comparison for the Different Demand Cases in the Decision Models

Fiscal Year of Fuel Delivery	Benchmark Model Costs ($)	Overcommitment Split Tails Model Costs ($)	Overcommitment Dynamic Model Costs ($)	Shortage Split Tails Model Costs ($)	Shortage Dynamic Model Costs ($)
1980	61,122,480	61,122,480	61,122,400	61,122,480	61,122,400
1981	32,345,520	36,414,300	29,539,660	39,331,900	35,567,420
1982	34,336,980	38,655,660	31,452,610	41,323,890	37,652,220
1983	29,473,070	33,181,070	27,110,110	35,149,600	32,172,210
1984	35,760,530	40,258,940	32,979,150	42,340,660	38,946,500
1985	34,415,020	38,744,820	31,687,540	40,730,590	37,540,400
1986	35,281,470	39,720,290	32,458,020	41,732,460	38,516,020
1987	37,115,380	41,784,910	34,052,780	43,904,780	40,624,140
1988	39,272,740	44,213,700	35,923,070	46,468,420	43,110,690
1989	41,752,080	47,004,980	38,058,340	49,421,600	45,972,480
Total	380,875,000	421,100,800	354,383,400	441,526,300	411,224,300

Table 5.22. Uranium Feed Comparison for the Different Demand Cases in the Decision Model

Fiscal Year of Fuel Delivery	Benchmark Uranium Feed (KgU)	Overcommitment Split Tails Model Feed (KgU)	Overcommitment Dynamic Model Feed (KgU)	Shortage Split Tails Model Feed (KgU)	Shortage Dynamic Model Feed (KgU)
1980	401,055.6	401,055.6	401,065.4	401,055.6	401,065.4
1981	179,132.9	179,132.9	152,626.7	216,704.0	209,597.9
1982	172,978.4	172,978.4	147,334.3	209,261.5	202,473.6
1983	138,999.9	138,999.9	118,395.1	168,143.2	162,560.6
1984	157,528.3	157,528.3	134,174.3	190,564.7	184,312.8
1985	146,359.9	146,359.9	124,663.3	177,047.6	171,249.4
1986	146,359.9	146,359.9	124,660.9	177,047.6	171,245.0
1987	146,359.9	146,359.9	124,660.6	177,047.6	171,245.1
1988	146,359.9	146,359.9	124,660.4	177,047.6	171,245.1
1989	146,359.9	146,359.9	124,605.6	177,047.6	171,229.3
Total	1,781,494.6	1,781,494.6	1,576,846.6	2,070,967.0	2,016,224.2

Table 5.23. Tails Enrichment Comparison for the Different Cases in the Decision Models

Fiscal Year of Fuel Delivery	Overcommitment Split Tails Model Operating Tails	Overcommitment Dynamic Model Variable Tails	Shortage Split Tails Model Operating Tails	Shortage Dynamic Model Variable Tails
1980	.0025	.002000174	.0025	.002000174
1981	.0025	.001632970	.002933887	.002377802
1982	.0025	.001632203	.002933887	.002378762
1983	.0025	.001632257	.002933686	.002376583
1984	.0025	.001632190	.002933786	.002377710
1985	.0025	.001632223	.002933686	.002377766
1986	.0025	.001632180	.002933686	.002377704
1987	.0025	.001632173	.002933686	.002377705
1988	.0025	.001632171	.002933686	.002377707
1989	.0025	.001630956	.002933686	.002377287

Table 5.24. The Amount of Enriched Product Calculated in the Split-Tails Model for the Overcommitment Demand Case

Fiscal Year of Fuel Delivery	Overcommitment Enriched Product (KgU) Assay = .032	Overcommitment Enriched Product (KgU) Assay = .024	Overcommitment Enriched Product (KgU) Assay = .022	Overcommitment Enriched Product (KgU) Assay = .018
1980	56,165.0	36,250.0	14,495.0	7,250.0
1981	17,797.8	11,483.0	4,593.8	2,299.7
1982	17,187.6	11,088.4	4,439.3	2,214.1
1983	13,808.5	8,913.5	3,564.0	1,784.2
1984	15,652.5	10,098.7	4,039.5	2,019.7
1985	14,542.8	9,383.4	3,749.6	1,879.8
1986	14,542.8	9,383.4	3,749.6	1,879.8
1987	14,542.8	9,383.4	3,749.6	1,879.8
1988	14,542.8	9,383.4	3,749.6	1,879.8
1989	14,542.8	9,383.4	3,749.6	1,879.8

Table 5.25. The Amount of Fuel Inventory Calculated in the Split-Tails Model for the Overcommitment Demand Case

Fiscal Year of Fuel Delivery	Overcommitment Inventory (KgU) Assay = .032	Overcommitment Inventory (KgU) Assay = .024	Overcommitment Inventory (KgU) Assay = .022	Overcommitment Inventory (KgU) Assay = .018
1980	0.0	0.0	0.0	0.0
1981	1,777.8	1,147.0	458.8	229.7
1982	1,716.6	1,107.4	443.3	221.1
1983	1,379.5	8,904.9	356.0	178.2
1984	1,563.5	1,008.7	403.5	201.7
1985	1,452.8	937.4	374.6	187.8
1986	1,452.8	937.4	374.6	187.8
1987	1,452.8	937.4	374.6	374.6
1988	1,452.8	937.4	374.6	374.6
1989	1,452.8	937.4	374.6	374.6

Table 5.26. The Amount of Enriched Product Calculated in the Dynamic Model for Different Demand Cases

Fiscal Year of Fuel Delivery	Benchmark Enriched Product (KgU) Assay = .032	Overcommitment Enriched Product (KgU) Assay = .032	Shortage Enriched Product (KgU) Assay = .032
1980	56,165.0	56,165.0	56,165.0
1981	17,800.0	16,025.8	19,580.3
1982	17,190.0	15,470.4	18,915.8
1983	13,810.0	12,429.5	15,184.4
1984	15,655.0	14,088.7	17,219.6
1985	14,545.0	13,090.3	15,999.4
1986	14,545.0	13,090.0	15,998.9
1987	14,545.0	13,090.0	15,998.9
1988	14,545.0	13,089.9	15,998.9
1989	14,545.0	13,084.0	15,998.9

Table 5.27. The Amount of Fuel Inventory Calculated in the Dynamic Model for the Overcommitment and Shortage Demand Cases

Fiscal Year of Fuel Delivery	Overcommitment Inventory (KgU) Assay = .032	Shortage Inventory (KgU) Assay = .032
1980	0.0	0.0
1981	5.8	0.29
1982	5.3	7.1
1983	5.8	0.61
1984	5.6	0.21
1985	5.9	0.60
1986	5.9	0.59
1987	5.9	0.58
1988	5.9	0.57
1989	0.0	0.0

Table 5.28. Comparison of the Enrichment Costs in the Decision Models Using the Benchmark Data at the 18 Month Decision Point

Fiscal Year of Fuel Delivery	Benchmark Split Tails Model ($)	Benchmark Dynamic Model ($)
1980	61,122,480.0	61,122,400.0
1981	32,345,520.0	32,348,190.0
1982	34,336,980.0	34,336,820.0
1983	29,473,070.0	29,472,340.0
1984	35,760,530.0	35,760,400.0
1985	34,415,020.0	34,414,530.0
1986	35,281,470.0	35,281,170.0
1987	37,115,380.0	37,115,220.0
1988	39,272,740.0	39,272,750.0
1989	41,752,080.0	41,748,540.0
Total	380,875,000.0	380,872,200.0

Table 5.29. Comparison of the Uranium Feed Requirements in the Decision Models Using the Benchmark Data at the 18 Month Decision Point

Fiscal Year of Fuel Delivery	Benchmark Split Tails Model Feed (KgU)	Benchmark Dynamic Model Feed (KgU)
1980	401,055.6	401,065.4
1981	179,132.9	179,172.8
1982	172,978.4	172,992.5
1983	138,999.9	139,007.4
1984	157,528.3	157,544.2
1985	146,359.9	146,371.4
1986	146,359.9	146,372.4
1987	146,359.9	146,372.5
1988	146,359.9	146,372.5
1989	146,359.9	146,344.7
Total	1,781,494.6	1,781,615.8

Table 5.30. Comparison of the Tails Enrichment in the Decision Models Using the Benchmark Data at the 18 Month Decision Point

Fiscal Year of Fuel Delivery	Benchmark Split Tails Model Transaction Tails	Benchmark Dynamic Model Variable Tails
1980	.002	.002000174
1981	.002	.002000887
1982	.002	.002000542
1983	.002	.002000472
1984	.002	.002000590
1985	.002	.002000529
1986	.002	.002000547
1987	.002	.002000550
1988	.002	.002000550
1989	.002	.001999873

Table 5.31. The Amount of Enriched Product Calculated in the Decision Models Using the Benchmark Data at the 18 Month Decision Point

Fiscal Year of Fuel Delivery	Benchmark Split Tails Model (KgU) Assay = .032	Benchmark Dynamic Model (KgU) Assay = .032
1980	56,165.0	56,165.0
1981	17,800.0	17,802.5
1982	17,190.0	17,189.9
1983	13,810.0	13,809.5
1984	15,655.0	15,655.2
1985	14,545.0	14,544.9
1986	14,545.0	14,544.9
1987	14,545.0	14,545.0
1988	14,545.0	14,545.0
1989	14,545.0	14,542.9

Table 5.32. The Amount of Fuel Inventory Calculated in the Decision Models Using the Benchmark Data at the 18 Month Decision Point

Fiscal Year of Fuel Delivery	Benchmark Split Tails Model (KgU) Assay = .032	Benchmark Dynamic Model (KgU) Assay = .032
1980	0.0	0.0
1981	0.0	2.53
1982	0.0	2.46
1983	0.0	2.00
1984	0.0	2.25
1985	0.0	2.13
1986	0.0	2.12
1987	0.0	2.11
1988	0.0	2.13
1989	0.0	0.0

Table 5.33. A Comparison Between the Actual and Interpolated Return Costs Using the Spline Fit Interpolation Method

Initial Inventory (KgU)	Actual Return Costs ($)	Interpolated Return Costs ($)	Interpolation Error %
2,518.26	25,861,620.0	25,724,420.0	.533
3,518.26	25,054,540.0	25,005,700.0	.195
4,264.75	24,705,180.0	24,571,710.0	.543
5,518.26	24,005,570.0	23,990,860.0	.061
6,633.50	23,322,800.0	23,481,200.0	.679
7,264.75	23,003,970.0	23,230,690.0	.985
8,998.59	22,459,470.0	22,459,630.0	.0007
9,633.50	22,560,190.0	22,550,180.0	.044
9,745.77	22,578,000.0	22,572,340.0	.025

APPENDIX II

THE RULES AND REGULATIONS OF THE FIXED-COMMITMENT CONTRACT

AGREEMENT FOR FURNISHING
URANIUM ENRICHMENT SERVICES
(LONG-TERM, FIXED-COMMITMENT) 66

THIS AGREEMENT, entered into this ______ day of ____________, 1974, by and between the UNITED STATES OF AMERICA (hereinafter referred to as the "Government"), as represented by the UNITED STATES ATOMIC ENERGY COMMISSION (hereinafter referred to as the "Commission"), and _________ _________, having an office at ___________ (hereinafter referred to as the "Customer");

WITNESSETH THAT:

WHEREAS, the Commission is authorized to enter into contracts for the producing or enriching of special nuclear material in facilities owned by the Commission; and

WHEREAS, the Customer desires to obtain certain uranium enriching services from the Commission; and

WHEREAS, the Commission is willing to provide such services, all under the terms and conditions more particularly hereinafter set forth; and

WHEREAS, this agreement is authorized by the Atomic Energy Act of 1954, as amended;

NOW, THEREFORE, the parties hereto do hereby agree as follows:

ARTICLE I - DEFINITIONS

As used throughout this agreement, the following terms shall have the meanings set forth below:

1. The term "Act" means the Atomic Energy Act of 1954 as amended.

2. The term "Commission" means the United States Atomic Energy Commission or any duly authorized representative thereof, including the Contracting Officer, except for the purpose of deciding an appeal under the article entitled "Disputes."

3. The term "Commission's established specifications" means the specifications for purity and other physical or

chemical properties of special nuclear material and source material (including tails material) as published by the Commission in the Federal Register from time to time applicable to material subject to this agreement on the date of delivery of such material.

4. The term "Commission facility" means a laboratory, plant, office or other establishment operated by or on behalf of the Commission.

5. The term "Contracting Officer" means the person executing this agreement on behalf of the Government, and includes his successors or any duly authorized representative of any such person.

6. The term "depleted uranium" means uranium depleted in the isotope 235.

7. The term "enriched uranium" means uranium enriched in the isotope 235.

8. The term "enriching services" means the separative work necessary to enrich or further enrich uranium in the isotope 235.

9. The term "established Commission pricing policy" means any applicable price or charge in effect at the time of performance of any services under this agreement (i) published by the Commission in the Federal Register for material or services subject to this agreement, or (ii) in the absence of such a published figure, determined in accordance with the Commission's pricing policy; provided, however, that for purposes of this definition, any enriching services performed by the Commission shall be deemed to have been performed on the date of delivery of related enriched uranium to the Customer. A statement of such pricing policy will be furnished the Customer upon request. The Commission's published prices or charges, as well as its pricing policy, may be amended from time to time.

10. The term "established Commission standard table of enriching services," which may also be referred to in this agreement as "Standard Table," means the table published from time to time by the Commission in the Federal Register and in effect at the time of delivery of any enriched uranium to the Customer under this agreement, which table is to be used in connection with the furnishing of enriching services by the Commission to determine the relationship between feed materials, enriched uranium produced therefrom and separative work thereby required to be performed as a

function of the quantities and assays of such materials. The (waste) assay set forth in the Standard Table is the assay basis on which the values in such table are computed for purposes of transactions under this agreement (transaction tails assay) and may vary from time to time from the tails assay at which the Commission enrichment facilities are operating.

11. The term "feed material" means the uranium constituting source material or special nuclear material to be furnished by the Customer to the Commission in connection with the providing of enriching services to the Customer under this agreement; provided, however, it shall not, except as may otherwise be agreed by the Commission and the Customer from time to time, mean uranium having an assay (weight percent U-235) below 0.711 unless such uranium was previously distributed by the Commission or has been derived solely from uranium previously distributed by the Commission or such uranium was previously irradiated in and discharged from a nuclear power or research reactor.

12. The term "fiscal year" means the U.S. Government's fiscal year.

13. The term "natural uranium" means uranium which has neither been enriched nor depleted in the isotope 235.

14. The term "persons acting on behalf of the Commission" includes employees and contractors of the Commission. and employees of such contractors, who implement or participate in the implementing of this agreement pursuant to their employment or their contracts with the Commission.

15. The term "source material" means (i) uranium, thorium, or any other material which is determined by the Commission pursuant to the provisions of Section 61 of the Act to be source material; or (ii) ores containing one or more of the foregoing materials, in such concentration as the Commission may by regulation determine from time to time.

16. The term "special nuclear material" means (i) plutonium, uranium-233, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the Commission, pursuant to the provisions of Section 51 of the Act, determines to be special nuclear material, but does not include source material; or (ii) any material artificially enriched by any of the foregoing, but does not include source material.

17. The term "tails material" means uranium produced as a result of the performance of enriching operations, and with an isotope 235 assay less than 0.711 weight percent U-235 in total uranium.

ARTICLE II - <u>ENRICHING SERVICES - DELIVERY SCHEDULES - SPECIFICATIONS - RESTRICTION ON FURNISHING FEED MATERIAL OF FOREIGN ORIGIN</u>

1. The Commission shall furnish to the Customer during the term of this agreement, and the Customer shall purchase, certain enriching services in connection with the operation of the Customer's proposed nuclear power facility designated as X17, in accordance with the time schedules and other terms and conditions set forth gereinbelow.

2. a. The Customer intends that the proposed facility shall have a rated generating capacity of not less than 1030 gross Mwe or more than 1230 gross Mwe. The purpose of such specification of size range of the proposed facility in this agreement is to establish: (i) the amount of the advance payment which the Customer shall make in accordance with Article VIII, Section 1. of this agreement; and, unless revised pursuant to subsections 2.b. or 2.c. below, (ii) the gross Mwe limits within which the parties shall agree upon the number of separative work units estimated to be necessary to support the designated facility in accordance with Sections 3. and 4. below.

b. In the event the rated Mwe generating capacity of the designated facility is in excess of the upper limit of the gross Mwe range specified above, the Commission shall have the option of (i) increasing the upper gross Mwe limit contained in subsection 2.a. above and agreeing to provide any resulting increase in the number of separative work units estimated to be necessary to support the designated facility or (ii) agreeing to provide for the requirements of the designated facility only the number of separative work units required for such facility within the maximum gross Mwe generating capacity initially specified in subsection 2.a. above. Such latter quantity of separative work shall be determined by multiplying the estimated requirements of the designated facility by the ratio of the upper gross Mwe limit specified in subsection 2.a. above to the rated Mwe generating capacity of the designated facility. Upon election by the Commission to increase the upper gross Mwe limit contained herein as provided above, the advance payment to be made by the Customer shall be adjusted as provided in Article VIII, Section 1.

c. In the event the rated Mwe generating capacity of the designated facility is less than the lower limit of the gross Mwe range specified in subsection 2.a. above, the advance payment to be made by the Customer shall be adjusted in accordance with Article VIII, Section 1., and the upper gross Mwe limit contained in subsection 2.a. above shall be decreased accordingly.

d. It is understood that upon agreement between the parties in accordance with Sections 3. and 4. below. subject to compliance with all applicable laws, regulations and ordinances of the Government, and of any state, territory or political subdivision, there shall be no restriction on the Customer's use or disposition of enriched uranium furnished by the Commission hereunder.

3. Unless otherwise agreed, within 30 days after the Customer files an application for a construction permit for the designated facility, but in no event later than October 1, 1975, the Customer and the Commission shall agree upon appendices to be made a part hereof as follows:

a. An Appendix "A" containing an enriching services schedule specifying the number of units of separative work to be furnished by the Commission and purchased by the Customer hereunder during each fiscal year or portion thereof for the initial firm period: October 1, 1979, through June 30, 1990.

(1) The amount of enriching services to be furnished by the Commission and purchased by the Customer during that portion of the initial firm period which begins on October 1, 1979, and extends through September 30, 1980, shall be that amount of enriching services that the Commission and the Customer agree to be required, within the Mwe limits specified in subsection 2.a. above or as they may be revised pursuant to subsections 2.b. or 2.c. above, for the first core of the designated facility and such number of spare fuel assemblies as the Customer may elect to obtain for the designated facility.

(2) The amount of enriching services to be furnished by the Commission and purchased by the Customer during the remaining portion of the initial firm period shall not be less than twice the amount of enriching services to be furnished during that portion of the initial firm period specified in subsection 3.a. (1) above, or more than an amount agreed upon by the Commission and the Customer, within the Mwe limits specified in subsection 2.a. above, or as they may be revised pursuant to subsections 2.b. or 2.c.

above, to be sufficient to satisfy the estimated requirements of the designated facility during the remaining portion of the initial fium period.

b. The Appendix "A" submitted hereunder shall include an estimated date for issuance by the cognizant regulatory body of a construction permit for the designated facility. The Customer shall also state the extent to which the agreed delivery schedule for the enriching services specified in Appendix "A" to be furnished after September 30, 1980, shall, unless otherwise agreed by the parties, be extended in the event there is a delay (beyond such estimated date) in the issuance of such construction permit. Upon agreement by the Commission that the proposed extension of the agreed delivery schedule is reasonable, such extension schedule shall be made a part of Appendix "A".

c. The schedule of enriching services contained in Appendix "A" shall be supported by a material schedule in Appendix "B" showing quantities (Kg U), assays (weight percent U-235) and times of deliveries of feed material other than natural uranium proposed to be delivered by the Customer and of enriched uranium proposed to delivered by the Commission upon performance of the enriching services contained in Appendix "A". Should the established Commission standard table of enriching services subsequently be revised, the amounts of enriching services set forth in the enriching services schedule in Appendix "A" hereof for services to be provided subsequent to the effective date of such change shall be adjusted by the Commission to be equal to the amounts of enriching services derived from the application of the revised Standard Table to the relevant portion of the material schedule set forth in Appendix "B" hereof. Prior to adjusting such separative work amounts in Appendix "A", the estimated monthly schedules of feed material other than natural uranium proposed to be delivered by the Customer and quantities and assays of enriched uranium proposed to be delivered by the Commission hereunder, submitted by the Customer in accordance with Section 6, below, shall be used to supplement and update the material schedule set forth in Appendix "B", provided that such estimated schedules were submitted to the Commission prior to the announcement of the change in the Standard Table.

d. In the event the Customer is required pursuant to this Section 3. to agree upon an Appendix "A" and a supporting Appendix "B" prior to the time the Commission, or any successor cognizant authority, announces generic approval of the use of plutonium as fuel in nuclear power reactors, the Customer may elect to include in this agreement a

Contingency Appendix "A" and a supporting Contingency Appendix "B". The Contingency Appendix "A" shall be identical to Appendix "A" except the enriching services schedule contained therein shall not take into consideration the use of plutonium as fuel in the designated facility. Contingency Appendix "A" and supporting Contingency Appendix "B" shall be effective in lieu of Appendix "A" and Appendix "B" hereunder until such time as the Commission, or any successor cognizant authority, announces generic approval of the use of plutonium as fuel in nuclear power reactors. Upon such announcement, Appendix "A" and Appendix "B" shall immediately become effective without further action by the contracting parties, and Contingency Appendix "A" and Contingency Appendix "B" shall no longer be of any force and effect. During the period of this agreement that Contingency Appendix "A" and Contingency Appendix "B" are in effect, the references herein to "Appendix 'A'" and "Appendix 'B'" shall be deemed to refer, whenever appropriate, to Contingency Appendix "A" and Contingency Appendix "B".

4. For each fiscal year covered by the term of this agreement beyond the initial firm period, the Commission agrees to furnish enriching services up to the agreed estimated requirements of the designated facility within the Mwe limits specified in subsection 2.a. above or as they may be revised pursuant to subsections 2.b. or 2.c. above. The Customer shall give the Commission written notice of the number of units of separative work desired to be furnished by the Commission during each additional fiscal year at least 10 years in advance of such fiscal year. Upon agreement by the Commission that the amount of enriching services desired by the Customer is not in excess of such requirements for the additional year, such notice shall constitute an amendment to the enriching services schedule contained in Appendix "A".

5. Failure of the parties to agree upon the amount of enriching services to be furnished pursuant to subsection 3.a. (1) above or the maximum amounts of enriching services to be furnished for the designated facility during the remaining portion of the initial firm period or subsequent fiscal years shall be deemed a dispute and shall be decided in accordance with the provisions of this agreement entitled "Disputes."

6. By January 1, 1978, and on or before January 1, of each succeeding year, the Customer shall provide the Commission with written schedules for the subsequent two-fiscal-year period of its estimated monthly quantities and assays of enriched uranium proposed to be delivered by the

Commission. The Customer may also provide the Commission from time to time with written schedules for part or all of the eight-fiscal-year period subsequent to such two-fiscal-year period of its estimated monthly or annual quantities and assays of enriched uranium proposed to be delivered by the Commission upon the performance of the agreed enriching services set forth in the enriching services schedule contained in Appendix "A", and proposed deliveries of feed material during such period. Except for the purposes set forth in subsection 3.c. above, such schedules shall not be binding on either the Commission or the Customer.

7. The Customer by written notice to the Commission shall specify its desired monthly period or periods within any fiscal year in which enriched uranium associated with the enriching services scheduled for such year in Appendix "A" is to be delivered and the amount of such enriching services to be furnished. Except as set forth hereinbelow or as may otherwise be agreed, any such notice must be given at least 315 days prior to the beginning of any such monthly period, hereinafter referred to as Month M. In such notice, the Customer may also request the specific delivery date or dates for the delivery of such enriched uranium within the Month M. Unless otherwise agreed, the Commission shall notify the Customer at least 240 days prior to the beginning of Month M of: (a) the firm monthly period or periods during which the enriched uranium, specified by the Customer to be delivered in Month M, will be delivered; (b) the firm date or dates within each such monthly period when such enriched uranium shall be delivered; and (c) the firm date or dates by which feed material associated therewith is to be furnished by the Customer to the Commission. Such enriched uranium, requested by the Customer for delivery in Month M, shall be agreed to be delivered in Month M by the Commission unless one or more of the conditions set forth hereinbelow are present, in which case the Commission's right to deliver such enriched uranium in a later month or months shall be as also set forth hereinbelow. For the fiscal year in which Month M occurs, the Commission shall determine the total enriching services to be furnished to all customers having Fixed-Commitment Agreements as set forth in the Appendix "A: of all such Agreements. One-twelfth of that total is termed the average monthly demand for that fiscal year. The total amount of associated enriching services specified by customers having Fixed-Commitment Agreements in their notices to the Commission for enriched uranium to be delivered in (a) Month M, (b) Month M and the preceding two months and (c) Month M and thepreceding 5 months are to be divided respectively by the average monthly demand for the fiscal year in which Month M occurs. If such ratios do not exceed 3.0,

4.5 or 7.0, respectively, the Commission shall deliver enriched uranium specified by such customers for delivery in Month M in that month. If one or more of such ratios are exceeded, but do not in turn exceed 4.0, 5.5 or 8.0, respectively, the Commission may deliver such enriched uranium in the period covered by Month M and the next succeeding month. If one or more of the immediately preceding ratios are also exceeded, but do not in turn exceed 5.0, 6.5 or 9.0, respectively, the Commission may deliver such enriched uranium in the period covered by Month M and the next two succeeding months. The above test process shall be continued, increasing each test ratio and the number of months over which the Commission may deliver such enriched uranium by one unit and one month at each step, to determine the maximum period of months over which the Commission may agree to deliver enriched uranium requested by customers to delivered in Month M. Unless otherwise agreed, and except for the circumstances set forth hereinbelow, deliveries of feed material to the Commission shall precede related deliveries of enriched uranium to the Customer from 90 to 180 days, as the Commission may elect. Should ratio (c) above--i.e., the total amount of enriching services specified to be associated with enriched uranium reuqested to be delivered during the period Month M plus the preseding 5 months divided by the average monthly demand--be less than 3.0, the Commission may, by 30 days prior written notice, require customers who are to be furnished enriched uranium in months of the fiscal year subsequent to Month M, as indicated by amounts of enriching services in their Appendices "A" not yet specified to be associated with enriched uranium scheduled for delivery in a given month, to furnish notice of the enriching services associated with their monthly requirements of enriched uranium more than 315 days prior to the beginning of the monthly period when such enriched uranium is desired to be delivered and also may require such customers to specify the associated quantities and assays of enriched uranium to be delivered to the Customer and feed material to be delivered to the Commission and to deliver associated feed material to to the Commission more than 180 days in advance of related deliveries of enriched uranium. In such cases, the number of days in excess of 315 for notice by the Customer, in excess of 240 for responding notice by the Commission, and in excess of 180 for advance delivery of feed material by the Customer and for specification by the Customer of associated quantities and assays of enriched uranium to be delivered to the Customer and feed material to be delivered to the Commission shall all be increased equally as determined by the Commission. Such increased periods shall remain in effect for deliveries of enriched uranium being scheduled for succeeding months until ratio (c) above again equals or exceeds 3.0, at which time the previous minimum times for notices (315 and 240 days) and maximum time for feed material deliveries and minimum time of notice for specification of quantities and assays of enriched uranium and feed material (180 days) shall be restored, beginning with the next month to be scheduled. Notice of such restoration shall be furnished by the Commission to affected customers. Except as provided hereinabove and in Section 8. below, at least 180 days prior to the firm delivery date or dates for the delivery of enriched uranium, the Customer shall by written notice to the Commission specify the specific associated quantities (kg U) and assays (weight percent U-235) of enriched uranium to be delivered to the Customer and feed material to be delivered to the Commission. In no event shall the maximum assay of enriched uranium to be delivered by the Commission exceed the maximum assay indicated to be so available in the established Commission standard table of enriching services; nor shall the minimum assay of feed material to be delivered by the Customer be less than the minimum assay indicated in such table.

8. In the event the Customer wishes to obtain, during any fiscal year, enriched uranium in such quantities (kg U) and assays (weight percent U-235) that would exceed that obtainable, pursuant to the established Commission standard table of enriching services, from the enriching services specified for such year in the Appendix "A", and to the extent that the Commission does not agree to furnish such additional enriching services such that the desired enriched uranium could be obtained pursuant to such table, the Customer may elect to obtain such additional enriched uranium through the provision of additional feed material to the Commission and the payment of a service charge to the Commission pursuant to Section 7. above, specifying the desired monthly period or periods within any fiscal year in which the enriched uranium associated with the enriching services scheduled for such year in Appendix "A" is to be delivered and the amount of such enriching services to be furnished, shall also specify the desired quantities and assays of the enriched uranium to be furnished to the Customer during such monthly period or periods and quantities and assays of feed material available for delivery to the Commission in accordance with Appendix "C". The Commission's notice to the Customer pursuant to Section 7. above shall then also specify the quantities and assays of feed material to be delivered to the Commission. If requested, the Commission shall advise the Customer, in advance of the Customer's election, of the quantities and assays of feed material to be delivered by the Customer and of the amount of the service charge to be paid by the Customer. The amount of feed material to be

delivered by the Customer and of the amount of the service charge to be paid by the Customer. The amount of feed material to be delivered by the Customer shall be determined by the Commission in accordance with the provisions and procedures set forth in Appendix "C".

9. It is recognized that deliveries of enriched uranium to the Customer or of feed material to the Commission may vary slightly from the quantity or assay intended to be delivered. It is agreed that variations in (i) quantities of material delivered of not greater than 0.50% in case of material of not more than 5% assay (weight percent U-235) and not greater than 0.25% in case of material of greater than 5% assay (weight percent U-235), and (ii) assay within the variations permitted by the Commission's established specifications shall be acceptable; provided, however, that in the event the quantity of feed material actually furnished and acceptable hereunder in less than that required under the established Commission standard table of enriching services to obtain the quantity and assay of enriched uranium actually delivered to the Customer or, where applicable, less than that required pursuant to Section 8. above, even though within the foregoing permissible variations, the Customer shall pay the Commission charges determined in accordance with the established Commission pricing policy for the additional feed material; and provided further, that in the event the quantity of feed material actually furnised and acceptable hereunder is yreater than that required, under the established Commission standard table of enriching services or, where applicable, greater than that required pursuant to Section 8. above, to obtain the quantity and assay of enriched uranium actually delivered to the Customer, such excess feed material shall, at the election of the Customer, either be retained by the Commission and applied against future deliveries feed material or delivered to the Customer at the Customer's expense, and the excess feed material shall not be taken into consideration in determining the amount to paid to the Commission. Feed material furnished in excess of the amounts acceptable hereunder shall, unless otherwise agreed, be delivered to the Customer at the Customer's expense. Any change in such Standard Table shall require at least 540 days days' notice to the Customer by publication in the Federal Register or otherwise.

10. All feed material to be furnished to the Commission and all enriched uranium to be delivered to the Customer hereunder shall be in the form of UF_6 and conform to the Commission's established specifications for such material. Any changes in such specifications shall require at

least 180 days' prior notice to the Customer by publication in the Federal Register or otherwise. Determinations of the quantities and properties of all such material delivered by or to the Commission shall be made in accordance with the provisions of this agreement. Upon final determination that any such material is not of the assay required by this agreement or does not conform to the Commission's established specifications for such material, the supplier of such material shall thereupon promptly elect either to (a) remove the rejected material, or (b) provide the receiver with instructions for its disposition. Any such removal or other disposition in accordance with (a) or (b) or the preceding sentence shall be at the expense of the supplier, and the supplier shall reimburse the receiver for the reasonable cost of disposing of such material. Where the receiver is the Commission, such reasonable cost shall be determined in accordance with the established Commission pricing policy.

11. Except as may be otherwise authorized by the provisions of the Federal Register Notice entitled "Uranium Enrichment Services Criteria," 38 F.R. 12180, May 9, 1973, as the same may be amended from time to time, feed material of foreign origin shall not be furnished by the Customer hereunder if the enriched uranium to be obtained from the Commission hereunder is intended for use in a utilization facility, as defined in the Act, within or under the jurisdiction of the United States.

ARTICLE III-CHARGES FOR ENRICHING SERVICES-OTHER CHARGES

1. The charges to be paid to the Commission for enriching services provided to the Customer hereunder shall be determined in accordance with the established Commission pricing policy for such services.

2. It is recognized that the Commission may, from time to time, during the term of this agreement, either increase or decrease its unit charge for enriching services. Any increase in such charge shall require at least 60 days' notice to the Customer by publication in the Federal Register or otherwise.

3. In addition to the charges to be paid for enriching services, the Customer shall pay the Commission's service charges, if any, for withdrawal, handling and packaging of enriched uranium, for storage of feed material to be applied against future deliveries of feed material, and for any other special service rendered, at the Customer's

request, in connection with providing enriching services hereunder, as determined in accordance with the established Commission pricing policy. The Customer shall also pay such rental charges on any AEC-owned containers and equipment furnished hereunder as may be provided elsewhere in this agreement.

ARTICLE IV-COMMISSION FACILITY PROVIDING ENRICHING SERVICES-POINT OF DELIVERY FOR FEED MATERIAL

All materials delivered or returned to the Customer shall be furnished by, and feed material furnished to the Commission shall be delivered to, the Commission facility or facilities specified by the Commission from time to time by written notice to the Customer at least sixty (60) days in advance of the relevant delivery dates specified in this agreement. Enriching services may be performed in whole or in part at the same or other facilities.

ARTICLE V-WARRANTY OF FEED MATERIAL FURNISHED BY CUSTOMER-INDEMNITY

The Customer warrants that all feed material furnished to the Commission hereunder is of the assay required by this agreement and conforms to the Commission's established specifications for such material. Notwithstanding the provisions of the article entitled "Force Majeure," the Customer shall hold and save the Government, the Commission, and persons acting on behalf of the Commission, harmless from any and all damages, liabilities and costs arising out of or in connection with a breach of this warranty; provided, however, that the Customer shall not be responsible for any damage, liability or cost (1) which would have been incurred even if the Customer had not breached this warranty, or (2) which is incurred subsequent to final acceptance of such feed material by the Commission. The Customer shall in no event be liable for indirect or consequential damages, and nothing contained herein shall deprive the Customer of any rights under Indemnification agreements entered into pursuant to Section 170 of the Act.

ARTICLE VI-CUSTOMER'S OPTION TO ACQUIRE TAILS MATERIAL

1. It is recognized that the performance of enriching services such as those provided hereunder results in the generation of tails material. The Customer shall have an option, exercisable upon written notice to the Commission at least 90 days prior to the scheduled delivery of the

related quantity of enriched uranium, to acquire tails material from the Commission (but not necessarily tails material resulting from feed material furnished by the Customer) in accordance with the terms and conditions as hereinafter set forth. Tails material subject to the Customer's option but not elected to be taken as provided above shall remain the property of the Government.

2. In the event the Customer elects to exercise its option to acquire tails material from the Commission, the written notice so advising shall specify the quantity (kg U) of tails material desired. The maximum quantity of tials material to be subject to the Customer's option shall be equal to the difference between the total quantity of uranium supplied by the Customer as feed material and the total quantity of enriched uranium furnished to the Customer; provided, however, that the maximum quantity so calculated shall be reduced to the extent of processing losses as determined by the Commission. The U-235 assay of tails material delivered to the Customer shall be within the sole discretion of the Commission.

3. Unless otherwise agreed, delivery of tails material shall be at the same time as delivery of related enriched uranium to the Customer.

4. Unless otherwise agreed, all tails material delivered to the Customer hereunder shall be in the form of UF_6 and shall conform to the Commission's established specifications for such material. The quantity and properties of tails material shall be determined in accordance with the provisions of this agreement.

5. It is recognized that deliveries of tails material to the Customer may vary slightly from the quantity intended to be delivered. It is agreed that variations in the quantity of tails material delivered of not greater than 0.50% shall be acceptable.

6. Except as provided in Section 7. below, no charge will be made in connection with furnishing tails material to the Customer. The Customer shall receive no credit for tails material subject to its option but not taken.

7. The Customer shall pay the Commission's service charges, if any, for withdrawal, handling and packaging, and for any other special service rendered, at the Customer's request, in connection with furnishing tails material hereunder, as determined in accordance with the established Commission pricing policy. The Customer shall pay all such

rental charges on any AEC-owned containers and equipment furnished hereunder as may be provided elsewhere in this agreement.

ARTICLE VII-TERM OF CONTRACT

The term of this agreement shall commence as of the date of execution thereof and continue for a period of thirty (30) years from the beginning of the fiscal year in which the first delivery is scheduled to be made hereunder, unless sooner terminated in accordance with the agreement terms.

ARTICLE VIII-ADVANCE PAYMENT-PAYMENT

1. The Customer shall make an advance payment for enriching services to be furnished hereunder in the amount of __________. Such advance payment is determined by multiplying the upper limit of the gross Mwe range specified in Article II, Section 2., by $3,300.00. The advance payment shall be made to the Commission. In three annual installments of equal amounts, the first such installment to be paid upon execution of this agreement, and the remaining installments to be paid not later than the first and second anniversary dates of the execution of the agreement. The Commission shall submit invoices to the Customer for advance payment installments. In the event the rated Mwe generating capacity of the designated facility is greater than the upper limit of the gross Mwe range upon which the advance payment was determined and the Commission elects pursuant to subsection 2.b. of Article II to increase the upper gross Mwe limit contained in subsection 2.a. of Article II, the advance payment amount specified above shall be increased to the amount determined in accordance with the above formula to be the advance payment amount associated with the rated Mwe generating capacity of the designated facility. The Customer shall pay to the Commission any additional annual installment amounts due as a result of the increased advance payment to be made by the Customer and interest on such amount from the date such annual installment amount was originally due the Commission until the date of payment at the per-annum rate (365-day basis) established from time to time by the Commission for general application to monies due the Commission. In the event the rated Mwe generating capacity of the designated facility is less than the lower limit of the gross Mwe range specified in subsection 2.a. of Article II, only the advance payment amount associated with the rated Mwe generating capacity of the designated facility as determined by multiplying such generating capacity by $3,300.00 will be credited against the initial

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amounts due the Commission for enriching services furnished the Customer hereunder; provided, however, any annual installment amount which would have been required if the advance payment amount had been determined initially upon the basis of the actual rated Mwe generating capacity of the designated facility. Except as otherwise provided above and in Sections 1. and 3. of Article IX in the event of termination or, if authorized by the Contracting Officer, assignment of this agreement by the Customer, the installments of the advance payment shall be credited against the initial amounts due the Commission for enriching services furnished to the Customer hereunder.

2. The Customer shall pay to the Commission the charges stated in Article III hereof for enriching services furnished to the Customer hereunder. Except as otherwise provided for advance payment installments, all such payments shall be made within thirty (30) days from the date of the Commission's invoice. The Commission shall submit an invoice for the charges stated in Article III promptly upon each shipment of enriched uranium to the Customer. In the event of disagreement as to the quantities or properties of uranium delivered by or to the Customer, provisional payments shall be made on the basis of the Commission's figures, and appropriate adjustments in amounts paid made promptly upon resolution of such disagreements in accordance with the provisions of this agreement.

3. Any other amounts due the Commission under this agreement shall be paid within thirty (30) days after the date of invoice therefor in accordance with instructions furnished with such invoice.

4. Remittances shall be payable to the United States Atomic Energy Commission and, unless otherwise directed by the Commission, shall be sent to the Director, Finance Division, United States Atomic Energy Commission, P.O. Box E, Oak Ridge, Tennessee 37830.

5. The Customer shall pay interest at the per-annum rate (365-day basis) established from time to time by the Commission for general application to monies due the Commission on all amounts not received by the Commission on or before the due date; except that, whenever the due date for any payment under this article falls on a Saturday, a Sunday, or a legal holiday, interest shall commence on the day immediately following the next day which is not a Saturday, Sunday, or a legal holiday.

ARTICLE IX - TERMINATION - SUSPENSION

1. In addition to any other rights the Commission may have, the Commission reserves the right, at no cost to the Government, to terminate or suspend this agreement, by written notice to the Customer, in the event (i) the Customer's right to possess enriched uranium to be delivered to the Customer hereunder expires or is suspended or terminated by any authority having power to take such action; (ii) the Customer shall fail to perform its obligations hereunder, and shall fail to take corrective action within 30 days of the date of the written notice of such failure to perform as provided above, unless such failure arises out of causes beyond the control and without the fault or negligence of the Customer, its contractors or agents; or (iii) bankruptcy or insolvency proceedings are commenced by or against the Customer, or if receivers are appointed to take possession of the business of the Customer. The Commission may also terminate this agreement in whole or in part at no cost to the Government, upon reasonable written notice to the Customer, at such times as commercial enriching services are provided by another domestic source; provided, however, that the Commission will, upon request made not later than 365 days after the Commission will, upon request made not later than 365 days after the Commission notice of termination, rescind the notice of termination and will continue performance of this agreement if the services of the domestic source are not available to the Customer: (a) to the extent provided for in this agreement by the Commission pursuant to the provisions of the immediately preceding sentence, the Commission shall return any advance payment amounts received from the Customer which have not been credited against amounts due the Commission for enriching services furnished to the Customer hereunder.

2. This agreement may be terminated either in whole or in part by the Customer at any time by delivery to the Commission of a written notice of termination stating the date after receipt of the notice upon which such termination shall become effective.

3. Upon termination of this agreement by the Commission pursuant to (i), (ii), or (iii) of Section 1. of this article or by the Customer pursuant to Section 2. of this article, the Customer shall pay to the Commission a termination charge. Applicable charges for termination based on the period of notice given will be those in effect at the time of receipt of the notice of termination as published in the Federal Register; provided, however, in the event

the rated Mwe generating capacity of the designated facility is less than the lower limit of the gross Mwe range specified in subsection 2.a. of Article II, such an event shall constitute a partial termination of this agreement by the Customer and the difference between the sum of the installments of the advance payment paid or due and the sum of the comparable installments of the advance payment associated with the rated Mwe generating capacity of the designated facility as determined by multiplying such generating capacity by $3,300.00 shall constitute the entire termination charge hereunder for such partial termination; provided, further, in the event the Customer terminates this agreement prior to receipt of the construction permit from the appropriate regulatory body for the designated facility, any advance payment amounts already paid by the Customer at the time of such termination plus any advance payment installment for which payment is due and outstanding, as provided in Section 1. of Article VIII, shall constitute the entire termination charge hereunder. In lieu of such latter termination, however, the Customer may assign this agreement if authorized by the Contracing Officer, as provided in Paragraph 8 of the General Terms and Conditions, in which event the advance payment shall be credited against the initial amounts due the Commission for enriching services furnished to the assignee. The enriching services charges applicable to the terminated enriching services shall be determined in accordance with the established charges for enriching services in effect on the date of receipt of the notice of termination; provided, however, that in the event revisions in the Standard Table, revisions in the established charges for enriching services, and/or automatic periodic changes in the enriching services charges have been announced and are to become effective subsequent to receipt of the notice of termination, the kg units of separative work and the enriching services charges applicable to the terminated enriching services which, but for such termination, would have been furnished under this agreement on and after the effective date of such revision or automatic periodic changes shall be determined in accordance with such revised Standard Table and/or revised or automatic periodic changes in charges for enriching services. Upon request of the Customer prior to its delivery of a notice of termination, the Commission will advise the Customer of the approximate amount of termination charges which would become payable by the Customer hereunder in the in the event of termination by the Customer.

4. Unless otherwise agreed, upon termination of this agreement, feed material delivered by the Customer for the performance of the enriching services so terminated or, to

the extent such feed material is unavailable to the Commission pricing policy shall be returned to the Customer at the Customer's expense.

ARTICLE X - AMENDMENTS

The provisions of this agreement have been developed in the light of the uncertainties necessarily attendant to long-term agreements. Accordingly, at the request of either the Commission or the Customer, the parties will negotiate and, to the extent mutually agreed, amend this agreement without additional consideration to eliminate or reduce restrictive provisions which the parties determine are inequitable, discriminatory or no longer required to protect their interests; provided, however, any such amendment shall be consistent with the provisions of the Federal Register Notice entitled "Uranium Enrichment Services Criteria," 38 F.R. 12180, May 9, 1973, as the same may be amended from time to time.

ARTICLE XI - NOTICES

All notices and communications pursuant to this agreement from either party to the other (except notices published in the Federal Register) shall be in writing and shall be sent to the following addressees:

To the Commission: Director
Uranium Enrichment Operations Division
United States Atomic Energy Commission
Post Office Box E
Oak Ridge, Tennessee 37830

ARTICLE XII - GENERAL TERMS AND CONDITIONS - CONFLICTS

1. The General Terms and Conditions attached hereto are hereby made a part of this agreement.

2. In the event of any conflict between the articles of this agreement and the attached General Terms and Conditions, the former shall govern.

IN WITNESS WHEREOF, the parties hereto have executed this agreement as of the day and year first above written.

UNITED STATES OF AMERICA

BY: UNITED STATES ATOMIC ENERGY COMMISSION

BY: ______________________

____
(Contracting Officer)

CUSTOMER: ________________

BY: ______________________

TITLE: ___________________

APPENDIX "A"

2. ENRICHING SERVICES SCHEDULE

Kg Units of Separative Work	Delivery Date(Fiscal Year)
137,800	Date A through end of 1981(First Core-spare fuel assemblies)
105,600	Beginning of 1982 through Date B(First Core-spare fuel assemblies)
0	Date B through end of 1982
146,200	1983
137,900	1984
105,200	1985
133,800	1986
106,800	1987
95,600	1988
101,900	1989
101,900	1990

APPENDIX "B"

1. MATERIAL SCHEDULE - UNIT I

Fiscal Year of Delivery of Product	Enriched Uranium Product: Assay w/o U-235	Enriched Uranium Product: Total Uranium-Kg	Separative Work Units
1981	2.00	27,114	59,500
1981	2.36	26,669	78,300
1982	2.97	24,891	105,600
1983	3.49	27,114	146,200
1984	3.39	26,669	137,900
1985	3.56	18,959	105,200
1986	3.56	20,509	113,800
1987	3.56	19,247	106,800
1988	3.56	17,229	95,600
1989	3.56	18,364	101,900
1990	3.56	18,364	101,900

APPENDIX "C"

1. COMMISSION DETERMINATION OF ADDITIONAL FEED MATERIAL REQUIREMENTS

A. Data to be supplied to the Commission by the Customer:

i) the quantities and assays of enriched uranium delivered, and the desired delivery schedule;

ii) the amount of the enriching services specified in Appendix "A" (for the fiscal year containing the month of delivery) which is to be applied to the aforementioned enriched uranium; and

iii) a listing1/ of the quantities and assays of feed material available for producing the enriched uranium.

B. Procedure for Commission determination of quantities of feed material to be delivered by the Customer:

i) determine the pro rata portion of the enriched uranium to be delivered which can be supplied under the Standard Table2/ (i.e., transaction tails assay) utilizing:

a) the amount of enriching services to be applied to the desired enriched uranium; and

b) the associated quantities and assays of feed material that would be required pursuant to the Standard Table and in accordance with the order of preference specified by the Customer.

1/ The listing of the available feed materials provided by the Customer should be in decreasing order of preference of use, with the quantity of feed material of lowest preference specified "as necessary."

2/ This refers to the Standard Table to be in effect at the time of delivery of the enriched uranium.

ii) determine the separative work and the amount of additional normal uranium[3] (i.e., in excess of the quantities and assays of feed material required pursuant to the Standard Table, as determined in i) above) that would be required to provide such pro rata portion of the enriched uranium on the basis of Commission's projection of the operating tails assay[4] for the month of delivery.

The resultant separative work requirement is the amount which will be taken to be available for use in providing the total enriched uranium to be delivered. The additional normal uranium requirement is the Commission's feed material contribution under the "split tails" mode of operation. These two requirements remain fixed and define the transaction that is consistent with the Standard Table and the Appendix "A".

iii) determine the additional feed material[5] requirements necessary to provide the total enriched uranium to be delivered utilizing:

a) the separative work requirement at the Commission's projected operating tails assay, as determined in ii) above;

b) the Commission's feed material contribution, if any, as determined in ii) above; and

c) the quantities and assays of feed material required pursuant to the Standard Table, as determined in i) above.

3/ Uranium having an assay of 0.711 weight percent U-235.

4/ If the transation and operating tails assays are equal, the separative work requirement is the same as the amount specified by the Customer under the Standard Table and the normal uranium contribution by the Commission is zero.

5/ This procedure continues to use the quantities and assays of available feed material in decreasing order of preference.

This is an iterative procedure which results in a revised operating tails assay that utilizes only the separative work (and Commission feed material contribution under "split tails") purchased by the Customer. The total feed material requirements to be supplied by the Customer include both the feed material consistent with the Standard Table and the additional feed material required at the revised operating tails assay.

C. Relationships used in Commission determination of quantities of feed material to be delivered by the Customer:

The following expressions, and relationships derived from the following expressions, are used in the determination of feed material to be delivered by the Customer:

I) $P + W = F$ (Uranium Balance);

II) $Px_p + Wx_w = Fx_f$ (U-235 Balance);

III) $SW = Pv(x_p) + Wv(x_w) - Fv(x_f)$

(Separative Work Equation or "Value" Balance);

where (a) P, W, and F are the quantities of product (or enriched uranium), tails material, and feed material, respectively; (b) x_p, x_w, and x_f are the assays (wt. percent U-235) of the product, tails, and feed, respectively, and; (c) $v(x)$ is the unit "value" of material of assay x as defined by

$$v(x) = (2x-1) \ln (x/(1-x)).$$

The above expressions can be expanded to cover cases where there are more than one assay for product and/or feed material.

EXAMPLE OF COMMISSION DETERMINATION OF ADDITIONAL FEED MATERIAL REQUIREMENTS

Data From Customer:

	Quantity (kg U)	Assay (wt. % U-235)
1. Enriched Uranium	8,000	3.0
	5,000	2.9
2. Available Feed Material (decreasing order of preference of use)	12,500	0.85
	"as necessary"	0.711

3. Apply 45,000 SWUs to the enriched uranium listed above.

Other Data:

Assay (wt. % U-235)	Feed Component (F/P) (normal kgU feed/ kgU product)	Sep. Work Component (kg SWU/kgU product) (SW/P)
(Based on Standard Table with Transaction Tails Assay of 0.2%)		
3.0	5.479	4.306
2.9	5.284	4.088
0.85	1.272	0.168
0.711	1.000	0
(Based on Projected Operating Tails Assay of 0.3%)		
3.0	6.569	3.425
2.9	6.326	3.245
0.85	1.338	0.115
0.711	1.000	0

CALCULATION:

I) Pursuant to the Standard Table (0.2% tails assay), the work requirement for the total amount of enriched uranium would be

(8000(4.306) + 5000(4.088)) - (12,500(0.168)) = 52,788 SWUs

Enriched U Requirement   Feed Material Credit but only 45,000 SWUs are avilable. The pro rata portion of the total enriched uranium which could be provided under the Standard Table is determined using the following equation:

X(8000(4.306+5000(4.088))-(12,500(0.168))=45,000 SWUs

The fraction X is equal to .85811, hence the pro rata portion of enriched uranium is 8000X or 6864.9 kgUs of 3.0% product and 5000X or 4290.6 kgUs of 2.9% product. The "as necessary" feed material required for these quantities of enriched uranium would be

(6864.9(5.479)+4290.6(5.284))-(12,500(1.272))=44,384 kgUs of 0.711% assay feed

This, combined with the 12,500 kgUs of 0.85% assay feed, would represent the feed material necessary for providing the pro rata potion of enriched uranium in accordance with the Standard Table.

II) The separative work and additional normal (0.711%) uranium requirements for the pro rata portion of the enriched uranium which are based on the Commission's projected operating tails assay (0.3%) are

Separative Work =
(6864.9(3,425)+4290.6(3.425))-(12,500(0.115)+44,384 (0))=35,998 SWUs

Normal U =
(6864.9(6.569)+4290.6(6.326))-(12,500(1.338)+44,384 (1.0)) 11,129 kgUs

The separative work requirement is the amount assumed to be available for providing the total enriched uranium to be delivered. The 11,129 kgUs of normal uranium is the AEC's feed contribution under the "split tails" mode of operation.

III) In order to find the revised operating tails assay that would yield the total enriched uranium requirement utilizing 35,998 SWUs of separative work, the following equation is established:

$(8000(SW/P)_{3.0,XW}=5000\ (SW/P)_{2.9,XW})-(12,500(SW/P)_{.85,XW})\ 35,998$ SWUs where $(SW/P)_{Y,XW}$ is the separative work component per unit product, of assay Y, at a tails assay of XW.

For a given product assay, (SW/P) is a complicated function of tails assay, consequently the above equation must be solved by iteration, that is by repeatedly trying different values of XW until both sides of the equation are equal. In this case, the calculated value of the revised operating tails is about .3873%. The additional feed material is then determined by using the following equation:

$$8{,}000\ (F/P)_{3.0,XW} + 5000(F/P)_{2.9,XW} - 12{,}500\ (F/P)_{.85,XW} + 44{,}384 + 11{,}129 = \text{kgUs of additional } 0.711\%\ \text{Assay feed,}$$

where $(F/P)_{Y,XW}$ is the normal feed component per unit product, of assay Y, at a tails assay of XW.

For the revised operating tails assay of .3873%, the additional feed material is about 30,016 kgUs. The following would be the total amount of feed material to be supplied by the Customer:

Assay (wt. % U-235)	Quantity (kgUs)
0.85%	12,500
0.711%	44,384 + 30,016 = 74,400

GENERAL TERMS AND CONDITIONS

(Agreement for Furnishing Uranium Enrichment Services)

1. Officials Not to Benefit. No member of or delegate to Congress, or resident commissioner, shall be admitted to any share or part of this agreement, or to any benefit that may arise therefrom; but this provision shall not be construed to extend to this agreement if made with a corporation for its general benefit.

2. Covenant Against Contingent Fees. The Customer warrants that no person or selling agency has been employed or retained to solicit or secure this agreement upon an agreement or understanding for a commission, percentage, brokerage, or contingent fee, excepting bona fide employees or bona fide established commercial or selling agencies maintained by the Customer for the purpose of securing business. For breach or violation of this warranty the Government shall have the right to annul this agreement without liability or in its discretion to deduct from the agreement price or consideration, or otherwise recover, the full amount of such commission, percentage, brokerage, or contingent fee.

3. Force Majeure. Neither the Government nor the Customer shall be liable under this agreement for damages occasioned by failure to perform its obligations hereunder if such failure arises out of causes beyond the control and without the fault or negligence of the party so failing to perform or its contractors or agents.

4. Limitation on Commission's Liability. The Commission's obligation to deliver both enriched uranium and tails material of the assay required by this agreement and conforming to the Commission's established specifications shall be deemed to have been satisfied (except as to claims arising out of unexcused delays in delivery) upon final acceptance of such material by the Customer.

5. Disclaimer. Neither the Government, the Commission, nor persons acting on behalf of the Commission warrant that materials delivered to the Customer under this agreement (i) will not result in injury or damage when used for any purpose, or (ii) are of merchantable quality, or (iii) are fit for any particular purpose.

6. Patent Indemnification. The Customer agrees to indemnity the Government, the Commission, and persons acting on behalf of the Commission against liability, including costs and expenses incurred, for infringement of any Letters Patent occurring in the performance of any service, analysis, or test performed for the Customer as a result of following specific instructions of the Customer in connection therewith, or occurring in the utilization by the Customer of any material procured hereunder; provided, that insofar as such materials are used or services utilized in the performance of a Government contract, this indemnity agreement shall not apply unless such Government contract contains provisions indemnifying the Government against patent infringement.

7. Disputes.

   a. Except as otherwise provided in this agreement, concerning a question of fact arising under this agreement which is not disposed of by agreement shall be decided by the Contracting Officer, who shall reduce his decision to writing and mail or otherwise furnish a copy thereof to the Customer. The decision of the Contracting Officer shall be final and conclusive unless, within thirty (30) days from the date of receipt of such copy, the Customer mails or otherwise furnishes to the Contracting Officer a written appeal addressed to the Commission. The decision of the Commission or its duly authorized representative for the determination of such appeals shall be final and conclusive unless determined by a court of competent jurisdiction to have been fraudulent or capricious, or arbitrary, or so grossly erroneous as necessarily to imply bad faith, or not supported by substantial evidence. In connection with any appeal proceeding under this article, the Customer shall be afforded an opportunity to be heard and to offer evidence in support of its appeal. Pending final decision of a dispute hereunder, the Customer shall proceed diligently with the performance of the agreement and in accordance with the Contracting Officer's decision.

   b. This "Disputes" article does not preclude consideration of law questions in connection with decisions provided for in Section a., above; provided, that nothing in this agreement shall be construed as making final the decision of any administrative official, representative, or board on a question of law.

8. Assignment. Neither this agreement nor any interest claim thereunder shall be assigned or transferred by the Customer except as expressly authorized in writing by the Contracting Officer.

9. Delivery - Title.

a. All material delivered or returned to the Customer hereunder shall be delivered to the Customer, f.o.b Customer's vehicle or commercial conveyance, at the Commission facility from which such material is to be furnished. Title to such material shall pass to the Customer upon delivery at such point.

b. All material delivered or returned to the Commission hereunder shall be delivered to the Commission, f.o.b. Customer's vehicle or commercial conveyance, at the Commission facility to be designated by the Commission. The Customer, at the time of shipment of material, shall notify the Commission of the date and method of shipment, and expected date of arrival. Title to such material shall pass to the Government upon delivery at such point, provided that title to any rejected material removed by the Commission pursuant to Section 9. of Article II hereof shall pass to the Government upon such removal.

10. Fulfillment of Obligations Through Operator. The Customer understands and agrees that the Commission may fulfill its obligations under this agreement through the operator of any of its facilities. No such operator is authorized to modify the terms of this agreement, waive any requirement thereof, or settle any claim or dispute arising hereunder.

11. Permits--Laws, Regulations and Ordinances. The Customer shall procure all necessary permits or licenses (including any special nuclear material licenses) and comply with all applicable laws, regulations, and ordinances of the United States and of any State, territory or political subdivision.

12. Containers and Equipment.

a. All shipments of material from the Commission to the Customer and from the Customer to the Commission, will be made in Customer-furnished containers; provided, hwoever, that in the event the Commission determines that the required containers are not reasonably available from commercial sources, the Commission may furnish such containers. Any AEC-owned containers to be used for shipment of material to the Commission will be made available to the Customer, f.o.b. Customer's vehicle or commercial conveyance, at a Commission facility designated by the Commission, unless otherwise agreed. Customer-furnished containers and equipment shall be delivered to a Commission facility designated by the Commission within a reasonable time specified by the Commission prior to the scheduled delivery of materials to be shipped to the Customer in such containers and equipment. Customer-furnished containers or equipment will be used by the Commission only for the shipment of material from the Commission to the Customer and for temporary storage of material shipped therein.

b. All containers and equipment, whether AEC-owned or Customer-furnished, must meet Commission regulations, specifications and practices as to safety, design criteria, cleanliness and freedom from contamination in effect at the time furnished, utilized or returned, of which the Commission shall be the sole judge. In the event feed material is furnished to the Commission in non-AEC-owned containers and tails material is to be delivered to the Customer, the Commission shall utilize to the extent practicable such non-AEC-owned containers for shipments of tails material if so desired by the Customer. The Commission will promptly return non-AEC-owned containers and other equipment identified as "Returnable" to the Customer, but will not be responsible for any loss of or damage to such containers or equipment except as may result from the fault or negligence of the Commission, its contractors, or agents. Such return shipments by the Commission will be made f.o.b. Customer's vehicle or commercial conveyance at the Commission facility to which they were shipped.

c. Title to AEC-owned containers and equipment shall remain in the Government. Customer shall pay such rental charge, for such containers and equipment as shall be established by the Commission for general application to users of such AEC-owned property. The Customer will promptly return AEC-owned containers and equipment to the Commission facility from which received, f.o.b. Customer's vehicle or commercial conveyance at the Commission facility. Customer will not be responsible for any loss of or damage to AEC-owned containers or equipment except as may result from the fault or negligence of the Customer, its contractors, or agents. AEC-owned containers or equipment will be used only for shipment of material to and from the Commission and for temporary storage of material shipped therein.

d. Whenever material or containers are shipped to the Commission or AEC-owned containers are returned to the Commission, and the Commission elects to decontaminate the containers, railroad cars, trucks or other shipping vehicles or the Commission's unloading area and machinery, because the containers, or the material or the method of shipment failed to meet the health and safety standards prescribed by the Commission or any other Federal or State agencies having jurisdiction over such matters, the Customer shall pay the Commission the full cost of such decontamination as determined by the Commission in accordance with established Commission pricing policy.

e. Whenever material or containers are shipped by the Commission and the Customer elects to decontaminate the containers, railroad cars, trucks, or other shipping vehicles or the Customer's unloading area and machinery, because the containers, or the material, or the method of shipment failed to meet the health and safety standards prescribed by the Commission or any other Federal or State agencies of the United States having jurisdiction over such matters, the Commission shall, if such failure results from the fault or negligence of the Commission, its contractors, or agents, pay the Customer for the reasonable cost of such decontamination as determined by the Commission.

13. <u>Determination of Material Quantities and Properties-Resolution of Measurement Differences</u>. The following

provisions and procedures shall apply to the determination of quantities and properties of material, and the resolution of measurement differences resulting from such determination, with respect to special nuclear material and tailsmaterial delivered to the Customer and with respect to feed material furnished by the Customer to the Commission. For the purposes of this article, the terms "supplier" and "receiver" shall refer to the Commission and the Customer as the case may be. The supplier will promptly furnish the receiver a statement of the quantities and properties of the material transferred including a statement of the gross weight of the container plus material and the tare weight of such container.

a. The Commission samples obtained at a Commission facility using the Commission's procedures will be the official samples and shall be binding upon the Commission, the Customer and the umpire unless the Commission and the Customer agree upon the use of other samples, procedures or sampling locations.

b. The following provisions and procedures apply to the determination of the net weight of material transferred as determined by the gross weight of the container plus material less the weight of such container and any residual heels. The net weight of material transferred shall be determined at a Commission facility using the Commission's procedures and facilities unless the Commission and the Customer agree upon other procedures or facilities. The net weight of feed material shall be determined as soon as operationally feasible but in any event prior to the transfer of associated enriched uranium. Upon written request submitted at least 30 days prior to the scheduled delivery of feed material, or at least 90 days prior to the scheduled delivery of enriched uranium, as the case may be, the Customer shall be given an opportunity to observe, at the Customer's expense, the weighing of the container and any residual heels and the container plus material and the taking of official samples by the Commission. The Commission shall notify the Customer of the dates and places for observance of such events. The net weight of material transferred shall be as determined by the results of such weighings and shall not be subject to the provisions of subsections c. and d. below.

c. If the receiver does not accept the supplier's of the other quantities and properties of the material transferred, the receiver shall within thirty (30) days after the receipt of the material or the supplier's statement of quantities and properties, whichever is later, submit a notice of disagreement in writing to the supplier. The notice of disagreement shall include measurement and/or analysis data supporting the disagreement. If such notice of disagreement is not submitted within such thirty (30) days, the supplier's measurements will be final and binding upon both parties. If the disagreement is solely with respect to qu ntitative determinations within specification limits, the receiver may use or dispose of the material in accordance with applicable State and Federal regulations prior to resolution of the disagreement. If the disagreement is with respect to whether the material is within specification limits, the receiver may handle the material as necessary for storage or protection against health and safety hazards; provided, however, should the rece ver further use or dispose of the material, the supplier's measurements will be final and binding on both parties. Any material rejected and returned to the Customer because of failure to meet specifications will be returned to the Customer because of failure to meet specifications will be returned without credit for samples removed.

d. In the case of a disagreement concerning results obtained from analysis of a sample which is not resolved by mutual agreement, an official sample shall be submitted to an umpire mutually agreed upon for analysis. The umpire's results shall be conclusive on both parties if such results are within the range determined by the receiver's and supplier's results. If the umpire's results are outside the range determined by the receiver's and supplier's results, the parties shall accept the party's results nearer to the umpire's results.

(i) In the case of a disagreement with respect to whether or not the material is within specification limits, and the supplier will pay the umpire cost if the umpire's result is not within specification limits.

(ii) In the case of a disagreement with respect to quantitative determinations within specification limits, the party whose result is furtherest from the umpire's result will pay the umpire cost; provided that in the event the umpire's result is equidistant between the supplier's and the receiver's results, the parties will each bear one-half of the umpire cost.

(iii) As used in this subsection d., the phrase, "umpire cost" means the umpire's charges, plus the additional cost, if any, of the packaging, handling, and transporting of the official sample to and from the umpire. In the event that the umpire is to employ an official sample for more than one determination as mutually agreed by the parties prior to the furnishing of the sample to the umpire, or in the absence of such agreement, as determined by the umpire.

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DECISION MODELS FOR OPTIMIZING FUEL ENRICHMENT SERVICES UNDER LONG-TERM FIXED-COMMITMENT CONTRACTS

by

Zeses Evangelos Karoutas

(ABSTRACT)

The purpose of this study is to construct and test decision models that will enable utility companies to identify cost effective strategies for dealing with enrichment service contracts. Specifically, three decision models are developed to analyze the 18 month decision points of the Long-Term Fixed-Commitment Contract for ten contracting years.

The first model indicates ERDA's current method for acquiring enrichment services assuming maintenance of the split-tails mode of enrichment plant operation. The second model, referred to as the static decision model, utilizes the variable tails concept at a single 18 month decision point. The third model uses the basic equations of the second model to develop a dynamic inventory system that is designed to manipulate the fuel inventories and tails enrichments at the 18 month decision points over ten years.

The application of the three decision models is done by using data from a typical ten year fuel contract for a 1000 Mwe reactor. A computer code is constructed to solve the decision models for the optimum decision policy in

contracting for fuel enrichment services.

The results indicate that the application of the dynamic inventory model produces a significant amount of savings in utility costs and uranium feed. The dynamic inventory process is more economical than the split-tails method because the utility company is allowed to manipulate the tails enrichment and the fuel inventories in the dynamic model. The dynamic inventory model appears to be an appropriate vehicle for improving the fixed-commitment contract and more study is merited.