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A SYSTEM OF CHAINED COMPUTER CODES FOR REACTOR FUEL CYCLE ANALYSIS

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A SYSTEM OF CHAINED COMPUTER CODES FOR REACTOR FUEL CYCLE ANALYSIS

The comparative evaluation of reactor fuel cycles is a complex problem in analysis, because, in addition to the sheer number of economic considerations, there are variations in fuel performance which are traceable to differences in cross sections, in neutron yield per fission, in heat liberation per fission, etc. Comparative evaluations based on a single performance factor such as the enrichment levels required to achieve a given exposure, or the exposures resulting from a given enrichment level, can be reported only when lengthy explanations and qualifications are attached. Reconciling such comparisons is further complicated by the inaccuracies inherent in theoretical calculations of fuel exposures and fuel depletion rates. The influence of such inaccuracies can be great because a fuel which may not even appear to reach criticality in one design may be superior in another. The effects of these inequities can be reduced by comparing fuel cycles at appropriately selected optimum operating points. The amounts of data, and the iterative procedures associated with such studies are so great that accurate and timely execution of the work is feasible only with fully automatic computers and data processing systems.

In 1961, when reactor burnup codes were still few and far between, we set out to calculate plutonium values in thermal reactors. Value calculations of this nature required burnup analyses of thermal reactor systems in which the fuel was either enriched uranium or a combination of uranium and plutonium. It also required an integrated economic analysis of these same systems so that the value could be determined by comparing the cost of a uranium fueled system with the cost of a recycle plutonium system. The codes used are listed on Slide I.

In order to complete a value calculation for each reactor type which was analyzed, about fifty burnup calculations were required for enrichments which reached exposures averaging 20,000 MWd/ton. Another set of fifty calculations was required for each of several variations of economic situations, fuel management schemes, lattice spacings, and fuel claddings for each reactor type. A total of approximately 7,500 burnup calculations were performed during the course of this one study.

To be able to make these 7,500 burnup calculations within a reasonable time, we were compelled to use a reactor burnup code that would be very rapid--one that would require less than about thirty seconds of machine time per case. This meant that we had to consider a burnup code which had a small number of groups, yet would give reliable results. This led us to develop MELEAGER, a burnup code which utilized the Westcott two-group cross section representation.

MELEAGER has since been modified to a four-group formalism. The calculation of the Westcott dilute g and s values in the SIGMA subroutine of MELEAGER is based on the neutron temperature from a preceding calculation. The effective s is computed by the single-level, narrow-resonance, infinite-mass absorber method using the concentration of the given isotope plus a fraction of the concentration of other isotopes with interfering resonances. Next, the portion of g in excess of 1.0 is reduced by the resonance integral correction factor just computed. The total thermal absorption cross section for the fuel is used to obtain the thermal flux depression needed for calculation of the effective value of g . The effective neutron temperature is computed, and the entire cross section calculation is repeated if necessary. The spectral index is essentially the ratio of the effective thermal absorption cross section of the cell divided by the slowing down power ($\xi\Sigma_s$) of the cell. However, the slowing down power must be reduced by a fraction of the resonance absorption cross section, especially in a reactor with a large epithermal reaction rate. Slowing down calculations in codes such as GAM have indicated that this fraction is about 0.8 in homogeneous systems, and we have found that still smaller values reproduce flux measurements and burnup data for heterogeneous systems. Reactivity, flux, and related data are then computed. The SIGMA subroutine of MELEAGER requires fifty to one hundred milliseconds per pass.

The actual burnup is conducted at constant flux and constant cross section by the Runge-Kutta technique, which amounts to a Simpson's rule integration of the rates of change of concentration of each isotope. The cross sections and decay constants are presented in two-dimensional arrays, in which the diagonal is the removal rate and the nondiagonals are the production rates from Isotope I to Isotope J. The third stage of the Runge-Kutta calculation provides a predicted concentration which is corrected in the fourth stage. We use this correction as an indication of precision. If the fractional value of this correction exceeds an input limit for any isotope, the time step is halved and the calculation repeated. If all are less than a lower limit, the time step will be doubled for the next calculation. Thus, small initial steps do not limit the speed later in the calculation. This subroutine requires one hundred to one hundred and fifty milliseconds per time step. Flux is recalculated at each time step, but an input number determines the number of time steps between cross section calculations. Output data not otherwise needed in the burnup calculation is computed only when required for writing to tape, and this is usually done while the preceding line is being transmitted.

In order to avoid the delays caused by transferring data from the burnup analysis into a code to do economic analysis, the two primary codes, MELEAGER and QUICK (each requiring over two-thirds of the

available 7090 memory space), where chained together. Since the start of the plutonium value studies, we have improved the system and added several more links to the chain. The system which has evolved from these efforts is shown in Slide II. The MELEAGER burnup code, which was zero-dimensional, has been expanded into a one-dimensional code; and optimization and report generating codes have been linked into the chain. Although the main use of this system is for surveys in which we make preliminary evaluations of concepts and outline the area where more intense investigation should be followed, the system must be capable of performing more exact and more detailed burnup calculations. For this reason, we have designed it so that we can substitute other burnup codes into it. The only requirement that another burnup code must meet is that it must produce a burnup data tape which is compatible with the rest of the system. The burnup tape contains the fuel concentrations, the heat produced, and a time reference at set intervals during the irradiation. Presently, at Battelle-Northwest, there are four burnup codes available which meet this requirement.

The ZODIAC system is one of the codes now being used at Battelle-Northwest. It uses a revision of GAM for the epithermal spectrum and is connected with the TEMPEST code for the thermal spectrum. It has one-dimensional capabilities with the diffusion calculation (HFN) and a burnup section called "ALCHEMY." This system, although more accurate

for certain cases then the MELEAGER code, requires approximately thirty minutes per burnup, whereas MELEAGER requires only five to thirty seconds per burnup. The ZODIAC coding system, although it requires more time, is used for detailed analyses; and the results are used to calibrate the constants which are used by the rapid burnup system to correct the neutron spectrum and some of the resonance shielding parameters. Recently, we have coupled the Battelle-Northwest basic cross section library to all of the codes in this fuel cycle analysis system which use cross sections. This library contains descriptions of the cross sections of four hundred isotopes. The descriptions consist of an arbitrary number of data sets which apply over specified energy ranges, each set takes one of four forms as a function of energy. These forms are linear, logarithmic, one-over-v, and Breit-Wigner. The G and S code computes the 2200 meter cross sections and the coefficients of a fourth order polynomial representation of g and s as functions of neutron temperature. It also computes the resonance and Doppler coefficients for shielding the dilute resonance integrals. Formulations of the GAM and TEMPEST libraries as well as the g and s parameters of the Westcott notation used in MELEAGER directly from the Battelle-Northwest nuclear data library is a feature which adds a very useful consistency to the entire analysis system.

To supplement the burnup code and to allow for rapid analysis, wholly external calculation of cell data is required. This is handled by the JASON code which, using the P-3 approximation to the transport equation, yields initial values of thermal utilization, fast effect, and the flux depression as functions of fuel blackness. This code also homogenizes the lattice and develops the required input parameters which are used to calculate the neutron spectrum and resonance shielding for a given cell in the MELEAGER code. The calculating time for this code is about two to five seconds.

To make this system still more reliable and to reduce user time in developing input, a case generating code has been developed which will define cases and produce the data required for economic analysis without requiring the user to make advance assumptions about the performance of a given fuel. In other words, the code called the SUPERCASE GENERATOR does not require that you tell it what fuel enrichments you would like run in order to supply suitable burnup data on tape to the economic system. Instead, you simply tell it the geometry and it will determine what enrichments should be run and define the cases for the burnup code, which then does the burnup calculations. If SUPERCASE finds that there are discontinuities in the data, it will automatically increase the density of the data around such discontinuities. If the user is interested in data over a particular range of, say, fuel exposures, fuel enrichments, or reactivities, he may increase the

importance weighting, or data density, in this range. During operation, the burnup code is under the control of the SUPERCASE code which defines two or three cases at a time. The burnup code then analyzes these cases. Then, based on these results, additional cases are defined by the SUPERCASE code to round out the burnup data as required to facilitate economic analysis.

Normally, the MELEAGER calculation is at constant local power, which is not truly representative of the behavior in a power reactor. In order to account for this, and to expand the applicability of this code, a code called PROTEUS analyzes and adjusts the burnup data to correct to flux conditions which are more realistic. PROTEUS curve fits all of the data on the burnup data tape against time, then adjusts the flux to an equivalent constant value and rewrites the burnup data tape. At the same time, because of the information this code has stored, it is also capable of performing a number of other services. PROTEUS, although using zero-dimensional burnup data, can calculate the average control requirement for a multiregion fuel irradiation. This is done by examining the reactivity of the fuel at various stages in its lifetime, and through proper integration of these data, determining the average loss of neutrons which must have occurred through either leakage or control system losses. Again, since curve fitted data exist, it is easy to terminate the calculation at some limit other than reactivity. For example, PROTEUS can determine

when heat transfer limits have been exceeded; and thus, superimpose engineering limitations on the physics limitations pertinent to the burnup code. One may also find that the leakage of the reactor may have been different than that which was initially used in the MELEAGER run. The final k_{eff} at which burnup was terminated can be adjusted by PROTEUS when it makes the new burnup data tape. In effect, a change in reactor size has been simulated without the necessity of rerunning the entire burnup. The PROTEUS code takes about one-third as long to generate any, or all, of these data as MELEAGER takes to do a complete burnup calculation.

In order to make valid comparative analyses of various reactor systems, it is necessary to make these comparisons between minimum cost operating conditions for each reactor. QUICK, the economics code, contains a subroutine for fuel cycle cost minimization, usually as a function of fuel exposure. With data from the burnup tape for a number of cases--each case calculated to some reactivity, power distribution, or heat transfer limited exposure--the fuel cost for a given economic environment is calculated. QUICK requires twenty milliseconds to complete the calculation of the total fuel cost for a given set of economic parameters. However, ten to eighteen economic parameter sets are often examined with the same burnup data. These data are curve fitted as a function of fuel exposure so that the operating conditions yielding minimum fuel cost can be determined. When the QUICK code was

first linked to the burnup code, we had considerable difficulty in determining exactly which operating condition was optimum, using either polynomial fits or analytical functions. One reason for this was that there were step functions in the fuel cycle cost: for example, how much fuel would one accumulate at a reactor site before sending it to a separations process--the cost of which is a function of the batch size. Also, we found that valid comparisons usually require accuracy in the fourth significant figure. While trying to eliminate these difficulties, we observed that if we arranged the components of fuel cost into appropriate terms, each could be a simple function when plotted against fuel exposure. These groupings, which are used by MINIMIZER, are shown on Slide III.

One such term is the net burnup cost plus the reprocessing costs. A second useful term is the fabrication cost plus any losses which occur in this process. A third term is the interest charges which occur out-of-reactor, and a fourth term is the in-reactor working capital charges. Grouping the cost components into these terms yields smooth functions of exposure. The accuracy of curve fitting could be improved still more if linear functions could be found. Consequently, each of these cost component terms has been transformed slightly and fitted as cost in dollars per cubic centimeter of fuel, instead of mils per kilowatt hour, as shown on Slide IV. This transformation, together with the grouping of terms, produces the required accuracy. In determining

the minimum fuel cost, we found that although these fits are simple polynomials, adding them together and solving for the derivative leads to several local fuel cost minima within the range of the data. To get around this, we use a simple "hunting" method in which we take rather large initial steps to avoid the local fuel cost minimum points which occur on the curve. This allows us to proceed to the vicinity of the primary minimum--the one of interest. Each time a minimum is found, the hunting step size is reduced and only the area immediately surrounding that of the indicated minimum is searched further. The curve fitting and minimization take approximately one hundred and sixty milliseconds per set of economic parameters.

We have found it necessary to add a second step to the optimization procedure, optimization of the lattice or fuel density, as well as enrichment. As shown on Slide II, another chained code, OPTIMIZER, was added to the economic system so that we are able to optimize the fuel cost as a function of physical or geometrical parameters such as, lattice spacing or fuel density. A curve fitting system, similar to that previously described, was adopted for the OPTIMIZER. The minimum fuel cost for a data tape containing the results of several burnup calculations for each of several lattice spacings is made available by the MINIMIZER routine and the ECONOMICS code to OPTIMIZER which then curve fits these minima, and calculates the lattice spacing, the fuel enrichment, and the discharge exposures which produce the minimum total fuel cost as shown in Slide V. If desired, this system

will also perform burnup calculations on that specific case so that a more detailed burnup analysis of the optimum point can be made available. We are now capable of starting with a choice of several reactor lattice designs and then optimizing under a given economic environment on the lattice which should be chosen to find some minimum for a reactor of a given type. We can optimize on such things as the amount of D_2O or total uranium usage. However, most optimization is done against fuel cycle cost. With the speed that is available with this system, an analysis similar to that just described would take about twenty minutes of 7090 time.

An alternate calculation to the cell optimization which may be based on a prior optimization involves the program PUVÉ. In this method, the enrichment producing minimum cost is transmitted to MELEAGER for a burnup calculation to obtain specific data for use in PUVÉ. The plutonium recycle amount and composition are transmitted to SUPERCASE GENERATOR to obtain a new series of burnup data for QUICK and MINIMIZER. In this way, several burnup calculations using recycled plutonium under optimum conditions are available for plutonium value calculations.

Variations in plutonium value can be reflected by a logical (although complex) extension of the simple indifference plutonium value determination which defines plutonium value as the price yielding the same fuel cost whether the plutonium discharged is sold

or recycled. Proper accounting must acknowledge that the plutonium being recycled within an operation is not "free" but is sold at a price from one cycle to the next. Thus recycling plutonium within an operation can be treated as the sale or purchase of goods among several operations. As indicated in Slide VI, a higher price for plutonium would lower the fuel cost for a U^{235} enriched cycle and would raise costs for plutonium enrichment. If the selling price of plutonium is less than its value, it is likely that it would be recycled and not sold. Thus, plutonium value is a basic number which must be considered for each reactor discharge to assure consistent selection of lowest cost operations. Since this determination is limited to a single operation, the resulting values should not be confused with market prices which reflect the influence of many operations.

Generally, the productivities of plutonium of feed composition and of the resulting ash composition in the same thermal reactor are different. This can be reflected in value by use of a method described as PUVF which employs the premise that the value of a discharged plutonium batch is determined by use of that batch as feed for the next cycle. PUVF recycle analysis uses an equation for each cycle involving the unknown value of the plutonium feed, the unknown value of the plutonium ashes, and the fuel cost. The fuel costs for successive plutonium recycle can, as indicated on Slide VII,

be written as a set of equations. The value of a batch leaving the reactor in cycle $j-1$ is conditionally determined by use of that batch as feed for the next cycle j . The recycle process is repeated until some logical constraint can be applied to obviate the necessity of further cycles. In some cases, final plutonium batch values can be set to an arbitrary figure representing some other use. If an equilibrium plutonium composition has been reached, the last two batch values can be set equal. If neither of the foregoing conditions can be applied, it is often possible to use an extrapolation technique based upon composition. Five to seven recycle steps will usually provide an adequate value for plutonium in twenty or thirty minutes of 7090 time.

Obviously, one of the main things we are going to produce is such a tremendous amount of output that it would take a considerable amount of effort to analyze.

To assist in this analysis, we have added another link to the chain shown in Slide II, the PLOTTER code--which prints out a three-page summary analysis for each burnup calculation. This summary includes such information as the initial, final, and average cross sections of all materials used in the burnup; the mass balances of all materials involved in the burnup; the alpha of the fissionable isotopes; the production of possible higher isotopes or fission products that might have economic value; the consumption of uranium; the heat output and the variation in heat transfer rates; the fluxes; initial and final fuel enrichment; and composition. The summary also includes complete neutron balances: initial, final, and averaged over the fuel cycle.

To further assist in reporting this information, the printer has been utilized in preparing graphical output. More recently, peripheral digital plotters working from machine-prepared tapes are being used to graph various output data combinations of interest. Our codes are set up in such a manner that by using normal input procedures, rather than by recompiling, we can plot any item of data that is either generated internally, or is printed out, against any other such item. These methods of output analysis have been developed to the point where the output is almost a complete report by itself. The output report is largely devoid of the esoteric notations and abbreviations which are common features of burnup and cell calculating codes.

Another analysis code is HESTIA, which evaluates the uranium conservation properties of a reactor. This code calculates such quantities as the tons of natural uranium required per megawatt (electrical) installed and per megawatt-year (electrical) generated, the fissile plutonium discharged per total fissile material charged, and various indexes of the uranium conservation performance of a reactor.

With these tools, we have the capability of starting with a basic lattice cell description, and then by varying this description, find the lattice and enrichment that should be chosen to produce optimum fuel cost for a stated economic environment. This same data

may be automatically plotted and reported in nearly complete form, all in a single twenty-minute computer pass. In addition to attaining our original objective of developing a system with high calculational speed, we have case generating codes and data expanding codes, which make the system more efficient to use by reducing the requirement for basic information and input effort (and, incidentally, input errors) on the part of the user. A typical complete optimization such as we have discussed requires about one hundred and fifty input cards, of which probably a hundred are almost standardized for a given type of analysis.

To review, the uses which have been made of this system include such diverse studies as: (1) definition of optimum cell geometry for a given cycle in a reactor type, (2) identification of the economic incentive for defining reactor physics parameters with greater accuracy, (3) estimation of the impact of changing economic environments, (4) evaluations of the cost impact of transplutonium isotope production, (5) evaluation of the type of reactor to be developed for a given economic or fuel shortage situation, (6) calculations of plutonium values, and (7) operation of reactors with bred fuel recycle. The system possesses the iterative capability of using the information from one optimization as input to generate additional cases--a technique used in automatic recycle of plutonium for plutonium value analysis.

As an example of the application of these chained computer codes to a typical survey problem, I would like to discuss the manner in which these codes are used to evaluate the uranium conservation characteristics of a reactor. The problem is to determine the amount of uranium which will be used over a long period of time by an expanding nuclear power economy. The uranium resources which are available to us are limited. We wish to make the best use of these natural resources and obtain the maximum amount of energy from them. Let us assume we also have available to us an estimate of the future growth of the nuclear power industry over the next several decades. The problem is one of determining which reactors, or which reactor types, can be introduced into our economy to fulfill the nuclear power demand which is represented by this growth projection without exhausting the fissile content of our natural resources.

There are several courses of action available to us. We can build thermal reactors which consume more fissile material than they produce. Obviously, after a long period of time, we will exhaust the supply of available fissile materials, and we will not have replaced the supply with sufficient fissile material to continue to provide the growth which was hypothesized. We can also build breeder reactors which do replace their fissile inventories. However, breeders will only be introduced as they become economical

and are able to produce nuclear power at a cost equal to, or possibly slightly greater than, the cost of production by thermal reactors.

Too, we can assume that breeder reactors will be built only as rapidly as we have plutonium available to fuel them. If we wait too long to introduce breeder reactors, all of the fissile material available to us will have been used without our reserves having been replenished. If we introduce breeder reactors before a sufficient plutonium inventory has been established, we will be limited by the rate at which plutonium is produced for inventories.

Let us suppose that the nuclear generating capacity which is to be installed in the near future to fill the demands of this growth curve will be predominately thermal reactors, probably similar to a PWR or BWR. Later growth demands will be met by fast reactor construction. Let us suppose that the fast reactor will be fueled with plutonium and will use depleted uranium in its blanket. Suppose that when fast reactors become available to us we will install them as rapidly as we have plutonium available for fueling them. Suppose further that the amount of plutonium available to fuel fast reactors will not be sufficient to allow us to build as many as we would wish. The deficit in new capacity will have to be met by the construction of additional thermal reactors.

Prior to the introduction of economic breeders; that is, for the next several years, thermal reactors will be constructed exclusively. These reactors will be recycling all the plutonium that they produce. However, by the time the plutonium which a reactor produces has gone through the separations and refabrication processes and then has been recycled to the point of being charged back into the reactor, a certain amount of time will have gone by. During this time, we will have constructed more reactors, presumably of the same type. So we wish to take the plutonium that was produced earlier by a smaller number of reactors and recycle it in a larger number of reactors. This is equivalent to recycling in a reactor only part of the plutonium which it produces. The rate of growth of the nuclear power industry can be expressed by the ratio of the total generating capacity installed as of some time and the total capacity installed one fuel cycle length earlier. This ratio can be considered a partial recycle rate and can also be used as a parameter to express the method of operation. Plutonium will only be recycled when we are not building fast reactors, or when there is an excess of plutonium above the amount required to fuel fast reactors.

As we look at the future growth of the economy, there will be four distinct periods to consider. First, thermal reactors alone will be constructed. These reactors will recycle the plutonium which they produce. Second, fast reactors fueled with plutonium will be

introduced into the economy as rapidly as we have plutonium available to supply their inventories. During this period of time, the thermal reactors will operate on uranium only and will not recycle their own plutonium. During the third period of time, we will have sufficient plutonium available to fuel enough breeder reactors to satisfy the growth of the economy, and still have some plutonium for partial recycle in the thermal reactors that have already been constructed. However, during this period of time there will not be enough plutonium for complete recycle in the thermal reactors. During the fourth period, there will be an excess of plutonium, even though we will recycle as much as is economical in thermal reactors.

How are these chained computer codes applied to this uranium conservation problem. For each reactor that will be constructed in the expanding economy hypothesized, we wish to optimize the way it will actually operate within each of the economic environments which we anticipate in the future. First, for one uranium price and for one rate of growth, which is expressed as a recycle fraction, we wish to go through a complete optimization using these codes. We know that the price of uranium will vary continuously over the future, but we will approximate this by the use of six discrete prices. The installation rate of the reactors will vary with the growth rate of the overall economy and with the rate of introduction of other types of reactor. So we will express a range of installation rates by six

discrete rates of plutonium recycle, or recycle fractions, and then use the optimized results for these points to curve fit and find the optimum operation for any growth rate that will be encountered at some time in the future.

The steps that will be required in the optimization for one recycle fraction and for one uranium price as shown on Slide VIII. First, we will use SUPERCASE and MELEAGER to calculate burnups using seven or eight uranium enrichments. Then, the results of these burnups will go to QUICK and to MINIMIZER to find the enrichment which gives us the net minimum fuel cost for this one uranium ore price. Now, with this enrichment, we will return to MELEAGER to calculate the burnup at this optimum enrichment. The next step will be to recycle a fraction of the plutonium which has been produced at this optimum enrichment, a fraction which corresponds to some given power reactor growth rate, with each of seven or eight uranium enrichments. These enrichments will be generated by the SUPERCASE program, and then the MELEAGER code will calculate the burnups. Finally, we return to QUICK and to MINIMIZER to find the enrichment which gives us the minimum fuel cost for this fraction recycle and for this uranium ore cost. We return to MELEAGER to compute burnup for the optimum enrichment with this fractional recycle. These optimum enrichments depend upon the value of plutonium to see whether or not we started with a reasonable estimate. If we did not, then the optimization should be repeated

using an improved estimate of plutonium value. The next step is to use the PLOTTER program to generate curves of the results and to produce neutron and material balance reports on the characteristics of this reactor for optimum plutonium recycle at this given uranium price. From PLOTTER we will go to the HESTIA program which calculates the uranium usage parameters which will be used as input data to VESTA program. HESTIA will calculate such quantities as the number of tons of natural uranium which will be required per megawatt of installed electrical capacity, the amount of natural uranium which will be required per megawatt-year of electrical energy generated, the initial and final enrichments of uranium and plutonium, and the amount of fissile plutonium produced per unit of fissile material that is charged to the reactor. Data such as these will be generated for each of six ore prices and five recycle rates. This requires thirty complete optimizations; thirty complete passes through this series of programs. Each pass through this series starting with SUPERCASE and MELEAGER and ending with PUVI and HESTIA, requires approximately seven minutes. The thirty optimizations require a total time of about 3-1/2 hours. The results of these machine calculations are sufficient to describe the characteristics of one reactor which will then be used by the VESTA program in making calculations on the hypothesized economy.

Slide IX shows some of the output from VESTA. First, the total installed capacity for each type of reactor that we assume will be introduced in the future. Slide X shows the amount of uranium which will be used as a function of time over the same period for the same economy. The discontinuities in the curve represent a change in ore price. When the price changes, we rework the cascade tails material before buying additional uranium at the higher price. In Slide XI, we see the amount of uranium that will be required for one hypothesized economy as well as a comparison between this amount of uranium and the results of similar calculations for other hypothesized economies. From this, we are able to make evaluations of the importance of the construction rates and of the types of breeder reactors which may be introduced. In this work, so far, there is no attempt to optimize the relative numbers of the different types of reactors which might be built. Each reactor is optimized without considering the impact it may have on other reactors and also without considering the impact that other reactors may have on it.

The next extensions to the system of chained codes which are planned include the use of the optimum operating parameters calculated for several types of reactors, together with forecasts of the expanding economy, to produce a linear programming formulation of the conservation problem. Then we can determine the minimum amount of uranium to be

used over a future period. So the next link in our chain will be a matrix maker program to take the output from the MELEAGER, QUICK, and VESTA codes, and combine them in linear programming descriptions of several reactors. Finally, the output from this link on the chain will be used as input to a linear programming code which will then proceed to solve for the overall optimum and determine the optimum amount of plutonium recycle for each reactor in order to minimize such quantities as the amount of fissile material, the amount of uranium, or the total energy cost over a short- or long-period of time.

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MELEAGER CHAIN COMPUTER CODE

MELEAGER	To Supply The Reactor Fuel Burn-Up Data ("Physics")
QUICK	To Supply The Cost Data By Operating on Meleager Results
MINIMIZER	To Determine The Minimum Fuel Cost
PUVE	To Establish The Plutonium Value Resulting From An Appropriate Recycle Sequence

SLIDE I

CHAINED FUEL CYCLE ANALYSIS SYSTEM

COST COMPONENTS AND FUEL EXPOSURE AS A FUNCTION OF FUEL ENRICHMENT

NUMERATOR OF COST COMPONENTS AND EXPOSURE AS A FUNCTION OF FUEL ENRICHMENT

TOTAL FUEL COSTS AS AFFECTED BY MODERATOR
INDEX AND ENRICHMENT OF FUEL FOR A WATER-
MODERATED REACTOR WITH STAINLESS STEEL CLAD
U²³⁵ ENRICHED URANIUM FUEL

SLIDE V

FUEL COST AND ASSIGNED Pu PRICE FOR A HYPOTHETICAL NON-BREEDING REACTOR

SLIDE VI

SUCCESSIVE PLUTONIUM RECYCLE FLOW SHEET

$$F_1 = A_1 + C_1 X_1$$

$$F_j = A_j + B_j X_{j-1} - C_j X_j$$

$$F_n = A_n + B_n X_{n-1} - C_n X_n$$

- $n-1$ = Number of Times Plutonium Produced in the Reactor is Recycled to the Reactor
- F_n = Total Fuel Cost in mill/kwh_e on the nth Step
- X_{n-1} = Value in \$/gram of Plutonium Supplied to the Reactor in the nth Step
- X_n = Value in \$/gram of Plutonium Discharged from the Reactor in the nth Step

A_n , B_n , and C_n are Coefficients Appropriate for Each Step

CHAIN CALCULATIONS FOR THE URANIUM CONSERVATION PROBLEM

1. Use SUPERCASE to Generate Cases for Fueling with Uranium Only
2. Use MELEAGER for Burnup Calculations
3. Use QUICK for Economics Calculations
4. Use MINIMIZER for Fuel Cost Optimization
5. Use MELEAGER for Burnup Calculations at Optimum Enrichment
6. Use SUPERCASE to Generate Cases for Fueling with Uranium and Recycle Plutonium from Optimum
7. Use MELEAGER for Burnup Calculations
8. Use QUICK for Economics Calculations
9. Use MINIMIZER for Fuel Cost Optimization
10. Use MELEAGER for Burnup Calculations at Optimum Enrichment
11. Use PUVe to Check Plutonium Value Estimates
12. Use PLOTTER to Generate Output Report Curves
13. Use HESTIA to Calculate Uranium Usage Parameters
14. Use VESTA (not on chain) to Evaluate Uranium Usage for a Hypothesized Economy

SLIDE VIII

MW_e INSTALLED CAPACITY IF 20-YEAR DOUBLER
INTRODUCED AFTER 1980 AND 7-YEAR DOUBLER
INTRODUCED AFTER 1990

URANIUM UTILIZATION OF 20-YEAR DOUBLER
INTRODUCED AFTER 1980 AND 7-YEAR DOUBLER
INTRODUCED AFTER 1990

RELATIVE URANIUM USAGE FOR VARIOUS BREEDER INTRODUCTION DATES