Decision Model for Evaluating Reactor Disposition of Excess Plutonium

Thomas Edmunds

February 1995

Lawrence
Livermore
National
Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

WW

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

**Decision Model for Evaluating Reactor
Disposition of Excess Plutonium**

**Thomas Edmunds
Lawrence Livermore National Laboratory**

September 1994

Abstract

The U. S. Department of Energy is currently considering a range of technologies for disposition of excess weapon plutonium. Use of plutonium fuel in fission reactors to generate spent fuel is one class of technology options. This report describes the inputs and results of decision analyses conducted to evaluate four evolutionary/advanced and three existing fission reactor designs for plutonium disposition. The evaluation incorporates multiple objectives or decision criteria, and accounts for uncertainty. The purpose of the study is to identify important and discriminating decision criteria, and to identify combinations of value judgments and assumptions that tend to favor one reactor design over another.

1. Introduction

This study is an extension of previous evaluations of options for disposition of excess plutonium¹. Standard decision analysis techniques are used to support an evaluation of reactor options for plutonium disposition. Functions that measure the relative desirability of each reactor option with respect to a number of different decision criteria (e.g., life cycle cost, time to complete disposition, radiation barrier of spent fuel) are developed and combined to get a single figure of merit for each reactor. The procedures for constructing and using these functions are well developed in the multiattribute utility theory literature, have been used for DOE decision making in the past, and have been recommended by the National Academy of Sciences². A second decision analysis technique (decision trees) is used to evaluate the impact of uncertainty regarding licensing schedules, construction schedules, and plant performance in terms of capacity factor. Standard modeling methods and a commercial computer code for implementing decision trees is used. Background material regarding decision analysis and an example application are included in *Reactor Options for Disposition of Excess Weapon Plutonium: Selection Criteria and Decision Process for Assessment*, LLNL Report LPDS-002, January 1994.

The decision analysis model is used to identify combinations of assumptions and value judgments that tend to favor certain reactor types. Relationships among the decision model and supporting data, assumptions and value judgments are depicted in Figure 1.

Figure 1 - Decision model inputs and outputs

Typically, decision analyses are used to support decision making, and the flow of information in Figure 1 would be from left-to-right. In this mode, data are collected, assumptions and subjective

¹ See U.S. DOE [1993] and Omberg and Walter [1993].

² See DOE/RW-0074 (May 1986). This report includes a letter dated October 10, 1985 from Frank L. Parker of the National Research Council (National Academy of Sciences) to Ben C. Rusche of DOE-OCRWM.

judgments are made, and the decision model is used to identify the optimal sequence of decisions. However, the reactor evaluation effort is intended to be a characterization of the alternatives rather than a final selection of a single reactor technology. Consequently, the flow of information for this study is from right-to-left. Specifically, a reactor is selected for evaluation and the decision model is used to identify combinations of assumptions and subjective judgments that lead to selection of that particular reactor technology.

The decision model and database are not intended to be used for final selection of a reactor technology but rather as a tool for identifying qualitative advantages and disadvantages of each reactor and to help structure a request for proposals from reactor vendors. More data should be collected before a final down select decision is made. For example, more information regarding the availability of existing reactors and the subsidies that utilities would require to switch to MOX burning operations would be needed to decide between using new or existing reactors.

2. Decision criteria

A list of potential decision criteria is documented in *Decision Criteria for Evaluation of Plutonium Disposition Decisions*, LLNL report LPDS-021, April 7, 1994. These decision criteria are intended to be comprehensive for the plutonium disposition effort, and they form the basis of an evolving decision criteria list to be used by DOE to evaluate a broader range of disposition options including, but not limited to, reactors. The evaluation criteria address a wide range of objectives, including: technical viability; proliferation resistance; environment, safety, and health; public and political acceptance; international transferability; and economics. Eighty-eight criteria are included in the comprehensive list.

Many of the criteria identified in the comprehensive list were not practical to use given the time frame and budget for the reactor evaluation effort, are not effective discriminators among the reactor options considered, or do not apply to the reactor options considered. For these reasons, a smaller set of decision criteria is derived from the comprehensive list to support development of a decision model. The criteria used in the decision model and the units used to quantify them are listed below in Table 1.

Table 1 - Criteria used in reactor evaluation decision model

	<u>Criteria</u>	<u>Units</u>
1	Life cycle cost	NPV (million 1993\$)
2	Time to start disposition	years (1993 = 0)
3	Time to complete disposition	years (1993 = 0)
4	Drawdown profile	MT-yr
5	Radiation barrier at 10 years	rem/hr
6	Isotopic suitability for weapons at 10 years	Pu-240/Pu
7	Thermal suitability for weapons at 10 years	kW/kg Pu
8	Net Pu destruction	fraction
9	Waste generation (TRU)	cubic m
10	Occupational dose	person-rem
11	Number of sites with Pu	sites
12	Radiation barrier at 100 years	rem/hr
13	Initial capital outlay	NPV (million 1993\$)
14	Number of similar reactors in Russia	reactors

Note that all cost and schedule calculations use 1993 as the base year. These decision criteria are used in the decision model described below.

3. Utility functions

3.1 Lottery questions and single attribute utility functions

The first step in development of the decision model is to specify a function, called a utility function, for each of the fourteen decision criteria listed above in Table 1. Each utility function reflects the desirability of achieving various values for the associated decision criterion. The utility functions for each of the fourteen decision criteria were assessed using input provided members of the Technical Evaluation Committee (TEC) assembled to evaluate the reactor options. Not all members of the TEC were interviewed. Standard utility function assessment techniques, involving lottery questions, were used (see Keeney and Raiffa 1976, and Keeney 1980).

The utility function for the first decision criterion, life cycle cost, is shown in Figure 2. The results for the other utility functions are shown in Appendix A.

Figure 2 - Utility function for life cycle cost

The life cycle cost ranges from a low of -\$4000 million to a high of \$5000 million for utility between 1 and 0, respectively. A negative cost implies a net profit to DOE (electricity revenues exceed costs). As shown in the figure, different TEC members specified different utility function curves. Most of the curves, however, do exhibit a general sigmoid, or "S" shape, with a transition in the range \$-1 to \$+3 billion. This reflects a general perception that DOE would view reactors that produced a profit favorably, but the level of satisfaction is not strongly dependent upon the amount of profit. The bold line in the figure is the average of the TEC member responses and is the function used in the decision model. For simplicity, the utility for a particular reactor disposition option is computed by evaluating this average function for the reactor's life cycle cost. Reactor evaluations could also be conducted for individual utility functions to determine the degree of consensus among TEC members.

3.2 Tradeoff questions and the multiattribute utility function

The next step in development of the model was to use responses to tradeoff questions to establish the relative importance of each of the fourteen decision criteria. In posing the tradeoff questions, TEC members were asked to construct two different options with which they were equally satisfied. The two options differed on two of the attributes. In general, one option scored well on one attribute and poorly on the other, while for the second option the scoring was reversed. An example response involving the life cycle cost and radiation barrier is shown in Table 2.

Table 2 - Tradeoff question to define two equally preferred options

Option A:	Option B:
Life cycle cost = \$3 billion	Life cycle cost = \$3.5 billion
Radiation barrier = 500 rem/hr	Radiation barrier = 1000 rem/hr

In this example, the TEC member is equally satisfied with options A or B. That is, the decision maker is willing to increase costs from \$3 to \$3.5 billion, or "trade off" an extra \$0.5 billion, to increase the radiation barrier performance from 500 rem/hr to 1000 rem/hr (making the spent fuel more difficult to handle and therefore more resistant to theft). The utilities for the costs and radiation barriers specified in Table 2 can be computed using the assessed utility functions. The tradeoffs between the two utility functions can then be established.

After tradeoffs between pairs of utilities have been established, a function that incorporates each of the fourteen decision criteria, called a multiattribute utility function, can be constructed. The functional form of the multiattribute utility function is a weighted sum of the fourteen single attribute utility functions, where the tradeoff questions are used to derive the weights.

$$U = \sum_{i=1}^{14} k_i u_i$$

where: U = multiattribute utility function

k_i = weight for single attribute utility function u_i

The responses to tradeoff questions posed to the TEC members were used to compute a set of weights. The results are shown in Figure 3, where the labels k1, k2, etc., refer to the fourteen criteria in Table 1. The shaded bars correspond to the individual assessments and the bold bars indicate the averages of the individual assessments.

Weight

Figure 3 - Weights in multiattribute utility function (see Table 1)

As indicated by the data in the figure, life cycle cost (k1), time to start (k2), time to complete (k3), and initial capital cost (k13) were viewed by TEC members as most important. In general, TEC members felt that all of the proposed reactor options met the spent fuel standard³, so that the decision criteria related to spent fuel characteristics (radiation barrier, isotopic suitability for weapons, and thermal suitability for weapons) were relatively unimportant in the range of values reflected by the available reactor alternatives.

³ The concept of a spent fuel standard was introduced in National Academy of Sciences [1994]. Proposed realizations of such a standard are still being developed.

The utility function assessments and curve fitting routines were implemented on an electronic spreadsheet (EXCEL™ by Microsoft Corp.). Although commercial packages are available for assessment of utility functions, the spreadsheet model was used so that results could be linked to the decision tree model described in the next section. This linking capability facilitates rapid turn-around of analysis results for evaluation of the impact of changes in the utility function.

4. Decision tree

The spreadsheet model used to assess and fit utility functions is linked to a decision tree model implemented on a commercial decision analysis package ADA Decision Systems [1992]. The DPL code is included in Appendix B. The purpose of the decision tree model is to represent uncertainty that can impact the cost and schedule for plutonium disposition. Four major sources of uncertainty are represented in the model as probability distributions over: 1) reactor licensing delays, 2) reactor construction delays, 3) plutonium fuel fabrication facility delays, and 4) capacity factors. The following acronyms are used in the tables below.

GE - General Electric evolutionary reactor
W - Westinghouse advanced reactor (PDR 600)
CE - Combustion Engineering evolutionary reactor
GA - General Atomics advanced reactor
EXGE - existing General Electric reactor
EXW - existing Westinghouse reactor
EXCE - existing Combustion Engineering reactor
EXCAN - existing CANDU reactor

4.1 Probability distribution assessments

Four members of the TEC provided estimates of probability distributions for the evolutionary/advanced and existing reactors. Averages of these estimates are shown in Tables 3, 4, 5, and 6. Additional analysis could be conducted using individual probability assessments to determine the degree of consensus among TEC members. As a first approximation, the probability distributions in Tables 3 through 6 are assumed to be independent of one another.

Table 3 - Probability distribution for reactor licensing delays

	-1 to 1 years	1 to 3 years	3 to 5 years	5 to 7 years	not licensed	sum
GE	0.55	0.23	0.13	0.08	0.02	1.00
W	0.40	0.35	0.15	0.08	0.02	1.00
CE	0.55	0.23	0.13	0.08	0.02	1.00
GA	0.20	0.25	0.30	0.14	0.11	1.00
EXGE	0.70	0.30	0	0	0	1.00
EXW	0.70	0.30	0	0	0	1.00
EXCE	0.60	0.40	0	0	0	1.00
EXCAN	0.75	0.25	0	0	0	1.00

Table 3 displays assessed probability distributions for delays during the licensing process for the evolutionary/advanced reactors and existing reactors, where a negative delay indicates licensing ahead of schedule. The table also includes an entry for the probability that the reactor is never licensed.

As indicated by the data in Table 3, the evolutionary/advanced reactors have a higher probability of licensing delay than the existing reactors. Among the four evolutionary/advanced reactor concepts, the GE and CE designs had higher probabilities of being licensed on schedule (0.55 probability of a delay between -1 and 1 years) than the other reactor designs. The W design had slightly higher probabilities of licensing delays in the 1 to 3 and 3 to 5 year ranges, while GA design had the highest probabilities of long licensing delays. Among the existing reactors, the EXCAN design is least impacted by the introduction of MOX fuel and consequently has the lowest probability of delay. The EXW and EXGE designs introduce burnable absorbers for reactivity control.

Table 4 - Probability distribution for reactor construction delays

	-1 to 1 years	1 to 3 years	3 to 5 years	5 to 7 years	sum
GE	0.48	0.28	0.19	0.06	1.00
W	0.40	0.35	0.19	0.06	1.00
CE	0.48	0.28	0.19	0.06	1.00
GA	0.28	0.40	0.23	0.10	1.00
EXGE	0.9	0.1	0	0	1.00
EXW	0.9	0.1	0	0	1.00
EXCE	0.9	0.1	0	0	1.00
EXCAN	0.9	0.1	0	0	1.00

The data in Table 4 indicate that of the evolutionary/advanced reactor designs, the GE and CE reactors are most likely to be constructed on schedule. The W design has a slightly higher probability of construction delays in the range of 1 to 3 years, while the GA design has a

significantly higher probability of longer construction delays. The construction, or retrofit, delays for existing reactors are assumed to be low.

Table 5 - Probability distribution for fuel fabrication facility delay

	-1 to 1 years	1 to 3 years	3 to 5 years	5 to 7 years	sum
EXCAN	0.80	0.20	0	0	1.00
all others	0.50	0.30	0.10	0.10	1.00

Table 5 shows the delay distributions for licensing and construction of the fuel fabrication facilities. Delay probabilities for the EXCAN facility are lower than for the other reactors because the EXCAN proposal makes use of an existing building at the DOE Hanford site (Fuels and Materials Examination Facility).

Table 6 - Probability distribution for capacity factors

	50% to 60%	60% to 70%	70% to 80%	80% to 90%	sum
GE	0.10	0.28	0.50	0.12	1.00
W	0.10	0.28	0.50	0.12	1.00
CE	0.10	0.29	0.50	0.11	1.00
GA	0.22	0.17	0.50	0.12	1.00
EXGE	0.10	0.28	0.50	0.12	1.00
EXW	0.10	0.28	0.50	0.12	1.00
EXCE	0.10	0.29	0.50	0.11	1.00
EXCAN	0.10	0.20	0.50	0.20	1.00

The data in Table 6 indicate that there is a 0.5 probability that each reactor operates near a 75% capacity factor. The distributions for GE, W, and CE evolutionary/advanced and existing reactors are almost identical, while the GA advanced reactor has a higher probability of a low (50% to 60%) capacity factor. The EXCAN reactor has a higher probability of achieving a high capacity factor due to the on-line refueling capability of the reactor.

4.2 Decision tree structure

Combinations of the chance events represented by the probability distributions in the four tables lead to a large number of possible scenarios. For example, one possible scenario is the selection of a GE reactor for licensing followed by a licensing delay in the range 1 to 3 years, a construction delay in the range 3 to 5 years, a fuel fabrication facility delay in the range 1 to 3 years, and a capacity factor in the range 50% to 60%. There are 16,384 possible scenarios of this type modeled in the decision tree. Diagrams of portions of the tree are shown in Figures 4 and 5.

Figure 4 - Diagram of decision tree (initial decisions)

The decision tree in Figure 4 displays information for the four evolutionary/advanced reactors only. Three existing reactor designs (EXGE, EXW, and EXCAN) are included in the model but have been omitted from the figure for brevity. The modeling structure used for the existing reactors is the same as that used for the evolutionary/advanced reactors.

The squares shown in Figure 4 represent decisions and the circles represent chance nodes. The first decision, labeled "LicAttempt1" in the figure, is to select one of the seven reactors for licensing. The four alternatives shown in the diagram correspond to the four advanced reactor types. The figure also shows a chance event labeled "LicFail" for each of the four reactor choices shown. As indicated in the figure, the two possible outcomes of this chance event are "License" and "NoLicense." If the outcome of the chance event "LicFail" is "NoLicense," then one of the six remaining reactor designs not initially selected must be selected for a second licensing attempt. For example, if the GE reactor is selected at decision node "LicAttempt1," and the outcome of chance event "LicFail" is "NoLicense," then the decision node "GEFailLic" is encountered where the choices are W, CE, and GA reactors. As indicated in the figure, the tree structure for the W branch is similar to that for the GE branch. The CE, GA, and existing reactor branches are also similar, but they have been suppressed in the figure for brevity.

The number in brackets above each branch is the expected utility associated with the branch. The branch with the highest expected utility is selected at each decision node. The numbers beneath

the expected utility values are the contributions for that particular branch at that particular point in the tree.

If the outcome of a "LicFail" node is "License," then a chance node representing the licensing delay, labeled "GELicDelay" in the upper branch, is encountered. The detail of the branch after the "GELicDelay" node is shown in Figure 5. Branches for the other reactor choices are similar.

Figure 5 - Diagram of decision tree (GE branch detail)

As indicated in the figure, the possible values for licensing delays are 0, 2, 4, and 6 years, which correspond to the midpoints of the intervals in the probability distribution assessment data. The next chance event encountered is labeled "GEConstDelay" in the figure. Possible values are 0, 2, 4, and 6 years.

The next chance event labeled, "OthFuelDelay," represents delay in operations of the fuel fabrication facility. Because licensing and construction of the fuel fabrication facility is done in parallel with the reactor, the reactor and fuel plant delays are not additive. For example, if the reactor is delayed by two years and the fuel plant is delayed by 4 years, the total delay is assumed to be the maximum of the two delays, or 4 years. In the decision model, the total delay is the greater of (reactor licensing delay + reactor construction delay) and (fuel fabrication facility delay).

Finally, the chance event for capacity factor includes 55%, 65%, 75%, and 85% as possible outcomes. Full details are included for only the top branch in the figure. Other branches are similar.

4.3 Simplified economic models

Detailed economic models were developed for base case scenarios (no delays and nominal capacity factor of 75%) by members of the Cost and Schedule Subcommittee of the TEC. Simplified economic models are included in the decision tree model to estimate the impacts of delays, performance levels, electricity prices, etc. The simplified economic models incorporate three basic features.

First, each vendor's set of reactors is represented by a single "equivalent" reactor for the purposes of computing life cycle costs under different assumptions about delays, capacity factors, electricity prices, and other parameters of interest. The life cycle cost of the equivalent reactor is normalized to the values computed by the Cost and Schedule Subcommittee for the base case set of reactors for each vendor. Capital costs and revenues are computed for the equivalent reactor by modifying base case results using standard engineering economics techniques for power generation units.

Second, licensing delays are modeled as shifts in expenditures to future dates by the amount of the delay. The effect of the delay is to discount the present value of the base case expenditures by the factor $(1/(1+d))^n$, where d is the discount rate and n is the number of years licensing delay.

Third, construction delays are assumed to happen early in the construction phase. We assume that delays shift 75% of the capital costs, all of the operating costs, and all of the revenues to future dates so that they are discounted by a factor $(1/(1+d))^n$. In addition, an annuity, with each annual payment equal to 20% of sunk capital at the time of delay, is added to construction costs during the delay period. This annuity represents the costs of retaining skilled craftsmen and engineers, of maintaining structures and the site, and of resolving the cause of the delay. Sensitivity analyses were conducted to evaluate the impact of the assumed 75% sunk capital and 20% annuity rates.

5. Results

The decision models identify optimal reactor choices for a given set of assumptions and value judgments. In this section, we use the decision models to identify combinations of assumptions and value judgments that imply a preference of one reactor over the others. The decision models also provide a measure of the sensitivity of decisions to assumptions and value judgments. Analyses are reported for the following parameters.

Table 6 - Parameters for sensitivity studies

Parameter	Base value	Minimum	Maximum
start time/life cycle cost tradeoff	1.59	0	5
completion time/life cycle cost tradeoff	0.72	0	5
initial capital/life cycle cost tradeoff	2.01	0	5
number of sites/life cycle cost tradeoff	0.56	0	10
net Pu destruction/life cycle cost tradeoff	0.60	0	5
electricity price real escalation rate	0.015	0	0.03

Results of these sensitivity analyses are shown in Figures 7-12.

Expected utility

Figure 7 - Start time/life cycle cost tradeoff

Figure 7 displays the sensitivity of the outcome, as measured in expected utility, to the tradeoff between start time and life cycle cost. This tradeoff is measured as the ratio of the coefficient for start time to the coefficient for life cycle cost in the multiattribute utility function discussed in Section 3.2. A value of zero for this ratio indicates that start time is not important relative to life cycle cost, and a large value (e.g., 5.0) indicates that start time is much more important than life cycle cost.

The labeling scheme used in Figure 7 references the reactors selected for the first and second licensing attempts depicted in Figure 4. For example, the label "EXW/EXCAN" in the figure indicates that the optimal decision sequence in the region is to initially attempt to license the existing Westinghouse (EXW) reactors (decision "LicAttempt1" in Figure 4), and to license the existing CANDU (EXCAN) reactors if the Westinghouse license attempt fails (decision "WFailLic" in Figure 4). Alternatively, the label "EXCAN/EXW" indicates that the EXCAN reactor license should be attempted first and the EXW reactor should be licensed if the EXCAN licensing attempt fails. The bold tic mark on the horizontal axis shows the tradeoff ratio assessed from members of the TEC. The overall qualitative conclusion one can draw from the figure is that the EXW reactor should be selected if schedule is unimportant relative to life cycle cost and the EXCAN reactor should be selected if the schedule is very important relative to life cycle cost.

Expected utility

Figure 8 - Completion time/life cycle cost tradeoff

The data in Figure 8 indicate that the initial choice of the EXCAN reactor is insensitive to the completion time/life cycle cost tradeoff ratio.

A sensitivity analysis for the initial capital/life cycle cost tradeoff ratio was conducted. The ratio k_{13}/k_1 was varied from a minimum of 0 (i.e., initial capital is not important) to a maximum of 5. The initial choice of the EXCAN reactor is not sensitive to the initial capital/life cycle cost tradeoff ratio in this range.

Next, the sensitivity of the EXCAN choice to the number of sites/life cycle cost tradeoff ratio was analyzed. The ratio k_{11}/k_1 was varied in the range [0,10]. The results are shown in Figure 9.

Expected utility

Figure 9 - Number of sites/life cycle cost tradeoff

As indicated in the figure, the CANDU reactor, which requires 2 sites, is selected if the number of sites is relatively unimportant. The advanced Westinghouse reactor, which requires a single site, is selected if the number of sites is very important.

Expected utility

Figure 10 - Net Pu destruction/life cycle cost tradeoff

The data shown in Figure 10 indicate that the GA reactor becomes the preferred option if net plutonium destruction is deemed to be very important. Also note that this tradeoff produces the most significant variation in expected utility. The three analyses depicted in Figures 7, 8, and 9 generate a variation in expected utility of approximately 0.04, while the analysis depicted in Figure 10 generates a variation in expected utility of 0.2.

Additional sensitivity analyses indicate that the value of choosing the EXCAN reactor, as measured by expected utility, is not affected by the electricity price escalation rate. This is because under the existing reactor operation scenarios all of the revenues from electricity sales belong to the utility.

However, DOE does receive the revenues from electricity sales in the advanced reactor operation scenarios. It was thought that if life cycle costs were very important and electricity price escalation rates were high then the advanced reactors might be chosen because they have high initial capital costs yet low life cycle costs when electricity prices rapidly escalate. To examine this issue further, the ratio k_{13}/k_1 was set to zero so that life cycle cost (k_1) would be considered much more important than initial capital cost (k_{13}). The electricity price escalation sensitivity run was then repeated. The results are that existing reactors (CANDU) are preferred in this case as shown in Figure 11. Note that the expected utility changes very little in the figure (a variation of only 0.001).

Expected utility

Figure 11 - Electricity price escalation rate

Finally, the coefficient for life cycle cost (k_1) was set equal to 1.0 and all other coefficients were set to zero. This implies that life cycle cost is the only criterion of interest. The results are shown in Figure 12.

Figure 12 - Electricity price escalation (life cycle cost only criterion)

As indicated in Figure 12, the existing W reactor is preferred under low electricity escalation rates. The curve in this region is flat because revenues from electricity sales are not received by DOE. The preference switches to the GA reactor when the electricity escalation rate exceeds 0.018 (or 1.8% per year). The evolutionary GE reactor is preferred if the escalation rate is 3.5% per year, and the W reactor is preferred if the escalation rate is closer to 4% per year. Note the large range (0.3) in expected utility for this analysis.

Results of the sensitivity analyses are summarized below.

Table 7 - Preferred reactors

Parameter	Low	Moderate	High
importance of start time	EXW	EXCAN	EXCAN
importance of completion time	EXCAN	EXCAN	EXCAN
importance of initial capital	EXCAN	EXCAN	EXCAN
importance of number of sites	EXCAN	EXCAN	W
importance of net Pu destruction	EXCAN	EXCAN	GA
electricity price real escalation rate	EXCAN	EXCAN	EXCAN
electricity price escalation life cycle cost only	GA	GE	W

Summary and Conclusions

In general, the existing reactor options are superior to the evolutionary/advanced reactor options with respect to two important decision criteria: initial capital cost and schedule. It requires less capital to retrofit an existing reactor to burn MOX fuel than to build a new reactor, and the time required to convert existing reactors to burn MOX fuel is less than the time required to build new reactors using plutonium based fuel. One advantage offered by the evolutionary/advanced reactors is the potential for high revenues from electricity sales that can be used by DOE to offset costs. If life cycle cost is the only criterion of interest and electricity prices increase at a rapid rate then the advanced reactor options would be preferred. One of the advanced reactors, the GA design, offers high net Pu annihilation, and is preferred if this criterion is given a high weight.

Among the existing reactors, the Westinghouse reactor is preferred if the time to start is unimportant relative to life cycle cost. The CANDU design is preferred under a wide range of circumstances. The existing Combustion Engineering design was not included in the evaluation due to insufficient data.

Decision criteria that were considered to be most important by some members of the TEC are: initial capital outlay, time to start, life cycle cost, time to complete, and number of sites.

References

DPL Advanced Version User Guide, ADA Decision Systems, Menlo Park, CA [1992].

Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, National Academy Press, Washington, D.C. [1994].

Edmunds, Thomas, William Sutcliffe, Booth Myers, and Lisa Buonpane, "Decision Criteria for Evaluation of Plutonium Disposition Decisions", Lawrence Livermore National Laboratory, LPDS-021, [April 7, 1994].

Edmunds, Thomas, *et. al.*, "Reactor Options for Disposition of Excess Weapon Plutonium: Selection Criteria and Decision Process for Assessment", Lawrence Livermore National Laboratory, LPDS-002 [January 1994].

Keeney, Ralph L., *Siting Energy Facilities*, Academic Press, New York, N.Y. [1980].

Keeney, R. L. and H. Raiffa, *Decisions with Multiple Objectives*, Prentice-Hall, Englewood Cliffs, N.J. [1979].

Omberg, Ronald P. and Carl E. Walter, "Disposition of Plutonium from Dismantled Weapons: Fission Options and Comparisons," UCRL-ID-113055 [February 5, 1993].

U.S. Department of Energy, Office of Civilian Radioactive Waste Management, "A Multiattribute Utility Analysis of Sites Nominated for Characterization for the First Radioactive-Waste Repository —A Decision-Aiding Methodology", DOE/RW-0074 [May 1986].

U.S. Department of Energy, Plutonium Disposition Study, "Technical Review Committee Reptot, Vol. II" [July 2, 1993].

Appendix A - Single Attribute Utility Function Assessments

Single attribute utility functions were assessed using standard techniques based upon lottery questions (see Keeney and Raiffa 1976). Responses to the lottery questions provide several points on the utility function curve, and a nonlinear function is fitted to the points. The assessed utility functions are shown below.

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

The parameters and corresponding utility function values for the seven reactor designs evaluated are shown in the two tables below. The existing CE design (EXCE) was not included in the evaluation because the data set was incomplete. Assumed values for the EXCE design are shown for illustration purposes only.

Table A-1 Utility Function Values for Advanced Reactor Designs

Multiattribute Utility Function Assessment								
Utility Function	GE		W		CE/ABB		GA-MHTGR	
	value	util	value	util	value	util	value	util
1: Life cycle cost	1123	0.6579	1413	0.6115	1213	0.6438	607	0.7315
2: Time to start disposition	11.00	0.4069	11.00	0.4069	9.00	0.5457	14.00	0.2584
3: Time to complete disposition	26.00	0.8081	26.00	0.8081	26.00	0.8081	26.00	0.8081
4: Drawdown profile	875	0.8877	894	0.8779	818	0.9182	996	0.8285
5: Radiation barrier at 10 years	16,000	0.9763	17,000	0.9826	63,484	0.9622	6,000	0.5367
6: Isotopic suitability for weapons	0.3374	0.6043	0.2535	0.0453	0.2488	0.0140	0.3440	0.6482
7: Thermal suitability for weapon	0.031	0.5414	0.023	0.0000	0.025	0.0692	0.023	0.0000
8: Net Pu destruction	0.3800	0.3627	0.2527	0.0455	0.2716	0.0842	0.6444	1.0000
9: Waste generation (TRU)	452	0.9278	450	0.9281	3629	0.3966	4.92	1.0000
10: Occupational dose	3257	0.9689	4270	0.9332	2240	1.0000	4632	0.9200
11: Number of sites with Pu	1	1.0000	1	1.0000	1	1.0000	1	1.0000
12: Radiation barrier at 100 years	1300	0.5601	1600	0.6798	6715.635	0.9980	620	0.0000
13: Initial capital outlay	4798	0.2401	4483.6	0.3282	5830.7	0.0137	5100	0.1595
14: Number of similar reactors in R	0	0.0000	17	1.0000	0	0.0000	0	0.0000
15: Title 15	0	0.0000	0	0.0000	0	0.0000	0	0.0000
	US _{static} :	1.78E-01	US _{static} :	2.36E-01	US _{static} :	9.76E-02	US _{static} :	1.59E-01
	UT _{total} :	5.13E-01	UT _{total} :	5.64E-01	UT _{total} :	4.65E-01	UT _{total} :	4.67E-01

Table A-2 Utility Function Values for Existing Reactors

Multiattribute Utility Function Assessment								
Utility Function	EXGE		EXW		EXCE		EXCAN	
	value	util.	value	util.	value	util.	value	util.
1: Life cycle cost	1311	0.6282	1069	0.6661	1500	0.5968	1481	0.6001
2: Time to start disposition	7.50	0.6746	10.00	0.4717	6.00	0.8220	5.00	0.9221
3: Time to complete disposition	26.00	0.8081	26.00	0.8081	26.00	0.8081	26.00	0.8081
4: Drawdown profile	829	0.9124	867	0.8918	768	0.9471	760	0.9524
5: Radiation barrier at 10 years	17,800	0.9870	21,000	1.0000	49,500	0.9666	6,050	0.5499
6: Isotopic suitability for weapons	0.3729	0.8408	0.3090	0.4151	0.2467	0.0000	0.3968	1.0000
7: Thermal suitability for weapon	0.075	1.0000	0.060	0.9930	0.033	0.6668	0.035	0.7508
8: NetPu destruction	0.3648	0.3202	0.3260	0.2155	0.2235	0.0000	0.3380	0.2471
9: Waste generation (TRU)	6251	0.0000	464	0.9258	1058	0.8259	1720	0.7139
10: Occupational dose	31400	0.0000	10200	0.7026	2240	1.0000	4250	0.9340
11: Number of sites with Pu	2	0.7335	2	0.7335	2	0.7335	2	0.7335
12: Radiation barrier at 100 years	1400	0.6058	1720	0.7154	5200	0.9862	680	0.0568
13: Initial capital outlay	1142	0.9547	853.9	0.9734	853.9	0.9734	486.7	0.9907
14: Number of similar reactors in	0	0.0000	17	1.0000	0	0.0000	0	0.0000
15: Title 15	0	0.0000	0	0.0000	0	0.0000	0	0.0000
	UStatic:	3.51E-01	UStatic:	4.08E-01	UStatic:	3.66E-01	UStatic:	3.73E-01
	UTotal:	7.46E-01	UTotal:	7.60E-01	UTotal:	7.93E-01	UTotal:	8.25E-01

The first four utility function values are baseline values that assume there are no delays and that the reactor performs at a 75% capacity factor. Utility function values for delays or different capacity factors are computed in the decision tree.

The values for utility functions five through fourteen are static, in that they are not affected by delays or different capacity factors. These values are summed, referenced as UStatic, and transmitted to the decision tree code where they are used without further modification.

Appendix B - DPL Code for Decision Tree Model

```
*****
//Decision Tree Model for Pu Disposition with Advanced Reactors
// LPDS-034
// Tom Edmunds
// September 20, 1994
*****

// Link to spreadsheet for utility function assessments
string Excel_1="c:\\weapdisp\\pu\\utils\\bob2.xls";

// Global parameters
value InitStockpile=50000; //kg Pu
value DiscountRate=.04; //per ORNL cost calculations
value d=1/(1+DiscountRate);
value ElecPrice=.01919; //1993$ per kwh in 1993
value ElecEsc=.015; //effective electrical energy price escalation
//matches ORNL escalation curve in year 2020
value CapPay=0.01; //1993$ per kwh does not escalate
value eps=.000001; //used to prevent divide by zero in utility fns.
value DelayCostFraction=.20; //Fraction of ConsCost1 expended each year
// during construction delay
value Gamma=((1+DiscountRate)/(1+ElecEsc))-1;
//equivalent discount factor for electricity
// price that takes into account discount and
// escalation rates (1+e)/(1+d)=1/(1+Gamma)

//All ORNL cost data are in 1993$
//Vendor schdules use 1994 as base year so add 1 year to convert to 1993 base year

// Parameters for advanced/evolutionary reactors: *****
// GE technology parameters
value GETimeLic=18/12; //years from project start to construction permit
value GETimeConst=11-GETimeLic; //years from const. permit to comm. ops. - ORNL
value GEInitCap=4798; // per ORNL spreadsheets
value GEConstCost1=0.25*GEInitCap; //costs prior to construction delay
value GEConstCost2=0.75*GEInitCap; //costs after delay
value GECoreInv=6631; //kg Pu
value GEElecCap=2*1300*1000; //kw
value GENormalize=0.973; //adjust so that multiple units represented
// by single equivalent unit
value GEOMCost=7752+1675-GEInitCap; //back out ORNL LEU ops costs and initial
// capital from total cost
value GEPuDispRate=(InitStockpile-GECoreInv)/(26-GETimeLic-GETimeConst);
//kg Pu/year at nominal capacity factor

// W technology parameters
value WTimeLic=54/12;
value WTimeConst=11-WTimeLic; // per ORNL
value WInitCap=4484;
value WConstCost1=0.25*WInitCap;
value WConstCost2=0.75*WInitCap;
value WCoreInv=4081;
```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```
value WElecCap=4*600*1000;
value WNormalize=0.989;
value WOMCost=8160+846-WInitCap;
value WPuDispRate=(InitStockpile-WCoreInv)/(26-WTimeLic-WTimeConst);

// CE technology parameters
value CETimeLic=18/12;
value CETimeConst=9-CETimeLic;           //per ORNL
value CEInitCap=5831;
value CEConstCost1=0.25*CEInitCap;
value CEConstCost2=0.75*CEInitCap;
value CECoreInv=6670;
value CEElecCap=2*1250*1000;
value CENormalize=0.997;
value CEOMCost=9343+724-CEInitCap;
value CEPuDispRate=(InitStockpile-CECoreInv)/(26-CETimeLic-CETimeConst);

// GA technology parameters
value GATimeLic=86/12;
value GATimeConst=14-GATimeLic;          //per ORNL
value GAINitCap=5100;
value GAConstCost1=0.25*GAINitCap;
value GAConstCost2=0.75*GAINitCap;
value GACoreInv=634;
value GAElecCap=14*286*1000; //GA plans to build 14 reactors
value GANormalize=0.923; //needed to represent 14 reactors by 1 equivalent reactor
value GAOMCost=9826+1931-GAINitCap;
value GAPuDispRate=(InitStockpile-GACoreInv)/(26-GATimeLic-GATimeConst);

// Parameters for existing reactors: *****
// EXGE technology parameters
value EXGETimeLic=2;                     //Assumption
value EXGETimeConst=7.5-EXGETimeLic;
value EXGEInitCap=1142;
value EXGEConstCost1=0.25*EXGEInitCap;
value EXGEConstCost2=0.75*EXGEInitCap;
value EXGECoreInv=6631;                 //Assume same as advanced reactors
value EXGEElecCap=0;                     //Assume existing plant output owned by utility
value EXGENormalize=1.0;
value EXGEOMCost=2310-999-EXGEInitCap;
value EXGEPuDispRate=(InitStockpile-EXGECoreInv)/(26-EXGETimeLic-EXGETimeConst);

// EXW technology parameters
value EXWTimeLic=2;                       //Assumption
value EXWTimeConst=10-EXWTimeLic;
value EXWInitCap=854;
value EXWConstCost1=0.25*EXWInitCap;
value EXWConstCost2=0.75*EXWInitCap;
value EXWCoreInv=4065;
value EXWElecCap=0;
value EXWNormalize=1.0;
value EXWOMCost=1898-829-EXWInitCap;
value EXWPuDispRate=(InitStockpile-EXWCoreInv)/(26-EXWTimeLic-EXWTimeConst);
```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```
// EXCE technology parameters - this reactor design excluded from analysis due to insufficient data
value EXCETimeLic=2; //Assume same as EXW
value EXCETimeConst=10-EXCETimeLic; //Assume same as EXW
value EXCEInitCap=1000; //Assumption
value EXCEConstCost1=0.25*EXCEInitCap;
value EXCEConstCost2=0.75*EXCEInitCap;
value EXCECoreInv=6670; //Assume same as advanced CE
value EXCEElecCap=0;
value EXCENormalize=1.0;
value EXCEOMCost=1898-829-EXCEInitCap; //Assume same as EXW
value EXCEPuDispRate=(InitStockpile-EXCECoreInv)/(26-EXCETimeLic-EXCETimeConst);

// EXCAN technology parameters
value EXCANTimeLic=1; //Assumption
value EXCANTimeConst=5-EXCANTimeLic;
value EXCANInitCap=487;
value EXCANConstCost1=0.25*EXCANInitCap;
value EXCANConstCost2=0.75*EXCANInitCap;
value EXCANCoreInv=1448;
value EXCANElecCap=0;
value EXCANNormalize=1.0;
value EXCANOMCost=1683-201-EXCANInitCap;
value EXCANPuDispRate=(InitStockpile-EXCANCoreInv)/(26-EXCANTimeLic-EXCANTimeConst);

//*****
// Utility function parameters read from spreadsheet
//excel(Excel_1,"k2_k1") value r21; //ratio of utility function coefficients
//excel(Excel_1,"k3_k1") value r31; // in multiattribute utility function
//excel(Excel_1,"k4_k1") value r41; // based on tradeoff questions in spreadsheet
//excel(Excel_1,"k5_k1") value r51;
//excel(Excel_1,"k6_k1") value r61;
//excel(Excel_1,"k7_k1") value r71;
//excel(Excel_1,"k8_k1") value r81;
//excel(Excel_1,"k9_k1") value r91;
//excel(Excel_1,"k10_k1") value r101;
//excel(Excel_1,"k11_k1") value r111;
//excel(Excel_1,"k12_k1") value r121;
//excel(Excel_1,"k13_k1") value r131;
//excel(Excel_1,"k14_k1") value r141;
//excel(Excel_1,"k15_k1") value r151;

// Hard-code utility function ratios to allow sensitivity analysis, 9/14/94 data
value r21=1.59;
value r31=0.722;
value r41=0.443;
value r51=0.0;
value r61=0.0142;
value r71=0.0152;
value r81=0.0601;
value r91=0.111;
value r101=0.00875;
value r111=0.575;
value r121=0.0021;
```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```
value r131=2.01;
value r141=0.254;
value r151=0.0000;

//computation of multiattribute utility function coefficients given ratios
value k1=1/(1+r21+r31+r41+r51+r61+r71+r81+r91+r101+r111+r121+r131+r141+r151);
value k2=k1*r21;
value k3=k1*r31;
value k4=k1*r41;
value k5=k1*r51;
value k6=k1*r61;
value k7=k1*r71;
value k8=k1*r81;
value k9=k1*r91;
value k10=k1*r101;
value k11=k1*r111;
value k12=k1*r121;
value k13=k1*r131;
value k14=k1*r141;
value k15=k1*r151;

//read in coefficients for first 4 utility functions
// 1=Cost
excel(Excel_1,"c_1") value c1;
excel(Excel_1,"b_1") value b1;
excel(Excel_1,"worst1") value worst1;
excel(Excel_1,"best1") value best1;
// 2=Time to start
excel(Excel_1,"c_2") value c2;
excel(Excel_1,"b_2") value b2;
excel(Excel_1,"worst2") value worst2;
excel(Excel_1,"best2") value best2;
// 3=Time to complete
excel(Excel_1,"c_3") value c3;
excel(Excel_1,"b_3") value b3;
excel(Excel_1,"worst3") value worst3;
excel(Excel_1,"best3") value best3;
// 4=MT-yr
excel(Excel_1,"c_4") value c4;
excel(Excel_1,"b_4") value b4;
excel(Excel_1,"worst4") value worst4;
excel(Excel_1,"best4") value best4;

//Utility function values for attributes that are independent of time and cost
//GE static utility function values
excel(Excel_1,"UGE5") value UGE5;
excel(Excel_1,"UGE6") value UGE6;
excel(Excel_1,"UGE7") value UGE7;
excel(Excel_1,"UGE8") value UGE8;
excel(Excel_1,"UGE9") value UGE9;
excel(Excel_1,"UGE10") value UGE10;
excel(Excel_1,"UGE11") value UGE11;
excel(Excel_1,"UGE12") value UGE12;
excel(Excel_1,"UGE13") value UGE13;
```

```
excel(Excel_1,"UGE14") value UGE14;
excel(Excel_1,"UGE15") value UGE15;
//W static utility function values
excel(Excel_1,"UW5") value UW5;
excel(Excel_1,"UW6") value UW6;
excel(Excel_1,"UW7") value UW7;
excel(Excel_1,"UW8") value UW8;
excel(Excel_1,"UW9") value UW9;
excel(Excel_1,"UW10") value UW10;
excel(Excel_1,"UW11") value UW11;
excel(Excel_1,"UW12") value UW12;
excel(Excel_1,"UW13") value UW13;
excel(Excel_1,"UW14") value UW14;
excel(Excel_1,"UW15") value UW15;
//CE static utility function values
excel(Excel_1,"UCE5") value UCE5;
excel(Excel_1,"UCE6") value UCE6;
excel(Excel_1,"UCE7") value UCE7;
excel(Excel_1,"UCE8") value UCE8;
excel(Excel_1,"UCE9") value UCE9;
excel(Excel_1,"UCE10") value UCE10;
excel(Excel_1,"UCE11") value UCE11;
excel(Excel_1,"UCE12") value UCE12;
excel(Excel_1,"UCE13") value UCE13;
excel(Excel_1,"UCE14") value UCE14;
excel(Excel_1,"UCE15") value UCE15;
//GA static utility function values
excel(Excel_1,"UGA5") value UGA5;
excel(Excel_1,"UGA6") value UGA6;
excel(Excel_1,"UGA7") value UGA7;
excel(Excel_1,"UGA8") value UGA8;
excel(Excel_1,"UGA9") value UGA9;
excel(Excel_1,"UGA10") value UGA10;
excel(Excel_1,"UGA11") value UGA11;
excel(Excel_1,"UGA12") value UGA12;
excel(Excel_1,"UGA13") value UGA13;
excel(Excel_1,"UGA14") value UGA14;
excel(Excel_1,"UGA15") value UGA15;
//EXGE static utility function values
excel(Excel_1,"UEXGE5") value UEXGE5;
excel(Excel_1,"UEXGE6") value UEXGE6;
excel(Excel_1,"UEXGE7") value UEXGE7;
excel(Excel_1,"UEXGE8") value UEXGE8;
excel(Excel_1,"UEXGE9") value UEXGE9;
excel(Excel_1,"UEXGE10") value UEXGE10;
excel(Excel_1,"UEXGE11") value UEXGE11;
excel(Excel_1,"UEXGE12") value UEXGE12;
excel(Excel_1,"UEXGE13") value UEXGE13;
excel(Excel_1,"UEXGE14") value UEXGE14;
excel(Excel_1,"UEXGE15") value UEXGE15;
//EXW static utility function values
excel(Excel_1,"UEXW5") value UEXW5;
excel(Excel_1,"UEXW6") value UEXW6;
excel(Excel_1,"UEXW7") value UEXW7;
```

```

excel(Excel_1,"UEXW8") value UEXW8;
excel(Excel_1,"UEXW9") value UEXW9;
excel(Excel_1,"UEXW10") value UEXW10;
excel(Excel_1,"UEXW11") value UEXW11;
excel(Excel_1,"UEXW12") value UEXW12;
excel(Excel_1,"UEXW13") value UEXW13;
excel(Excel_1,"UEXW14") value UEXW14;
excel(Excel_1,"UEXW15") value UEXW15;
//EXCE static utility function values
excel(Excel_1,"UEXCE5") value UEXCE5;
excel(Excel_1,"UEXCE6") value UEXCE6;
excel(Excel_1,"UEXCE7") value UEXCE7;
excel(Excel_1,"UEXCE8") value UEXCE8;
excel(Excel_1,"UEXCE9") value UEXCE9;
excel(Excel_1,"UEXCE10") value UEXCE10;
excel(Excel_1,"UEXCE11") value UEXCE11;
excel(Excel_1,"UEXCE12") value UEXCE12;
excel(Excel_1,"UEXCE13") value UEXCE13;
excel(Excel_1,"UEXCE14") value UEXCE14;
excel(Excel_1,"UEXCE15") value UEXCE15;
//EXCAN static utility function values
excel(Excel_1,"UEXCAN5") value UEXCAN5;
excel(Excel_1,"UEXCAN6") value UEXCAN6;
excel(Excel_1,"UEXCAN7") value UEXCAN7;
excel(Excel_1,"UEXCAN8") value UEXCAN8;
excel(Excel_1,"UEXCAN9") value UEXCAN9;
excel(Excel_1,"UEXCAN10") value UEXCAN10;
excel(Excel_1,"UEXCAN11") value UEXCAN11;
excel(Excel_1,"UEXCAN12") value UEXCAN12;
excel(Excel_1,"UEXCAN13") value UEXCAN13;
excel(Excel_1,"UEXCAN14") value UEXCAN14;
excel(Excel_1,"UEXCAN15") value UEXCAN15;

//Computation of fixed utility
value UGEFixed=k5*UGE5+k6*UGE6+k7*UGE7+k8*UGE8+k9*UGE9+k10*UGE10
+k11*UGE11+k12*UGE12+k13*UGE13+k14*UGE14+k15*UGE15;
value UWFxed=k5*UW5+k6*UW6+k7*UW7+k8*UW8+k9*UW9+k10*UW10
+k11*UW11+k12*UW12+k13*UW13+k14*UW14+k15*UW15;
value UCEFixed=k5*UCE5+k6*UCE6+k7*UCE7+k8*UCE8+k9*UCE9+k10*UCE10
+k11*UCE11+k12*UCE12+k13*UCE13+k14*UCE14+k15*UCE15;
value UGAFixed=k5*UGA5+k6*UGA6+k7*UGA7+k8*UGA8+k9*UGA9+k10*UGA10
+k11*UGA11+k12*UGA12+k13*UGA13+k14*UGA14+k15*UGA15;
value UEXGEFixed=
    k5*UEXGE5+k6*UEXGE6+k7*UEXGE7+k8*UEXGE8+k9*UEXGE9+k10*UEXGE10
    +k11*UEXGE11+k12*UEXGE12+k13*UEXGE13+k14*UEXGE14+k15*UEXGE15;
value UEXWFixed=k5*UEXW5+k6*UEXW6+k7*UEXW7+k8*UEXW8+k9*UEXW9+k10*UEXW10
+k11*UEXW11+k12*UEXW12+k13*UEXW13+k14*UEXW14+k15*UEXW15;
value UEXCEFixed=
    k5*UEXCE5+k6*UEXCE6+k7*UEXCE7+k8*UEXCE8+k9*UEXCE9+k10*UEXCE10
    +k11*UEXCE11+k12*UEXCE12+k13*UEXCE13+k14*UEXCE14+k15*UEXCE15;
value UEXCANFixed=
    k5*UEXCAN5+k6*UEXCAN6+k7*UEXCAN7+k8*UEXCAN8+k9*UEXCAN9
    +k10*UEXCAN10+k11*UEXCAN11+k12*UEXCAN12+k13*UEXCAN13

```


+k14*UEXCAN14+k15*UEXCAN15;

// Definition of decision and chance nodes

// Decision node for first licensing attempt with possible failure to license

decision LicAttempt1.{GE,W,CE,GA,EXGE,EXW,EXCE,EXCAN};

chance LicFail.{License,NoLicense}|LicAttempt1=

{.98}, // LicAttempt1.GE (license success probability)
 {.98}, // LicAttempt1.W
 {.98}, // LicAttempt1.CE
 {.86}, // LicAttempt1.GA
 {.98}, // LicAttempt1.EXGE
 {.98}, // LicAttempt1.EXW
 {.98}, // LicAttempt1.EXCE
 {.98}; // LicAttempt1.EXCAN

//GE chance nodes *****

// Licensing delay for GE given licensing is successful

chance GELicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.55/.98,.23/.98,.13/.98,}=

0, // GELicDelay.None
 2, // GELicDelay.Delay_2_yr
 4, // GELicDelay.Delay_4_yr
 6; // GELicDelay.Delay_6_yr

// Construction delay for GE

// (assumed to occur after ConstCost1 is expended)

chance GEConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.48,.28,.19,}=

0, // GEConstDelay.None
 2, // GEConstDelay.Delay_2_yr
 4, // GEConstDelay.Delay_4_yr
 6; // GEConstDelay.Delay_6_yr

// Capacity factor for GE

chance GECapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.28,.5,}=

.55, // GECapFact.Cap55
 .65, // GECapFact.Cap65
 .75, // GECapFact.Cap75
 .85; // GECapFact.Cap85

//W chance nodes *****

//Licensing delay given W is licensed

chance WLicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.4/.98,.35/.98,.15/.98,}=

0, // WLicDelay.None
 2, // WLicDelay.Delay_2_yr
 4, // WLicDelay.Delay_4_yr
 6; // WLicDelay.Delay_6_yr

//Construction delay for W

chance WConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.4,.35,.19,}=

0, // WConstDelay.None
 2, // WConstDelay.Delay_2_yr
 4, // WConstDelay.Delay_4_yr
 6; // WConstDelay.Delay_6_yr

```
//Capacity factor for W
chance WCapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.28,.5,}=
    .55,          // WCapFact.Cap55
    .65,          // WCapFact.Cap65
    .75,          // WCapFact.Cap75
    .85;          // WCapFact.Cap85

//CE chance nodes *****
//Licensing delay for CE
chance CELicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.55/.98,.23/.98,.13/.98,}=
    0,            // CELicDelay.None
    2,            // CELicDelay.Delay_2_yr
    4,            // CELicDelay.Delay_4_yr
    6;            // CELicDelay.Delay_6_yr

//Construction delay for CE
chance CEConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.48,.28,.19,}=
    0,            // CEConstDelay.None
    2,            // CEConstDelay.Delay_2_yr
    4,            // CEConstDelay.Delay_4_yr
    6;            // CEConstDelay.Delay_6_yr

//Capacity factor for CE
chance CECapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.29,.5,}=
    .55,          // CECapFact.Cap55
    .65,          // CECapFact.Cap65
    .75,          // CECapFact.Cap75
    .85;          // CECapFact.Cap85

//GA chance nodes *****
//Licensing delay for GA
chance GALicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.20/.86,.25/.86,.30/.86,}=
    0,            // GALicDelay.None
    2,            // GALicDelay.Delay_2_yr
    4,            // GALicDelay.Delay_4_yr
    6;            // GALicDelay.Delay_6_yr

//Construction delay for GA
chance GAConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.28,.4,.23,}=
    0,            // GAConstDelay.None
    2,            // GAConstDelay.Delay_2_yr
    4,            // GAConstDelay.Delay_4_yr
    6;            // GAConstDelay.Delay_6_yr

//Capacity factor for GA
chance GACapFact.{Cap55,Cap65,Cap75,Cap85}={.22,.17,.5,}=
    .55,          // GACapFact.Cap55
    .65,          // GACapFact.Cap65
    .75,          // GACapFact.Cap75
    .85;          // GACapFact.Cap85

//EXGE chance nodes *****
//Licensing delay for EXGE
chance EXGELicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.70/1,.30/1,0/1,}=
```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```
0,          // EXGELicDelay.None
2,          // EXGELicDelay.Delay_2_yr
4,          // EXGELicDelay.Delay_4_yr
6;          // EXGELicDelay.Delay_6_yr

// Construction delay for EXGE (assumed to occur after ConstCost1 is expended on first reactor)
chance EXGECnstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.9,.1,0,}=
0,          // EXGECnstDelay.None
2,          // EXGECnstDelay.Delay_2_yr
4,          // EXGECnstDelay.Delay_4_yr
6;          // EXGECnstDelay.Delay_6_yr

// Capacity factor for EXGE
chance EXGECapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.28,.5,}=
.55,        // EXGECapFact.Cap55
.65,        // EXGECapFact.Cap65
.75,        // EXGECapFact.Cap75
.85;        // EXGECapFact.Cap85

//EXW chance nodes *****
//Licensing delay given EXW is licensed
chance EXWLicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.70/1,.30/1,0/1,}=
0,          // EXWLicDelay.None
2,          // EXWLicDelay.Delay_2_yr
4,          // EXWLicDelay.Delay_4_yr
6;          // EXWLicDelay.Delay_6_yr

//Construction delay for EXW
chance EXWConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.9,.1,0,}=
0,          // EXWConstDelay.None
2,          // EXWConstDelay.Delay_2_yr
4,          // EXWConstDelay.Delay_4_yr
6;          // EXWConstDelay.Delay_6_yr

//Capacity factor for EXW
chance EXWCapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.28,.5,}=
.55,        // EXWCapFact.Cap55
.65,        // EXWCapFact.Cap65
.75,        // EXWCapFact.Cap75
.85;        // EXWCapFact.Cap85

//EXCE chance nodes *****
//Licensing delay given EXCE is licensed
chance EXCELicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.60/1,.40/1,0/1,}=
0,          // EXCELicDelay.None
2,          // EXCELicDelay.Delay_2_yr
4,          // EXCELicDelay.Delay_4_yr
6;          // EXCELicDelay.Delay_6_yr

//Construction delay for EXCE
chance EXCEConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.9,.1,0,}=
0,          // EXCEConstDelay.None
2,          // EXCEConstDelay.Delay_2_yr
4,          // EXCEConstDelay.Delay_4_yr
```

```

6;          // EXCEConstDelay.Delay_6_yr

//Capacity factor for EXCE
chance EXCECapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.29,.5,}=
    .55,      // EXCECapFact.Cap55
    .65,      // EXCECapFact.Cap65
    .75,      // EXCECapFact.Cap75
    .85;      // EXCECapFact.Cap85

//EXCAN chance nodes *****
//Licensing delay given EXCAN is licensed
chance EXCANLicDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.75/1,.25/1,0/1,}=
    0,        // EXCANLicDelay.None
    2,        // EXCANLicDelay.Delay_2_yr
    4,        // EXCANLicDelay.Delay_4_yr
    6;        // EXCANLicDelay.Delay_6_yr

//Construction delay for EXCAN
chance EXCANConstDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.9,.1,0,}=
    0,        // EXCANConstDelay.None
    2,        // EXCANConstDelay.Delay_2_yr
    4,        // EXCANConstDelay.Delay_4_yr
    6;        // EXCANConstDelay.Delay_6_yr

//Capacity factor for EXCAN
chance EXCANCapFact.{Cap55,Cap65,Cap75,Cap85}={.1,.2,.5,}=
    .55,      // EXCANCapFact.Cap55
    .65,      // EXCANCapFact.Cap65
    .75,      // EXCANCapFact.Cap75
    .85;      // EXCANCapFact.Cap85

//Time spent on first licensing attempt in years *****
// (second licensing effort started after this time)
value LicFailTime|LicAttempt1,LicFail=
    // LicAttempt1.GE
    0,        // LicFail.License
    6,        // LicFail.NoLicense
    // LicAttempt1.W
    0,        // LicFail.License
    6,        // LicFail.NoLicense
    // LicAttempt1.CE
    0,        // LicFail.License
    6,        // LicFail.NoLicense
    // LicAttempt1.GA
    0,        // LicFail.License
    6,        // LicFail.NoLicense
    // LicAttempt1.EXGE
    0,        // LicFail.License
    3,        // LicFail.NoLicense
    // LicAttempt1.EXW
    0,        // LicFail.License
    3,        // LicFail.NoLicense
    // LicAttempt1.EXCE
    0,        // LicFail.License

```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```

3,          //      LicFail.NoLicense
           // LicAttempt1.EXCAN
0,          //      LicFail.License
3;          //      LicFail.NoLicense

//cost expended on licensing attempt, million $
value LicFailCost|LicAttempt1,LicFail=
           // LicAttempt1.GE      Assume spend $1 billion in license attempt
0,          //      LicFail.License
1000, //      LicFail.NoLicense
           // LicAttempt1.W
0,          //      LicFail.License
1000, //      LicFail.NoLicense
           // LicAttempt1.CE
0,          //      LicFail.License
1000, //      LicFail.NoLicense
           // LicAttempt1.GA
0,          //      LicFail.License
1000, //      LicFail.NoLicense
           // LicAttempt1.EXGE
0,          //      LicFail.License
500,  //      LicFail.NoLicense      Assume spend $500 million in license attempt
           // LicAttempt1.EXW
0,          //      LicFail.License
500,  //      LicFail.NoLicense
           // LicAttempt1.EXCE
0,          //      LicFail.License
500,  //      LicFail.NoLicense
           // LicAttempt1.EXCAN
0,          //      LicFail.License
500;      //      LicFail.NoLicense

//MOX fuel plant delay
//CANDU MOX fuel plant delay
chance CANFuelDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.8,.2,0,}=
0,          // CANFuelDelay.None
2,          // CANFuelDelay.Delay_2_yr
4,          // CANFuelDelay.Delay_4_yr
6;          // CANFuelDelay.Delay_6_yr

//Other MOX fuel plant delay
chance OthFuelDelay.{None,Delay_2_yr,Delay_4_yr,Delay_6_yr}={.5,.3,.1,}=
0,          // OthFuelDelay.None
2,          // OthFuelDelay.Delay_2_yr
4,          // OthFuelDelay.Delay_4_yr
6;          // OthFuelDelay.Delay_6_yr

//Delay adjustment (assumes both fuel fabrication facility and
// reactor are on critical path, delay = max (fuel plant delay, reactor delay)
value GEDelayAdjust=max(OthFuelDelay-(GELicDelay+GEConstDelay+LicFailTime),0);
value WDelayAdjust=max(OthFuelDelay-(WLicDelay+WConstDelay+LicFailTime),0);
value CEDelayAdjust=max(OthFuelDelay-(CELicDelay+CEConstDelay+LicFailTime),0);
value GADelayAdjust=max(OthFuelDelay-(GALicDelay+GAConstDelay+LicFailTime),0);
value EXGEDelayAdjust=max(OthFuelDelay-(EXGELicDelay+EXGConstDelay+LicFailTime),0);

```

```

value EXWDelayAdjust=max(OthFuelDelay-(EXWLicDelay+EXWConstDelay+LicFailTime),0);
value EXCEDelayAdjust=max(OthFuelDelay-(EXCELicDelay+EXCEConstDelay+LicFailTime),0);
value EXCANDelayAdjust=max(CANFuelDelay-
(EXCANLicDelay+EXCANConstDelay+LicFailTime),0);

//*****
//Computation of outcomes and utility function values
//GE outcomes
value GETimeStart=LicFailTime+GETimeLic+GELicDelay+GETimeConst
+(GConstDelay+GEDelayAdjust);
value GEMTyr=(InitStockpile*(LicFailTime+GETimeLic+GELicDelay+GETimeConst
+(GConstDelay+GEDelayAdjust))
+0.5*((InitStockpile-GECoreInv)^2)/(GEPuDispRate*(GECapFact/0.75)))/1000;
// divide by 1000 to convert to from kgYr to MTyr
value GETimeComplete=LicFailTime+GETimeLic+GELicDelay+GETimeConst
+(GConstDelay+GEDelayAdjust)
+(InitStockpile-GECoreInv)/(GEPuDispRate*(GECapFact/0.75));
value GENPVConst=GConstCost1*(d^(LicFailTime+GELicDelay))
+GConstCost2*(d^(LicFailTime+GELicDelay+(GConstDelay+GEDelayAdjust)))
+GConstCost1*DelayCostFraction
*(1/DiscountRate*(1-(d^(GConstDelay+GEDelayAdjust))))
*(d^(LicFailTime+GELicDelay)); //last term is annuity for const. delay period
value GENPVOM=GEOMCost*(d^(LicFailTime+GELicDelay+(GConstDelay+GEDelayAdjust)));
value GENPVRev=GENormalize*GEElecCap*GECapFact*8760/1000000
*((1+ElecEsc)^(LicFailTime+GETimeLic+GELicDelay+GETimeConst
+(GConstDelay+GEDelayAdjust)))
*ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))
*(d^(LicFailTime+GETimeLic+GELicDelay+GETimeConst+(GConstDelay+GEDelayAdjust)))
;
value GENPVTot=LicFailCost+GENPVConst+GENPVOM-GENPVRev;
value UGETimeStart=1/(1+c2*((@abs(best2-GETimeStart))
/(@abs(GETimeStart-worst2)+eps))^b2);
value UGETimeComplete=1/(1+c3*((@abs(best3-GETimeComplete))
/(@abs(GETimeComplete-worst3)+eps))^b3);
value UGEMTyr=1/(1+c4*((@abs(best4-GEMTyr))/(@abs(GEMTyr-worst4)+eps))^b4);
value UGENPVTot=1/(1+c1*((@abs(best1-GENPVTot))/(@abs(GENPVTot-worst1)+eps))^b1);

//W outcomes
value WTimeStart=LicFailTime+WTimeLic+WLicDelay+WTimeConst+(WConstDelay+WDelayAdjust);
value WMTyr=(InitStockpile*(LicFailTime+WTimeLic+WLicDelay+WTimeConst
+(WConstDelay+WDelayAdjust))
+0.5*((InitStockpile-WCoreInv)^2)/(WPuDispRate*(WCapFact/0.75)))/1000;
value WTimeComplete=LicFailTime+WTimeLic+WLicDelay+WTimeConst
+(WConstDelay+WDelayAdjust)
+(InitStockpile-WCoreInv)/(WPuDispRate*(WCapFact/0.75));
value WNPVConst=WConstCost1*(d^(LicFailTime+WLicDelay))
+WConstCost2*(d^(LicFailTime+WLicDelay+(WConstDelay+WDelayAdjust)))
+WConstCost1*DelayCostFraction*(1/DiscountRate
*(1-(d^(WConstDelay+WDelayAdjust))))*(d^(LicFailTime+WLicDelay));
value WNPVOM=WOMCost*(d^(LicFailTime+WLicDelay+(WConstDelay+WDelayAdjust)));
value WNPVRev=WNormalize*WElecCap*WCapFact*8760/1000000
*((1+ElecEsc)^(LicFailTime+WTimeLic+WLicDelay+WTimeConst
+(WConstDelay+WDelayAdjust)))
*ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))

```



```

*(d^(LicFailTime+WTimeLic+WLicDelay+WTimeConst+(WConstDelay+WDelayAdjust)));
value WNPVTot=LicFailCost+WNPVConst+WNPVOM-WNPVRev;
value UWTimeStart=1/(1+c2*((@abs(best2-WTimeStart))
/(@abs(WTimeStart-worst2)+eps))^b2);
value UWTimeComplete=1/(1+c3*((@abs(best3-WTimeComplete))
/(@abs(WTimeComplete-worst3)+eps))^b3);
value UWMTyr=1/(1+c4*((@abs(best4-WMTyr))/(@abs(WMTyr-worst4)+eps))^b4);
value UWNPVTot=1/(1+c1*((@abs(best1-WNPVTot))/(@abs(WNPVTot-worst1)+eps))^b1);

//CE outcomes
value CETimeStart=LicFailTime+CETimeLic+CELicDelay+CETimeConst
+(CEConstDelay+CEDelayAdjust);
value CEMTyr=(InitStockpile*(LicFailTime+CETimeLic+CELicDelay+CETimeConst
+(CEConstDelay+CEDelayAdjust))
+0.5*((InitStockpile-CECoreInv)^2)/(CEPuDispRate*(CECapFact/0.75)))/1000;
value CETimeComplete=LicFailTime+CETimeLic+CELicDelay+CETimeConst
+(CEConstDelay+CEDelayAdjust)
+(InitStockpile-CECoreInv)/(CEPuDispRate*(CECapFact/0.75));
value CENPVConst=CEConstCost1*(d^(LicFailTime+CELicDelay))
+CEConstCost2*(d^(LicFailTime+CELicDelay+(CEConstDelay+CEDelayAdjust)))
+CEConstCost1*DelayCostFraction*(1/DiscountRate
*(1-(d^(CEConstDelay+CEDelayAdjust))))*(d^(LicFailTime+CELicDelay));
value CENPVOM=CEOMCost*(d^(LicFailTime+CELicDelay+(CEConstDelay+CEDelayAdjust)));
value CENPVRev=CENormalize*CEElecCap*CECapFact*8760/1000000
*((1+ElecEsc)^(LicFailTime+CETimeLic+CELicDelay+CETimeConst
+(CEConstDelay+CEDelayAdjust)))
*ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))
*(d^(LicFailTime+CETimeLic+CELicDelay+CETimeConst+(CEConstDelay+CEDelayAdjust)));
value CENPVTot=LicFailCost+CENPVConst+CENPVOM-CENPVRev;
value UCETimeStart=1/(1+c2*((@abs(best2-CETimeStart))
/(@abs(CETimeStart-worst2)+eps))^b2);
value UCETimeComplete=1/(1+c3*((@abs(best3-CETimeComplete))
/(@abs(CETimeComplete-worst3)+eps))^b3);
value UCEMTyr=1/(1+c4*((@abs(best4-CEMTyr))/(@abs(CEMTyr-worst4)+eps))^b4);
value UCENPVTot=1/(1+c1*((@abs(best1-CENPVTot))/(@abs(CENPVTot-worst1)+eps))^b1);

//GA outcomes
value GATimeStart=LicFailTime+GATimeLic+GALicDelay+GATimeConst
+(GAConstDelay+GADelayAdjust);
value GAMTyr=(InitStockpile*(LicFailTime+GATimeLic+GALicDelay+GATimeConst
+(GAConstDelay+GADelayAdjust))
+0.5*((InitStockpile-GACoreInv)^2)/(GAPuDispRate*(GACapFact/0.75)))/1000;
value GATimeComplete=LicFailTime+GATimeLic+GALicDelay+GATimeConst
+(GAConstDelay+GADelayAdjust)
+(InitStockpile-GACoreInv)/(GAPuDispRate*(GACapFact/0.75));
value GANPVConst=GAConstCost1*(d^(LicFailTime+GALicDelay))
+GAConstCost2*(d^(LicFailTime+GALicDelay+(GAConstDelay+GADelayAdjust)))
+GAConstCost1*DelayCostFraction*(1/DiscountRate
*(1-(d^(GAConstDelay+GADelayAdjust))))*(d^(LicFailTime+GALicDelay));
value GANPVOM=GAOMCost*(d^(LicFailTime+GALicDelay+(GAConstDelay+GADelayAdjust)));
value GANPVRev=GANormalize*GAElecCap*GACapFact*8760/1000000
*((1+ElecEsc)^(LicFailTime+GATimeLic+GALicDelay+GATimeConst
+(GAConstDelay+GADelayAdjust)))
*ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))

```

```

    *(d^(LicFailTime+GATimeLic+GALicDelay+GATimeConst+(GACnstDelay+GADelayAdjust)
));
value GANPVTot=LicFailCost+GANPVConst+GANPVOM-GANPVRev;
value UGATimeStart=1/(1+c2*((@abs(best2-GATimeStart))
    /(@abs(GATimeStart-worst2)+eps))^b2);
value UGATimeComplete=1/(1+c3*((@abs(best3-GATimeComplete))
    /(@abs(GATimeComplete-worst3)+eps))^b3);
value UGAMTyr=1/(1+c4*((@abs(best4-GAMTyr))/(@abs(GAMTyr-worst4)+eps))^b4);
value UGANPVTot=1/(1+c1*((@abs(best1-GANPVTot))/(@abs(GANPVTot-worst1)+eps))^b1);

//EXGE outcomes
value EXGETimeStart=LicFailTime+EXGETimeLic+EXGELicDelay+EXGETimeConst
    +(EXGEConstDelay+EXGEDelayAdjust);
value EXGEMTyr=(InitStockpile*(LicFailTime+EXGETimeLic+EXGELicDelay+EXGETimeConst
    +(EXGEConstDelay+EXGEDelayAdjust))
    +0.5*(InitStockpile-
EXGECoreInv)^2)/(EXGEPuDispRate*(EXGECapFact/0.75))/1000;
value EXGETimeComplete=LicFailTime+EXGETimeLic+EXGELicDelay+EXGETimeConst
    +(EXGEConstDelay+EXGEDelayAdjust)
    +(InitStockpile-EXGECoreInv)/(EXGEPuDispRate*(EXGECapFact/0.75));
value EXGENPVConst=EXGEConstCost1*(d^(LicFailTime+EXGELicDelay))
    +EXGEConstCost2*(d^(LicFailTime+EXGELicDelay+(EXGEConstDelay+EXGEDelayAdjust)
)
    +EXGEConstCost1*DelayCostFraction*(1/DiscountRate
    *(1-(d^(EXGEConstDelay+EXGEDelayAdjust))))*(d^(LicFailTime+EXGELicDelay));
value EXGENPVOM=EXGEOMCost
    *(d^(LicFailTime+EXGELicDelay+(EXGEConstDelay+EXGEDelayAdjust)));
value EXGENPVRev=EXGENormalize*EXGEElecCap*EXGECapFact*8760/1000000
    *((1+ElecEsc)^(LicFailTime+EXGETimeLic+EXGELicDelay+EXGETimeConst
    +(EXGEConstDelay+EXGEDelayAdjust)))
    *ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))
    *(d^(LicFailTime+EXGETimeLic+EXGELicDelay+EXGETimeConst
    +(EXGEConstDelay+EXGEDelayAdjust)));
value EXGENPVTot=LicFailCost+EXGENPVConst+EXGENPVOM-EXGENPVRev;
value UEXGETimeStart=1/(1+c2*((@abs(best2-EXGETimeStart))
    /(@abs(EXGETimeStart-worst2)+eps))^b2);
value UEXGETimeComplete=1/(1+c3*((@abs(best3-EXGETimeComplete))
    /(@abs(EXGETimeComplete-worst3)+eps))^b3);
value UEXGEMTyr=1/(1+c4*((@abs(best4-EXGEMTyr))/(@abs(EXGEMTyr-worst4)+eps))^b4);
value UEXGENPVTot=1/(1+c1*((@abs(best1-EXGENPVTot))/(@abs(EXGENPVTot-worst1)+eps))^b1);

//EXW outcomes
value EXWTimeStart=LicFailTime+EXWTimeLic+EXWLicDelay+EXWTimeConst
    +(EXWConstDelay+EXWDelayAdjust);
value EXWMTyr=(InitStockpile*(LicFailTime+EXWTimeLic+EXWLicDelay+EXWTimeConst
    +(EXWConstDelay+EXWDelayAdjust))
    +0.5*(InitStockpile-EXWCoreInv)^2)/(EXWPuDispRate*(EXWCapFact/0.75))/1000;
value EXWTimeComplete=LicFailTime+EXWTimeLic+EXWLicDelay+EXWTimeConst
    +(EXWConstDelay+EXWDelayAdjust)
    +(InitStockpile-EXWCoreInv)/(EXWPuDispRate*(EXWCapFact/0.75));
value EXWNPVConst=EXWConstCost1*(d^(LicFailTime+EXWLicDelay))
    +EXWConstCost2*(d^(LicFailTime+EXWLicDelay+(EXWConstDelay+EXWDelayAdjust)
    +EXWConstCost1*DelayCostFraction*(1/DiscountRate
    *(1-(d^(EXWConstDelay+EXWDelayAdjust))))*(d^(LicFailTime+EXWLicDelay));

```



```

value EXWNPVOM=EXWOMCost*(d^(LicFailTime+EXWLicDelay
+(EXWConstDelay+EXWDelayAdjust)));
value EXWNPVRev=EXWNormalize*EXWElecCap*EXWCapFact*8760/1000000
*((1+ElecEsc)^(LicFailTime+EXWTimeLic+EXWLicDelay+EXWTimeConst
+(EXWConstDelay+EXWDelayAdjust)))
*ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))
*(d^(LicFailTime+EXWTimeLic+EXWLicDelay+EXWTimeConst
+(EXWConstDelay+EXWDelayAdjust)));
value EXWNPVTot=LicFailCost+EXWNPVConst+EXWNPVOM-EXWNPVRev;
value UEXWTimeStart=1/(1+c2*((@abs(best2-EXWTimeStart))
/(@abs(EXWTimeStart-worst2)+eps))^b2);
value UEXWTimeComplete=1/(1+c3*((@abs(best3-EXWTimeComplete))
/(@abs(EXWTimeComplete-worst3)+eps))^b3);
value UEXWMTyr=1/(1+c4*((@abs(best4-EXWMTyr))/(@abs(EXWMTyr-worst4)+eps))^b4);
value UEXWNPVTot=1/(1+c1*((@abs(best1-EXWNPVTot))/(@abs(EXWNPVTot-worst1)+eps))^b1);

//EXCE outcomes
value EXCETimeStart=LicFailTime+EXCETimeLic+EXCELicDelay+EXCETimeConst
+(EXCEConstDelay+EXCEDelayAdjust);
value EXCEMTyr=(InitStockpile*(LicFailTime+EXCETimeLic+EXCELicDelay+EXCETimeConst
+(EXCEConstDelay+EXCEDelayAdjust))
+0.5*(InitStockpile-
EXCECoreInv)^2)/(EXCEPuDispRate*(EXCECapFact/0.75))/1000;
value EXCETimeComplete=LicFailTime+EXCETimeLic+EXCELicDelay+EXCETimeConst
+(EXCEConstDelay+EXCEDelayAdjust)
+(InitStockpile-EXCECoreInv)/(EXCEPuDispRate*(EXCECapFact/0.75));
value EXCENPVConst=EXCEConstCost1*(d^(LicFailTime+EXCELicDelay))
+EXCEConstCost2*(d^(LicFailTime+EXCELicDelay+(EXCEConstDelay+EXCEDelayAdjust)))
+EXCEConstCost1*DelayCostFraction*(1/DiscountRate
*(1-(d^(EXCEConstDelay+EXCEDelayAdjust))))*(d^(LicFailTime+EXCELicDelay));
value EXCENPVOM=EXCEOMCost
*(d^(LicFailTime+EXCELicDelay+(EXCEConstDelay+EXCEDelayAdjust)));
value EXCENPVRev=EXCENormalize*EXCEElecCap*EXCECapFact*8760/1000000
*((1+ElecEsc)^(LicFailTime+EXCETimeLic+EXCELicDelay+EXCETimeConst
+(EXCEConstDelay+EXCEDelayAdjust)))
*ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))
*(d^(LicFailTime+EXCETimeLic+EXCELicDelay+EXCETimeConst
+(EXCEConstDelay+EXCEDelayAdjust)));
value EXCENPVTot=LicFailCost+EXCENPVConst+EXCENPVOM-EXCENPVRev;
value UEXCETimeStart=1/(1+c2*((@abs(best2-EXCETimeStart))
/(@abs(EXCETimeStart-worst2)+eps))^b2);
value UEXCETimeComplete=1/(1+c3*((@abs(best3-EXCETimeComplete))
/(@abs(EXCETimeComplete-worst3)+eps))^b3);
value UEXCEMTyr=1/(1+c4*((@abs(best4-EXCEMTyr))/(@abs(EXCEMTyr-worst4)+eps))^b4);
value UEXCENPVTot=1/(1+c1*((@abs(best1-EXCENPVTot))/(@abs(EXCENPVTot-worst1)+eps))^b1);

//EXCAN outcomes
value EXCANTimeStart=LicFailTime+EXCANTimeLic+EXCANLicDelay+EXCANTimeConst
+(EXCANConstDelay+EXCANDelayAdjust);
value
EXCANMTyr=(InitStockpile*(LicFailTime+EXCANTimeLic+EXCANLicDelay+EXCANTimeConst
+(EXCANConstDelay+EXCANDelayAdjust))
+0.5*(InitStockpile-
EXCANCoreInv)^2)/(EXCANPuDispRate*(EXCANCapFact/0.80))/1000;

```

```

value EXCANTimeComplete=LicFailTime+EXCANTimeLic+EXCANLicDelay+EXCANTimeConst
    +(EXCANConstDelay+EXCANDelayAdjust)
    +(InitStockpile-EXCANCoreInv)/(EXCANPuDispRate*(EXCANCapFact/0.80));
    //80% capacity factor
value EXCANNPVConst=EXCANConstCost1*(d^(LicFailTime+EXCANLicDelay))
    +EXCANConstCost2*(d^(LicFailTime+EXCANLicDelay
    +(EXCANConstDelay+EXCANDelayAdjust)))
    +EXCANConstCost1*DelayCostFraction*(1/DiscountRate
    *(1-(d^(EXCANConstDelay+EXCANDelayAdjust))))
    *(d^(LicFailTime+EXCANLicDelay));
value EXCANNPVOM=EXCANOMCost*(d^(LicFailTime+EXCANLicDelay
    +(EXCANConstDelay+EXCANDelayAdjust)));
value EXCANNPVRev=EXCANNormalize*EXCANElecCap*EXCANCapFact*8760/1000000
    *((1+ElecEsc)^(LicFailTime+EXCANTimeLic+EXCANLicDelay+EXCANTimeConst
    +(EXCANConstDelay+EXCANDelayAdjust)))
    *ElecPrice*(1/Gamma*(1-1/(1+Gamma)^40))+CapPay*(1/DiscountRate*(1-d^40))
    *(d^(LicFailTime+EXCANTimeLic+EXCANLicDelay+EXCANTimeConst
    +(EXCANConstDelay+EXCANDelayAdjust)));
value EXCANNPVTot=LicFailCost+EXCANNPVConst+EXCANNPVOM-EXCANNPVRev;
value UEXCANTimeStart=1/(1+c2*((@abs(best2-EXCANTimeStart))
    /(@abs(EXCANTimeStart-worst2)+eps))^b2);
value UEXCANTimeComplete=1/(1+c3*((@abs(best3-EXCANTimeComplete))
    /(@abs(EXCANTimeComplete-worst3)+eps))^b3);
value UEXCANMTyr=1/(1+c4*((@abs(best4-EXCANMTyr))/(@abs(EXCANMTyr-worst4)+eps))^b4);
value UEXCANNPVTot=1/(1+c1*((@abs(best1-EXCANNPVTot))/(@abs(EXCANNPVTot-
    worst1)+eps))^b1);

```

```

//decision nodes for failure of first reactor licensing attempt
decision GEFailLic.{W,CE,GA,EXGE,EXW,EXCE,EXCAN};
decision WFailLic.{GE,CE,GA,EXGE,EXW,EXCE,EXCAN};
decision CEFailLic.{GE,W,GA,EXGE,EXW,EXCE,EXCAN};
decision GAFailLic.{GE,W,CE,EXGE,EXW,EXCE,EXCAN};
decision EXGEFailLic.{GE,W,CE,GA,EXW,EXCE,EXCAN};
decision EXWFailLic.{GE,W,CE,GA,EXGE,EXCE,EXCAN};
decision EXCEFailLic.{GE,W,CE,GA,EXGE,EXW,EXCAN};
decision EXCANFailLic.{GE,W,CE,GA,EXGE,EXW,EXCE};

```

//*****

//Decision tree

sequence:

decide

to LicAttempt1.GE then gamble

on LicFail.License and

```

a:      get UGEFixed then
gamble on GELicDelay then
gamble on GEConstDelay then
gamble on OthFuelDelay and get k2*UGETimeStart then
gamble on GECapFact and
get k1*UGENPVTot+k3*UGETimeComplete+k4*UGEMTyr

```

//GE debug*****

```

//      a: gamble on GELicDelay then
//      gamble on GEConstDelay then
//      gamble on OthFuelDelay then

```

```
//          gamble on GECapFact and get GENPVTot
//*****
      on LicFail.NoLicense then decide
        to GEFailLic.W and
          b:    get UWFixed then
              gamble on WLicDelay then
              gamble on WConstDelay then
              gamble on OthFuelDelay and get  $k2 * UWTimeStart$  then
              gamble on WCapFact and
              get  $k1 * UWNPVTot + k3 * UWTimeComplete + k4 * UWMtyr$ 
//W debug*****
//          b: gamble on WLicDelay then
//          gamble on WConstDelay then
//          gamble on OthFuelDelay then
//          gamble on WCapFact and get WNPVTot
//*****
        to GEFailLic.CE and
          c: get UCEFixed then
              gamble on CELicDelay then
              gamble on CEConstDelay then
              gamble on OthFuelDelay and get  $k2 * UCETimeStart$  then
              gamble on CECapFact and
              get  $k1 * UCENPVTot + k3 * UCETimeComplete + k4 * UCEMTyr$ 
//CE debug*****
//          c: gamble on CELicDelay then
//          gamble on CEConstDelay then
//          gamble on OthFuelDelay then
//          gamble on CECapFact and get CENPVTot
//*****
        to GEFailLic.GA and
          d:    get UGAFixed then
              gamble on GALicDelay then
              gamble on GAConstDelay then
              gamble on OthFuelDelay and get  $k2 * UGATimeStart$  then
              gamble on GACapFact and
              get  $k1 * UGANPVTot + k3 * UGATimeComplete + k4 * UGAMtyr$ 
//GA debug*****
//          d: gamble on GALicDelay then
//          gamble on GAConstDelay then
//          gamble on OthFuelDelay then
//          gamble on GACapFact and get GANPVTot
//*****
        to GEFailLic.EXGE and
          e:    get UEXGEFixed then
              gamble on EXGELicDelay then
              gamble on EXGECostDelay then
              gamble on OthFuelDelay and get  $k2 * UEXGETimeStart$  then
              gamble on EXGECapFact and
              get
               $k1 * UEXGENPVTot + k3 * UEXGETimeComplete + k4 * UEXGEMtyr$ 
//EXGE debug*****
//          e: gamble on EXGELicDelay then
//          gamble on EXGECostDelay then
//          gamble on OthFuelDelay then
```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```
//
//***** gamble on EXGECapFact and get EXGENPVTot
//*****
      to GEFailLic.EXW and
        f: get UEXWFixed then
        gamble on EXWLicDelay then
        gamble on EXWConstDelay then
        gamble on OthFuelDelay and get k2*UEXWTimeStart then
        gamble on EXWCapFact and
        get k1*UEXWNPVTot+k3*UEXWTimeComplete+k4*UEXWMTyr
//EXW debug*****
//
//      f: gamble on EXWLicDelay then
//      gamble on EXWConstDelay then
//      gamble on OthFuelDelay then
//      gamble on EXWCapFact and get EXWNPVTot
//*****
      to GEFailLic.EXCE and
        g: get UEXCEFixed then
        get -999 then //suppress selection of EXCE
        gamble on EXCELicDelay then
        gamble on EXCEConstDelay then
        gamble on OthFuelDelay and get k2*UEXCETimeStart then
        gamble on EXCECapFact and
        get
        k1*UEXCENPVTot+k3*UEXCETimeComplete+k4*UEXCETMtyr
//EXCE debug*****
//
//      g: gamble on EXCELicDelay then
//      gamble on EXCEConstDelay then
//      gamble on OthFuelDelay then
//      gamble on EXCECapFact and get EXCENPVTot
//*****
      to GEFailLic.EXCAN and
        h: get UEXCANFixed then
        gamble on EXCANLicDelay then
        gamble on EXCANConstDelay then
        gamble on CANFuelDelay and get k2*UEXCANTimeStart then
        gamble on EXCANCapFact and
        get k1*UEXCANNPVTot+k3*UEXCANTimeComplete
        +k4*UEXCANMTyr
//EXCAN debug*****
//
//      h: gamble on EXCANLicDelay then
//      gamble on EXCANConstDelay then
//      gamble on CANFuelDelay then
//      gamble on EXCANCapFact and get EXCANNPVTot
//*****
      to LicAttempt1.W then gamble
      on LicFail.License then
      perform b
      on LicFail.NoLicense then decide
      to WFailLic.GE and
      perform a
      to WFailLic.CE and
      perform c
      to WFailLic.GA and
      perform d
```

```

    to WFailLic.EXGE and
      perform e
    to WFailLic.EXW and
      perform f
    to WFailLic.EXCE and
      perform g
    to WFailLic.EXCAN and
      perform h
  to LicAttempt1.CE then gamble
    on LicFail.License then
      perform c
    on LicFail.NoLicense then decide
      to CEFailLic.GE and
        perform a
      to CEFailLic.W and
        perform b
      to CEFailLic.GA and
        perform d
      to CEFailLic.EXGE and
        perform e
      to CEFailLic.EXW and
        perform f
      to CEFailLic.EXCE and
        perform g
      to CEFailLic.EXCAN and
        perform h
  to LicAttempt1.GA then gamble
    on LicFail.License then
      perform d
    on LicFail.NoLicense then decide
      to GAFailLic.GE and
        perform a
      to GAFailLic.W and
        perform b
      to GAFailLic.CE and
        perform c
      to GAFailLic.EXGE and
        perform e
      to GAFailLic.EXW and
        perform f
      to GAFailLic.EXCE and
        perform g
      to GAFailLic.EXCAN and
        perform h
  to LicAttempt1.EXGE then gamble
    on LicFail.License then
      perform e
    on LicFail.NoLicense then decide
      to EXGEFailLic.GE and
        perform a
      to EXGEFailLic.W and
        perform b
      to EXGEFailLic.CE and
        perform c

```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

```

    to      EXGEFailLic.GA and
           perform d
    to      EXGEFailLic.EXW and
           perform f
    to      EXGEFailLic.EXCE and
           perform g
    to      EXGEFailLic.EXCAN and
           perform h
to LicAttempt1.EXW then gamble
  on LicFail.License then
    perform f
  on LicFail.NoLicense then decide
    to      EXWFailLic.GE and
           perform a
    to      EXWFailLic.W and
           perform b
    to      EXWFailLic.CE and
           perform c
    to      EXWFailLic.GA and
           perform d
    to      EXWFailLic.EXGE and
           perform e
    to      EXWFailLic.EXCE and
           perform g
    to      EXWFailLic.EXCAN and
           perform h
to LicAttempt1.EXCE then gamble
  on LicFail.License then
    perform g
  on LicFail.NoLicense then decide
    to      EXCEFailLic.GE and
           perform a
    to      EXCEFailLic.W and
           perform b
    to      EXCEFailLic.CE and
           perform c
    to      EXCEFailLic.GA and
           perform d
    to      EXCEFailLic.EXGE and
           perform e
    to      EXCEFailLic.EXW and
           perform f
    to      EXCEFailLic.EXCAN and
           perform h
to LicAttempt1.EXCAN then gamble
  on LicFail.License then
    perform h
  on LicFail.NoLicense then decide
    to      EXCANFailLic.GE and
           perform a
    to      EXCANFailLic.W and
           perform b
    to      EXCANFailLic.CE and
           perform c
```

Decision Model for Evaluating Reactor Disposition of Excess Plutonium

to EXCANFailLic.GA and
perform d
to EXCANFailLic.EXGE and
perform e
to EXCANFailLic.EXW and
perform f
to EXCANFailLic.EXCE and
perform g