A PROPOSED METHODOLOGY FOR THE ANALYSIS AND SELECTION OF ALTERNATIVES FOR THE DISPOSITION OF SURPLUS PLUTONIUM

James S. Dyer, Amarillo National Resource Center for Plutonium
Thomas Edmunds, University of California - LLNL
John C. Butler, Amarillo National Resource Center for Plutonium
Jianmin Jia, Amarillo National Resource Center for Plutonium

Submitted by the

Amarillo National Resource Center for Plutonium

March 1996

This report was prepared with the support of a cooperative agreement between ANRCP and U.S. Department of Energy, (Agreement No. DE-FC04-95AL85832) and Lawrence Livermore National Laboratory (LLNL) under contract W-7405-Eng-48. This work was conducted through the Amarillo National Resource Center for Plutonium and the Lawrence Livermore National Laboratory. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE or LLNL.

Abstract

A Proposed Methodology for the Analysis and Selection of Alternatives for the Disposition of Surplus Plutonium

The nuclear states are currently involved in the development of comprehensive approaches to the long-term storage and management of fissile materials. A major objective of this effort is to provide a framework for prevention of the proliferation of nuclear weapons. The evaluation should include non-proliferation, economic, technical, institutional, schedule, environmental, and health and safety issues.

The ANRCP has proposed that an evaluation of alternatives be guided by the principles of decision analysis, a logical and formal approach to the solution of complicated problems that are too complex to solve informally. This approach would consist of four steps:

1) identification of alternatives and objectives,
2) estimation of the performance of the alternatives with respect to the objectives,
3) development of values and weights for the objectives, and
4) evaluation of the alternatives and sensitivity analysis.

In order to facilitate the evaluation process, the ANRCP proposes the use of nine objectives grouped into the following categories:

1) Non-proliferation objectives (which includes resistance to theft and diversion by unauthorized parties, resistance to retrieval and reuse by the host nation, schedule, and fostering progress and cooperation with other nations and Russia)
2) Operational effectiveness (which includes cost, technical viability, and other benefits)
3) Environmental, safety, and health considerations.

In order to evaluate alternatives on the basis of these objectives, they have been clarified through the definition of secondary objectives in some cases. Once the objectives were defined, the next step is to develop measures of performance associated with these objectives. Some of these measures of performance use natural scales, such as cost (dollars), time (months), and environmental impacts (cubic meters of secondary waste). Other measures require specially constructed verbal scales and the performance of each alternative is assessed based on expert judgment.

TABLE OF CONTENTS

List of Figures

A Methodology for the Analysis and Selection of Alternatives for the Disposition of Surplus Plutonium

1. Background

The end of the Cold War and subsequent arms limitation and reduction agreements have led to a surplus of weapons-usable plutonium in the United States and Russia. In order to prevent the proliferation of nuclear weapons, steps must be taken to manage this plutonium in a manner which takes into account non-proliferation, economic, technical, institutional, schedule, environmental, and health and safety issues.

The purpose of this paper is to define a model and the methodology that could be used to support the selection of alternatives for the disposition of surplus plutonium. There are a number of methods that have been proposed to model preferences and support decisions, and each of them may be used constructively in some contexts. However, we believe that the significance of decisions regarding the disposition of plutonium requires the use of a methodology that can evaluate alternatives involving risk and multiple performance measures, and that is practical, theoretically sound, and transparent to external reviewers and interest groups. The one methodology that meets these requirements is multi-attribute utility theory (MAU), which has been supported for use in similar situations by the National Research Council, an agency of the United States National Academy of Sciences. [1]

MAU (Keeney and Raiffa, 1976) is one of the major analytical tools associated with the field of decision analysis (Clemen, 1991; Holloway, 1979; McNamee and Celona, 1990; Raiffa, 1968; von Winterfeldt and Edwards, 1986). Simply, decision analysis is a logical and formal approach to the solution of problems that are too complex to solve informally. In the past, decision analysis has been applied to problems such as siting electricity generation facilities (Keeney, 1980), choosing among vendors for the

[1]National Research Council, letter to Ben Rusche, DOE/OCRWM, dated October 10, 1985.

evaluation of alternatives for the commercial generation of electricity by nuclear fusion (Dyer and Lorber, 1982), and selecting a nuclear waste clean up strategy (Keeney and von Winterfeldt, 1994).

The MAU methodology for the evaluation of alternatives for the disposition of plutonium consists of the following steps:

1. Identification of alternatives and objectives
2. Estimation of the performance of the alternatives with respect to the objectives
3. Development of values and weights for the objectives
4. Evaluation of the alternatives and sensitivity analysis

As a first step, reasonable alternatives for the disposition of plutonium must be identified along with the objectives that are used in the analysis. The alternatives and the objectives form a matrix in which each row corresponds to an alternative and each column represents an objective. The cells of the matrix contain estimates of the performance of each alternative on each of the objectives. When these estimates are uncertain, it is often appropriate to quantify them with ranges or with probability distributions determined using risk analysis methods (e.g., Clemen, 1991; Keeney and von Winterfeldt, 1991).

Typically, it is possible to gain a number of insights regarding the alternatives simply through a careful inspection of this matrix. For example, one or more alternatives may be "dominated" by another alternative, meaning that the dominating alternative performs as well or better on every objective than the dominated alternative. Alternatives that are dominated can often be eliminated from further consideration in the decision process, which may significantly simplify the remaining steps in the analysis.

Step three creates a value model based on the objectives by defining value functions, if necessary, on the measures of the performance of the alternatives, and by assigning weights to the objectives. This process is carried out with decision makers or their designated representatives, and allows the measures of performance on each objective to be aggregated into a single figure of merit. Finally, this value model can be used to determine a ranking of each of the alternatives, and a sensitivity analysis is typically conducted to determine if this ranking is robust relative to reasonable changes in the weights or the other parameters that determine the value model. This sensitivity analysis may include changes in the value model that are suggested by interactions with representatives of other interest groups or stakeholders.

This process should summarize the critical information needed for an evaluation of alternatives, and provide the insights that both support and explain the basis for this evaluation. However, it is important to emphasize that the decision analysis process does not lead to a computerized model that actually determines the decision for a complex problem. Rather, this process highlights the strengths and weaknesses of alternatives, the implications of tradeoffs among these strengths and weaknesses, and the sensitivity of the evaluation to the underlying assumptions so that better informed choices can be made.

Any model of a physical process or of subjective preferences will omit some details in the abstraction from the real-world in order to crystallize the essence of the problem. Some of these omitted details may be relevant in the final selection of alternatives by a decision maker or decision makers, particularly when the alternatives are determined to be "very close" in the formal analysis. Further, the appropriate value model for use as a guide to public policy is, in general, not sharply defined. As a result, the decision analysis process will emphasize the support of the decision makers charged with the responsibility for the selection of alternatives, and will attempt to clarify the consequences of each choice. We subscribe to the philosophy that the result of using models should be insights, not numbers.

Sections 2-5 of this report will describe these four steps of the MAU methodology in more detail. Section 6 will summarize the discussion.

2. Identification of Alternatives and Objectives

2.1 Alternatives

The evaluation process begins with the identification of the set of reasonable alternatives that are appropriate for serious consideration. This screening process may be aided by reference to a set of criteria that identify the most important considerations guiding this preliminary selection process. Examples of the use of screening processes to determine reasonable alternatives for the disposition of surplus plutonium are provided by the studies conducted by the National Academy of Sciences (1994) and by Office of Fissile Materials Disposition of the United States Department of Energy (OFMD, 1995).

The reasonable alternatives for plutonium disposition determined in these studies fall into three categories: reactor alternatives, immobilization alternatives, and borehole alternatives. The reactor alternatives would use surplus plutonium to fabricate mixed oxide (MOX) fuel for nuclear reactors that generate electrical power. The spent fuel from these reactors would ultimately be transferred to a national waste management system for ultimate disposition. The immobilization alternatives combine the surplus plutonium materials in borosilicate glass or ceramics; additional radionuclides may be added to provide a radiation barrier to inhibit recovery and reuse. This material would also be transferred to a national waste management system for ultimate disposition. The borehole alternatives involve the placement of the plutonium in a deep borehole, possibly after the material is immobilized in an inert matrix.

Other alternatives may eventually be considered by the United States and Russia. However, the general methodology for the evaluation of these alternatives should be flexible enough to evaluate and compare any reasonable approach to the disposition of the surplus plutonium.

2.2 Objectives and Measures

The first step in the application of MAU is the development of a "hierarchy" of objectives, criteria, and measures. Objectives are often broad statements of goals. Typically two or more criteria are associated with objectives at the next level of the hierarchy to provide more specific statements of desirable characteristics of alternatives, and to help define the objectives in more detail. In complex decision problems, these criteria may be decomposed further into sub-criteria, and so on, until a sufficient level of detail is reached to allow measures to be identified.

In some cases, these measures may be quantified as estimates on a natural scale, for example, net present value of cost, time, travel miles, etc. In other cases, it may be necessary to construct scales that are more descriptive in nature, and that may require estimates for the alternatives based on expert judgment. In many cases, these measures are surrogates for higher-level issues.

Useful reference points for the identification of measures for evaluating plutonium disposition alternatives include measures proposed for previous studies involving technology choices (e.g., Keeney, Lathrop, and Sicherman, 1986; Keeney and von Winterfeldt, 1994; Merkhofer and Keeney, 1987), for previous studies concerned with the management and disposition of surplus plutonium (National Academy of Sciences, 1994), and for evaluations of technologies and sites for tritium supply and recycling.

Objectives. The objectives for any decision provide the basis for evaluating the relative desirability of available alternatives. For the purpose of illustrating the methodology, we present the objectives recommended by the National Academy of Sciences (1994) and used by the Office of Fissile Materials Disposition (OFMD, 1995) for the purpose of a preliminary screening. The objectives used by the OFMD for screening the alternatives for the disposition of plutonium were the following:

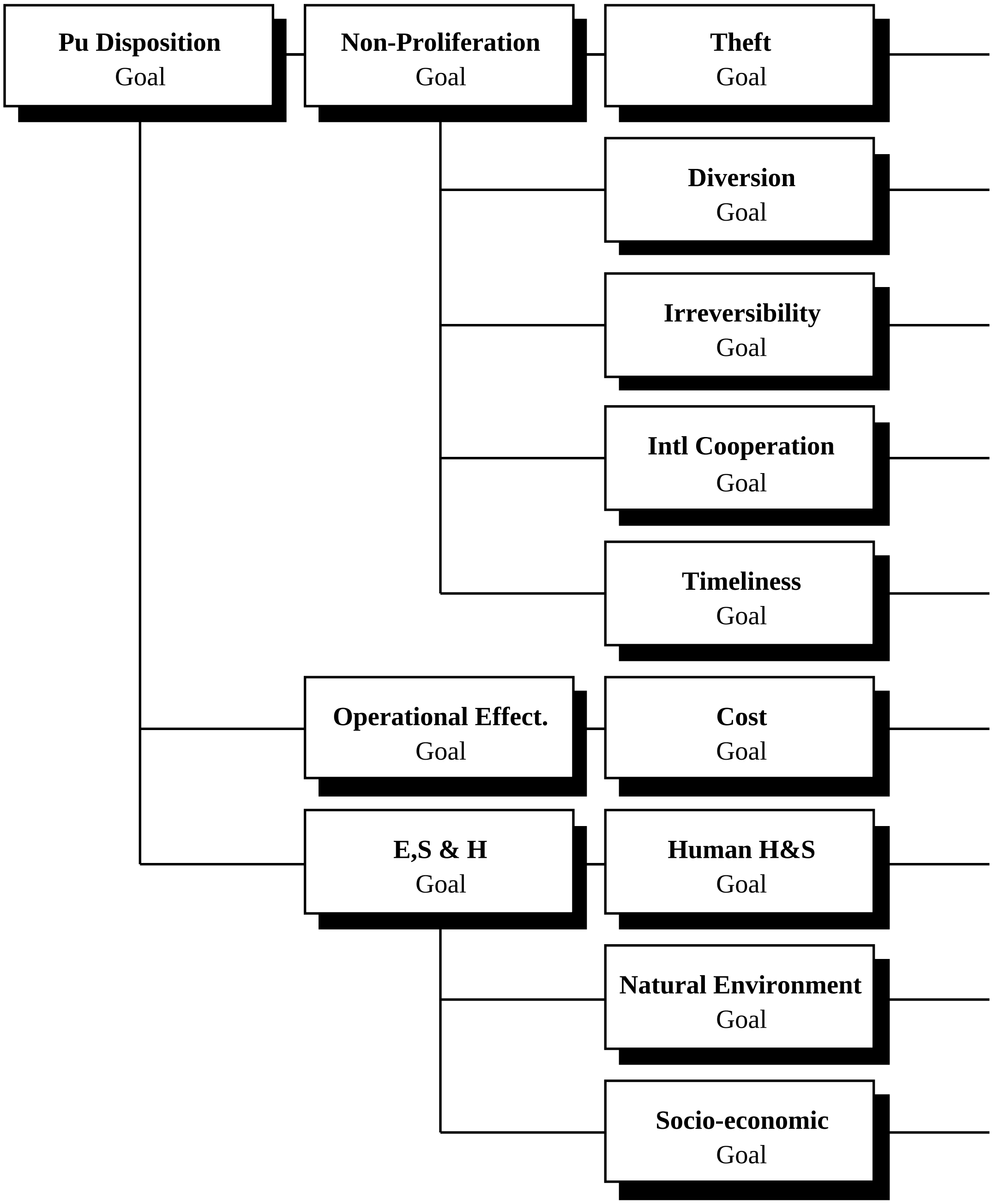
1. Resistance to theft and diversion by unauthorized parties
2. Resistance to retrieval, extraction, and reuse by the host nation
3. Technical viability
4. Environmental, safety, and health
5. Cost effectiveness
6. Timeliness
7. Fostering progress and cooperation with Russia and other nations
8. Public and institutional acceptance
9. Additional benefits

For this illustration of the methodology, these nine objectives have been reorganized to emphasize the commonality among some of them, and to provide additional detail regarding others. This reorganization is shown in the form of a hierarchy of objectives in Figure 1.

At the highest level of this hierarchy, we have identified three major categories of objectives:

1. Non-proliferation which includes resistance to theft, resistance to reuse, international cooperation, and timeliness (objectives 1, 2, 6 and 7 from the original list of nine)
2. Operational effectiveness which includes and cost effectiveness (objectives 1 and 5 from the original list of nine)
3. Environmental, safety, and health (objective 4 from the original list of nine) which has been decomposed into human health and safety, environmental protection, and socio-economic effects at the next level in the hierarchy.

FIGURE 1 -- HIGH LEVEL OBJECTIVES FOR PLUTONIUM DISPOSITION



Such a reorganization of the nine objectives would simplify the task of creating a value model, and particularly the assessments of weights on the objectives, as we discuss in Section 4. In addition, this simplified structure would provide a natural means for transferring the insights from the model to the decision maker.

It should also be noted that objectives 3, 8 and 9 from the original list, technical viability, public and institutional acceptance, and additional benefits, have been dropped from the proposed hierarchy. Technical viability refers to the level of technological development associated with the alternative, and is essentially a surrogate for the risk of possible delays and cost overruns. These concerns can be captured in an evaluation through the use of probability distributions on measures of time and cost, if necessary.

Public and institutional acceptance is a major concern in any screening process, and the basis for the elimination of many of the alternatives that may originally be considered. However, the other objectives that have been selected for this illustration are based on meeting public concerns. Therefore, we believe that an alternative selected based on the other eight objectives will be one that would also be ranked highly on the objective of public acceptability. In addition, the economic impacts of the alternatives on local communities have been included in the proposed measures of the Environmental, Safety, and Health objective, as we shall discuss.

Also, we have deleted the objective of "additional benefits" from this hierarchy. Some of the alternatives may offer the possibility of producing useful by-products, such as the production of electric power by nuclear reactors or the possibility of sharing costs with other programs. However, the most significant examples of these "other benefits" can be captured as offsetting costs, and will be effectively measured by the cost effectiveness objective.

As previously mentioned, Figure 1 represents the highest level of the objectives for selecting a plutonium disposition alternative. Figures 1a, 1b and 1c provide the details for the three main objectives of the analysis: Non-proliferation, Operational Effectiveness and Environment, Health and Safety respectively.

Two comments are in order regarding Figures 1, 1a, 1b and 1c. First, the major purpose of these diagrams, particularly Figure 1, is to assist the decision makers in "making sense" of an evaluation of alternatives based on thirty eight detailed performance measures. The reorganization of the objectives as shown in this hierarchy is neither unique nor fixed. It could be altered based on feedback from those involved in determining policy toward plutonium disposition. Second, the fact that one objective or sub-objective appears at a "lower level" in the hierarchy than another does not imply that it is less important, or that it should receive a smaller "weight" in the analysis than another objective.

The objectives categorized as providing assurance against non-proliferation (Figures 1 and 1a) indicate five distinctly different areas of concern. The first objective is to minimize the opportunities for theft of the materials by unauthorized parties. Generally, an alternative will be more resistant to theft during the processing steps required to transform the material from weapons-usable plutonium into its final form for permanent disposition if these steps are relatively simple and transparent, if the form of the material is not "attractive" to potential thieves because of size, radioactivity, or other concerns, and if effective safeguards and security can be applied.

The second objective is to maximize the resistance of the disposition alternative to the diversion of the plutonium by the host nation during processing, and to provide an internationally verifiable and acceptable process. Providing adequate accessibility safeguards, and measurement capability will allow an alternative to satisfy international inspection standards and provide assurance that diversion by the host nation is not taking place. Many of the factors considered in the theft subobjective can also apply here.

FIGURE 1A -- DETAIL FOR NON-PROLIFERATION OBJECTIVE

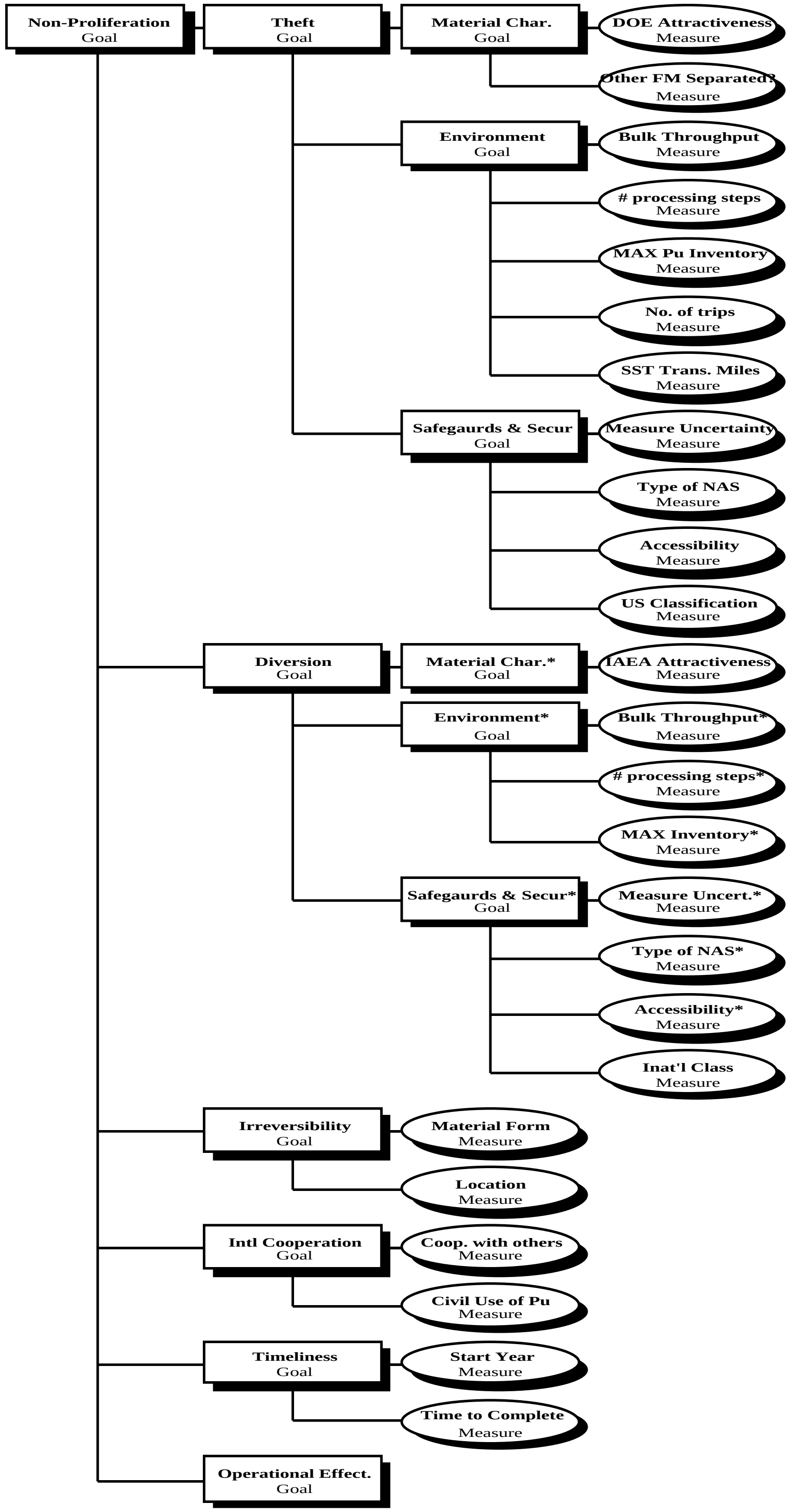


FIGURE 1B -- DETAIL FOR OPERATIONAL EFFECTIVENESS OBJECTIVE

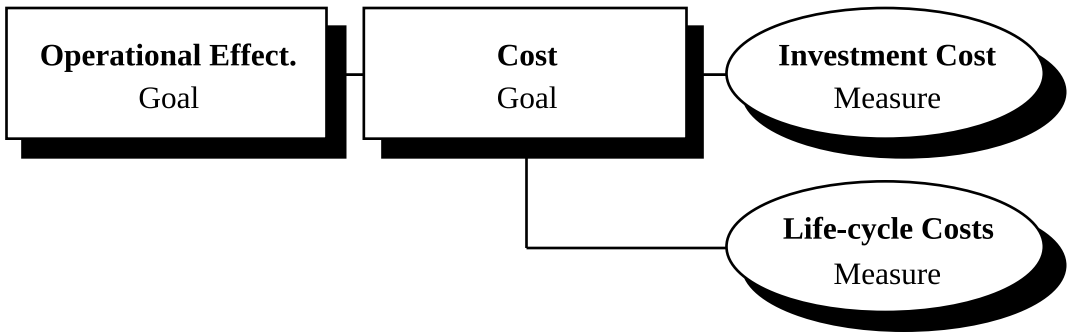
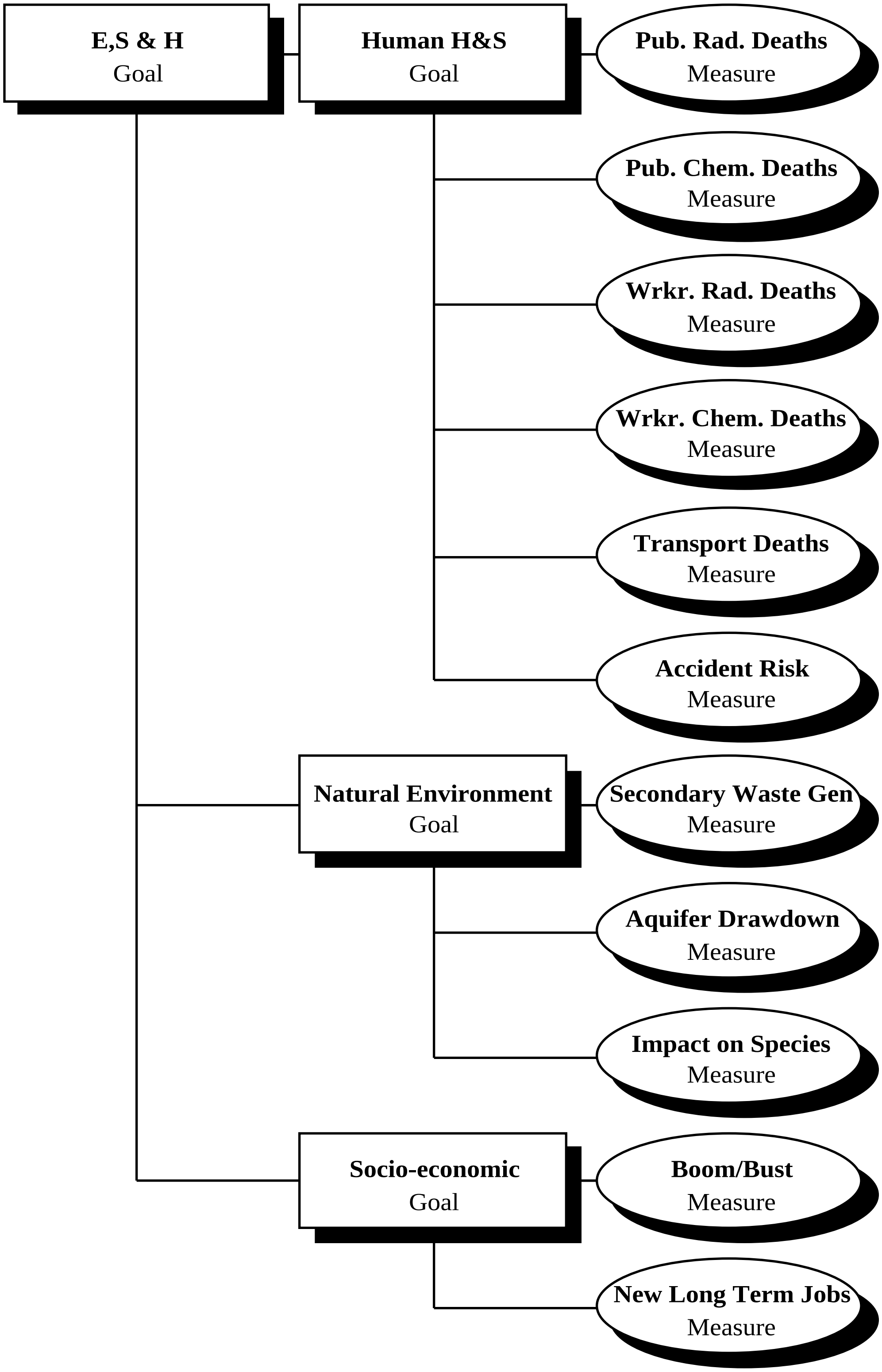


FIGURE 1C -- DETAIL FOR ENVIRONMENTAL SAFETY AND HEALTH OBJECTIVE



The third objective is to maximize the difficulty of recovering the disposed material after processing has been completed. The disposed material will be less attractive for reuse by the host nation if it meets the "spent fuel standard", or would be as costly, detectable, and time consuming to retrieve and fabricate into weapons as the recovery of plutonium from spent commercial reactor fuel. The final form and location of the disposed material will determine its long-term resistance to reuse.

The fourth non-proliferation objective is concerned with fostering international cooperation with the disarmament and nuclear non-proliferation goals. This objective may be related to international relationships, and to issues concerning the civil use of plutonium.

The fifth objective, Timeliness, is based on an estimate of the time required for the disposition effort to begin, and on the time required for the completion of the effort once it has begun. These time estimates may be highly uncertain for some of the alternatives, and can be represented as probability distributions when necessary. The assessment of the uncertainty associated with the time to begin an alternative's disposition process may be influenced by its technical maturity and by its regulatory history. Timeliness influences both international cooperation and the "window of vulnerability" of the material.

An alternative will be considered operationally effective (Figures 1 and 1b) if it has low cost. The cost may consider both life-cycle costs and the initial investment costs, and estimates of both may be uncertain. If so, these estimates should be represented by probability distributions. Revenues resulting from by-products such as electric power may offset some of the costs. The potential for cost sharing with other related projects may also be considered to offset costs.

The objective of protecting the environment, safety, and health has three sub-objectives. The first is minimizing human health and safety risks, which requires minimizing risks to the public from normal operations, minimizing risks to workers from normal operations, and minimizing risks to both from accidents that could result from operations or inter-site transportation activities.

The second sub-objective is maximizing environmental protection. This objective requires the minimization of direct impacts on animal species, the minimization of impacts on local water supply, and the minimization of secondary wastes.

The third sub-objective is related to the socio-economic impacts of the alternatives. The short-term socio-economic disruptions by the alternatives should be minimized, while any long-term economic and social benefits should be maximized. These socio-economic impacts also relate to the screening objective of encouraging public acceptance of the alternative, particularly in the local communities that would be affected by construction and operation.

Measures. In order to evaluate the alternatives, a measure or a set of measures is needed for each of the objectives, as shown in Figures 1a, 1b and 1c. These measures should be selected so that each alternative can be evaluated on each of them, and so that each measure is then logically linked to one or more of the objectives.

The measure or set of measures associated with an objective should cover all aspects of the objective. In some cases the selection of an appropriate measure may be clear. For example, it is customary to measure the life-cycle cost of an alternative in terms of discounted net present value dollars. Similarly, concerns regarding the timeliness of the disposition activities associated with an alternative may be captured by measures of the "time to start the disposition activities" and the "time to complete the disposition activities". However, when no relevant and/or natural scales are closely linked to an objective, such as maximizing the likelihood of international cooperation, it may be necessary to work with experts to construct a measure to indicate different levels of achievement.

3. Estimation of the Performance of the Alternatives on the Objectives

Given the identification of the alternatives and the definitions of the measures, the next step is to obtain estimates of the performance of each alternative on each measure. This step defines the alternative-by-objective (and measure) matrix that summarizes the overall performance of each alternative on the relevant measures. An example of such a matrix is provided in Figure 3, where performances of three hypothetical alternatives are evaluated on five measures used for illustration purposes only. The entries in the cells in this matrix may be in the form of point estimates, ranges, or in the form of probability distributions. For example, a probability distribution might be represented by a simple three point distribution of the form (0.05 fractile, median, 0.95 fractile), that reflects the uncertainty associated with the estimates of performance. Probability distributions are included for the life cycle and investment costs of an alternative in Figure 2.

FIGURE 2 -- EXAMPLE OF ALTERNATIVES BY OBJECTIVES MATRIX

	Measures				
	Life Cycle Costs ($B)	Investment Cost ($B)	Expected Worker Fatalities	Impacts on Species (# species)	Completion Time (yr.)
Alternative A	(1, 2, 5)	(2, 2.5, 3)	.001	1	2010
Alternative B	(2, 4, 10)	(2, 3, 5)	.002	0	2025
Alternative C	(-1, 0, 5)	(2, 3, 5)	.001	3	2025

A careful inspection of this simple matrix may provide some rich insights regarding the alternatives. For example, one or more alternatives may be identified as clearly inferior because of their poor performance on most if not all of the relevant objectives. Others may obviously "rise to the top" because of superior performance on many of the objectives.

In order to obtain the performance estimates with respect to these measures, a series of assessment meetings may be necessary to focus on the major objectives. For example, experts in the area of safeguards and security (S&S) may be asked to evaluate the performance of the alternatives on the non-proliferation objectives. Other teams may be involved to develop estimates of cost and time, while still other groups may focus on the analysis necessary to develop the measures of environment and health impacts.

4. Development of Value Functions and Weights

Once the performance of each alternative on each measure in the alternatives-by-objectives matrix has been obtained, the next step in the analysis involves assembling the measures into a “super-measure” of the desirability of each alternative. The aggregation procedure is complicated by the diversity of the types and scales of the individual measures. As evident in Figure 2, some measures may be represented by probability distributions while some are expressed as point estimates. Some measures units are dollars and some are cubic meters of secondary waste, while others are defined over constructed scales, further complicating the aggregation procedure.

Utility theory provides the basis for the appropriate approach to aggregate the seemingly disparate measures. It is a logically consistent and tractable means of representing the degree to which each alternative fulfills the objectives shown in Figure 1. The use of utility theory ensures that any recommendation reflects:

- the relative attractiveness of a specific level on a measure
- the relative attractiveness of performance on different measures and objectives
- the interactions, if any, between objectives.

These three issues will be addressed in the following sections. For a more detailed presentation of these topics see Keeney and Raiffa (1976) and von Winterfeldt and Edwards (1986).

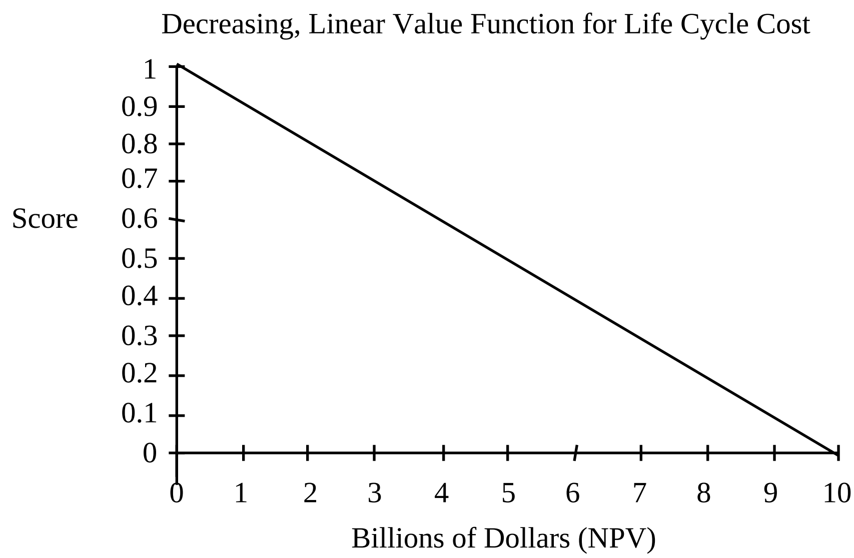
4.1 Single Attribute Value Functions

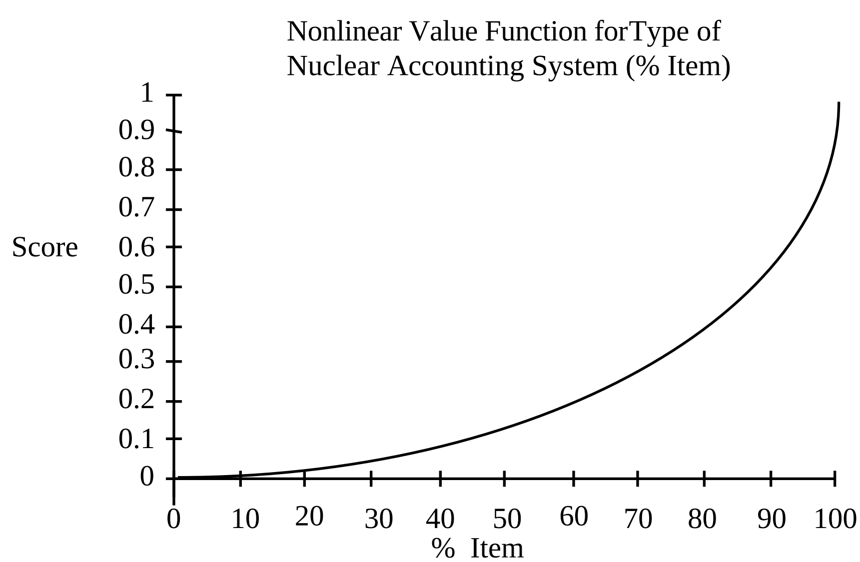
The relative attractiveness of performance outcomes on a measure is captured by a single attribute value function. A value function is constructed or assessed so that it incorporates a decision maker's preferences for performance on a measure in a utility value or score; a superior objective measure will score higher on the value scale. Value functions can be linear or non-linear as dictated by both normative concerns and the nature of the decision maker’s preferences. Once constructed, value functions can be combined with probability distributions to ensure that the risk associated with an alternative is properly evaluated.

Figure 3 illustrates two *hypothetical* value functions. It is particularly important to emphasize that these value functions are used here only for the sake of exposition. The first value function represents the value associated with different levels of the Life Cycle Cost of an alternative. The function is decreasing because lower cost is preferred to higher cost; hence, lower costs receive higher value scores. The function is linear because the range of dollar amounts being considered may be small in comparison to the national budget, so the marginal value of each incremental dollar over this range is assumed to be equal.

The second value function representing "Type of Nuclear Accounting System" (defined per facility as the percentage of time in the facility that “item" accounting is used) is a bit more complicated. Intuitively, the ideal facility would utilize 100% item accounting and receive the highest value. Due to the comparative ease of measuring

FIGURE 3 -- TWO EXAMPLE VALUE FUNCTIONS





material that is classified as item, even a small decrease from 100% item accounting receives a stiff penalty. Looking at the scores for facilities that use very little item accounting (these facilities rely heavily on “bulk” accounting), it is also clear that moving from 0% item to 10% does not receive a substantial increase in score relative to moving from 90% to 100%. The scale for Type of Nuclear Accounting System is “exponentially biased toward item accounting”.

4.2 Weights

Each objective, sub-objective, and measure in the attribute hierarchy is given a weight. These weights reflect the value tradeoffs among objectives (or sub-objectives and measures within objectives), and are dependent on the ranges of the outcomes considered in the analysis.

As a simple example, consider the problem of choosing among disposition alternatives based on the objectives of cost, ES&H, and non-proliferation. Suppose that three alternatives are under consideration with costs of $2.2, $2.4, and $2.5 billion, respectively, and with representative values on the other two objectives. Now, suppose that a fourth alternative is added to the list with a cost of $3.0 billion, and with values on the other two measures that lie within the ranges of values determined by the original three alternatives. Utility theory prescribes that the weight on cost in choosing among the original three alternatives (where costs range from $2.2 to $2.5 billion) should be *smaller* than the weight on cost in choosing among the four alternatives (where costs range from $2.2 to $3.0 billion). Intuitively, this is because a wider range of costs is considered in choosing among the four alternatives; i.e., cost is more of a discriminating factor in choosing among the four alternatives than in choosing among the original three.

As a result of this insight, it should be clear that weights on objectives are not simply measures of the "relative importance" of each objective. Loosely speaking, they are measures of the importance of the *increase* from the worst to the best level of performance on one objective compared to the *increase* from the worst to the best level of performance on another objective. Therefore, weights must be assessed carefully to ensure that the results of the evaluation are consistent with the preferences of the decision maker or decision makers.

This assessment procedure can be based on a dialogue with a decision maker (or a group of stakeholders) that can take the following form. First, we assume that we have specified the ranges over which the performances of the alternatives can vary on each objective; that is, we have identified the "worst" and "best" feasible levels of performance on each objective. Next, we assume that an alternative achieves only the worst levels of performance on each of two objectives, say objective A and objective B. Holding its levels of performance constant on all of the other objectives, we ask the decision maker if it would be appropriate to pay more to increase the performance of this alternative from the worst to the best level on objective A, or to increase its performance from the worst to the best level on objective B?

Suppose that the decision maker responds, "I would pay more to increase objective A from its worst to its best level of performance." Next, we would ask her to identify a level of performance on objective A so that she believes it would be appropriate to pay the same amount to increase objective A from its worst level to this level of performance as to increase objective B from its worst to its best level of performance. The response to this question determines the ratio of the weights on objectives A and B, and additional questions comparing the other objectives provide sufficient information to specify the numerical values of these weights.

In some cases, it may appear that responses to questions of this type would be extremely difficult to make. However, the assessment process can be aided by the skills of a trained analyst, and a variety of "consistency checks" can be used to ensure that the responses are meaningful. These assessment protocols are also scripted to minimize biases in the responses, systematic errors that are known to occur as a result of the limitations of human information processing capabilities. For additional details and examples of assessment dialogues, see Keeney and Raiffa (1976) or von Winterfeldt and Edwards (1986).

Weights can be used to combine objectives and measures at different levels of the hierarchy, and the individuals who provide the judgments required to develop these weights may be different, depending on the level. For example, the judgments required to combine the measures for the sub-objectives "minimize number of processing steps" and "minimize attractiveness of material" for the objective Maximize Resistance to Theft may be more appropriately obtained from S&S experts who help evaluate alternatives as described in Section 3.

At the highest level of the hierarchy of objectives, the weights are less related to expert judgment, and much more to questions of policy. These higher level weights should be obtained in interviews with persons representing national policy makers.

4.3 Aggregation Methods

In order to obtain an overall evaluation for each disposition alternative on a higher level objective, we may use an aggregation model that can combine different measures into a single value. The model also must show the results of "sub-aggregation" at lower levels of the objectives hierarchy so that decision makers can better compare the attractiveness of alternatives. Since the decision for plutonium disposition involves both multiple criteria and risk, it is appropriate to use multi-attribute utility models for this study (Keeney and Raiffa, 1976) .

If stakeholder preferences are consistent with some special independence conditions, then a multi-attribute utility model $u(x_1, x_2, \ldots, x_n)$, where x_i represents the level of performance on measure i, can be decomposed into an additive, multiplicative, or other well-structured form that simplifies assessment. An additive multi-attribute utility model can be represented as follows:

$$u(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} w_i u_i(x_i) \qquad (1)$$

where $u_i()$ is a single-attribute value function over measure i that is scaled from 0 to 1, w_i is the weight for measure i and $\sum_{i=1}^{n} w_i = 1$. If the decision maker's preference structure is not consistent with the additive model (1), then the following multiplicative model may be used, which is based on a weaker independence condition:

$$1 + ku(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} [1 + kk_i u_i(x_i)] \qquad (2)$$

where $u_i()$ is also a single-attribute value function scaled from 0 to 1, the k_i's are positive scaling constants satisfying $0 \le k_i \le 1$, and k is an additional scaling constant that characterizes the interaction effect of different measures on preference. The value of k can be determined from one additional question similar to the questions used to determine the objective weights. As a special case when $\sum_{i=1}^{n} k_i = 1$, the multiplicative model (2) reduces to the additive model (1).

The choice of the appropriate model for aggregation will be based on information collected from interviews with policy makers. For approaches to the assessment of an additive utility model and a multiplicative utility model, see Keeney and Raiffa (1976).

5. Evaluation of the Alternatives and Sensitivity Analysis

5.1 Evaluation and Ranking

Once the single measure value functions have been completely defined, the data from the alternatives-by-objectives matrix (see Figure 2) are converted to component utilities. For measures that are known with a high degree of certainty, this process amounts to supplying the measure as an argument to the value function to obtain a score for each alternative on each measure. If a measure has been defined with a probability distribution, the appropriate value function is applied to the distribution to provide an expected utility value for the measure.

The component value function scores are aggregated, using the correct multi-attribute utility function, within each of the major objectives, and within each of the categories of objectives identified by the decision maker as illustrated in Figure 1. During this aggregation, the weights are used to reflect the tradeoffs between measures, and are multiplied by the corresponding scores. This stage of the evaluation process is important and useful for decision makers as it provides scores for each alternative for the major objectives of the plutonium disposition problem, and on the three categories of objectives identified in Figure 1. At this stage it is possible to examine the relative strengths and weaknesses of the alternatives. A hypothetical example of the results of this phase of the analysis is provided in Figure 4.

It is often possible to obtain important insights from an inspection of this table of scores. In addition to highlighting the relative strengths of the alternatives on the major objectives or the objective categories, alternatives that are dominated may also be identified. For example, these hypothetical scores indicate that Alternative A dominates the No Action alternative since its scores are as good or better on every major category. Note that this table could be created at a “lower level” in the hierarchy as well, highlighting the nine objectives used in the screening process. Comparisons among objectives and sub-objectives at different levels in the hierarchy may also be used to provide additional insights.

FIGURE 4 -- EXAMPLE OF PHASE I AGGREGATION

	MAJOR CATEGORIES		
	Non-Proliferation	Operational Effectiveness	Environmental Safety and Health
Alternative A	0.7	0.3	0.7
Alternative B	0.5	0.8	0.1
Alternative C	0.4	0.4	0.4

Note: Scores are from 0 (least preferred) to 1 (most preferred). Scores are purely hypothetical.

Weights may be assessed to represent tradeoffs between the major objectives. This will allow another level of aggregation to provide a measure of the overall utility of each alternative. This step will allow for quick comparisons regarding the relative desirability of the alternatives, and should provide an excellent means of ranking the field of contending disposition alternatives.

5.2 Sensitivity Analysis

Before final disposition recommendations are made, the analysis must be tested to see if the evaluation of alternatives is robust. This sensitivity analysis basically amounts to making changes in the performance on the measures and/or weights and observing changes in the resulting evaluations and rankings.

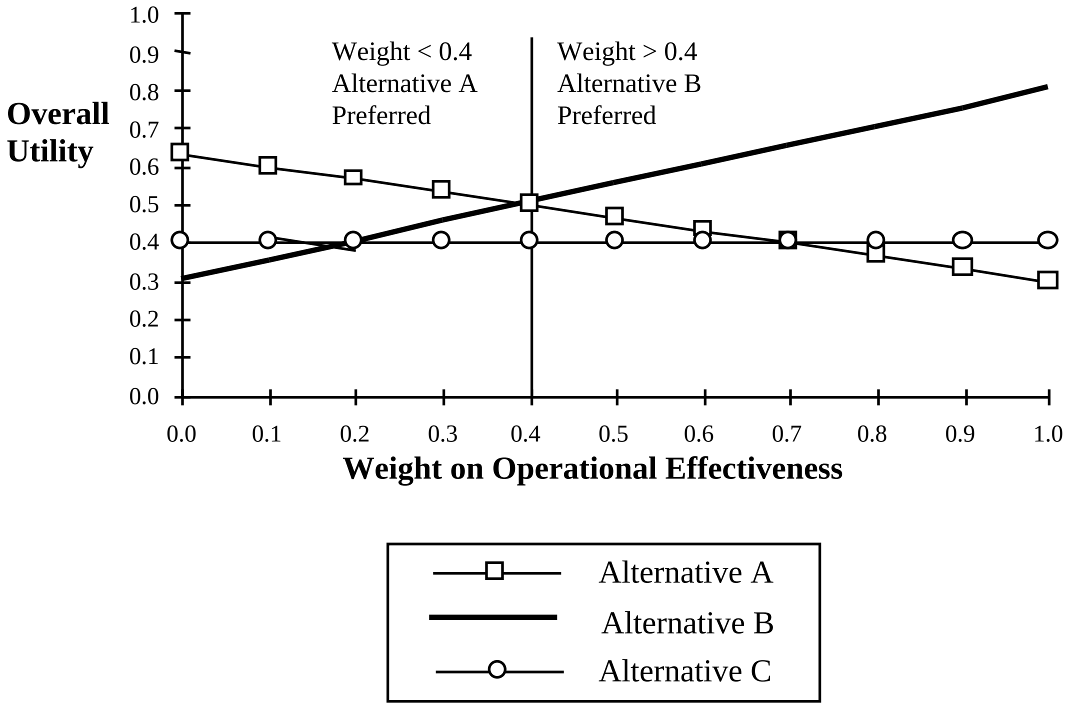
It is impossible to predict exactly what sensitivity analyses would be performed as the evaluation process is problem specific and iterative. The following types of analyses have been useful when examining similar problems:

- Change the weight of an important objective while leaving the ratios between weights on other objectives unchanged. This will highlight the effect of changing the emphasis placed on an objective.
- Investigate specific entries in the alternatives-by-objectives matrix (over a reasonable range). In cases where ranges of values or probability distributions are provided as estimates, values other than the mean (average) may be selected for the sensitivity analyses (e.g. the 10th and/or 90th percentile levels). This process helps test the robustness of the ranking to the assumptions and facts that form the basis of the analysis.
- Manipulate the measures and/or probability distributions to reflect specific viewpoints. For example, it may be appropriate to investigate the implications of an optimistic perspective about the life cycle costs of an alternative. This analysis will demonstrate the effect of different perspectives about the alternatives.

Any sensitivity analyses performed will be summarized in several formats. Numerical results are presented and, where appropriate, graphical representations are also provided. These results should also be explained intuitively to ensure that all participants understand the implications and are able to contribute to discussions.

Figure 5 provides an example of the first type of sensitivity analysis based on the hypothetical scores in Figure 4. The weight placed on Operational Effectiveness is varied from 0 to 1 holding the ratio of all other weights unchanged. This analysis indicates that if the weight on Operational Effectiveness is less than 0.4 (holding the ratios of other weights constant), then Alternative A will be preferred; if it is greater than 0.4, then Alternative B is preferred. Similar analyses could be performed on all other objectives and sub-objectives.

FIGURE 5 -- EXAMPLE OF SENSITIVITY ANALYSIS ON "WEIGHTS"



6. Summary and Conclusions

This presentation presents a proposed methodology for the analysis and selection of alternatives for the disposition of surplus plutonium. The approach is intended to be general, and could easily be modified to address specific issues and concerns unique to a country or a stakeholder group.

This approach to the evaluation of alternatives has several advantages over the presentation of a great deal of technical information in the form of discussion and tables, and then a verbal argument regarding the selection of the preferred alternative. First, the approach brings some order and structure to the evaluation process. It helps to focus the different teams of personnel who are responsible for generating information regarding one or more aspects of the complex alternatives required for plutonium disposition. Second, it provides a “scorecard” that can be used by policy makers and stakeholders to understand, relatively easily, the strengths and weaknesses of the various alternatives. Third, the evaluation and sensitivity analysis can easily reduce the set of “reasonable alternatives” to a smaller subset that may be viable candidates for the final choice, depending on the implied “weights” that are assigned to the objectives.

The selection of alternatives for the disposition of plutonium is a critical issue that requires simultaneous consideration of many conflicting objectives. We believe that this approach can help countries to make these decisions in a logical and informed manner, and to communicate with each other more effectively regarding the rationale behind these choices.

7. References

Clemen, R. T. (1991). *Making Hard Decisions.* Boston: PWS Kent Publishing.

Dyer, J. S. and Lorber, H. W. (1982). The Multi-attribute Evaluation of Program-Planning Contractors. *OMEGA*, *6,* 673-678.

Hertz, D. B., and Thomas, H. (1983). *Risk Analysis and its Applications.* New York: John Wiley.

Holloway, C. A. (1979). *Decision Making Under Uncertainty: Models and Choices.* Englewood Cliffs, N.J.: Prentice-Hall.

Keeney, R. L. (1980). *Siting Energy Facilities.* New York: Wiley.

Keeney, R. L., Lathrop, J., and Sicherman, A. (1986). An Analysis of Baltimore Gas and Electric Company's Technology Choice. *Operations Research, 34,* 18-49.

Keeney, R. L. and Raiffa, H. (1976). *Decisions with Multiple Objectives.* New York: Wiley.

Keeney, R. L. and von Winterfeldt, D. (1991). Eliciting Probabilities from Experts in Complex Technical Problems. *IEEE Transactions on Engineering Management, 38,* 191-201.

Keeney, R. L. and von Winterfeldt, D. (1994). Managing Nuclear Waste from Power Plants. *Risk Analysis, 14* , 107-130.

Krantz, D. H., Luce, R. D., Suppes, P., and Tversky, A. (1971). *Foundations of Measurement.* New York: Academic Press.

McNamee, P. and Celona, J. (1990). *Decision Analysis with Supertree.* 2nd edition. San Francisco: Scientific Press.

Merkhofer, M. L. and Keeney, R. L. (1987). A Multi-attribute Utility Analysis of Alternative Sites for the Disposal of Nuclear Waste. *Risk Analysis, 7,* 173-194.

OFMD (1995). Summary Report of the Screening Process to Determine Reasonable Alternatives for Storage and Disposition of Weapons-usable Fissile Materials. March 17, 1995.

National Academy of Sciences (1994). *Management and Disposition of Excess Weapons.* Washington D.C.: National Academy Press.

Raiffa, H. (1968). *Decision Analysis.* Reading, MA: Addison Wesley.

von Winterfeldt, D. and Edwards, W. (1986). *Decisional Analysis and Behavioral Research.* New York: Cambridge University Press.