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

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AMARILLO NATIONAL RESOURCE CENTER FOR PLUTONIUM/
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A Report on

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

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Submitted to the

ANRC Nuclear Program

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Executive Summary

The Department of Energy (DOE) - Office of Fissile Materials Disposition (OFMD) has announced a Record of Decision (ROD) selecting alternatives for disposition of surplus plutonium. A major objective of this decision was to further U.S. efforts to prevent the proliferation of nuclear weapons. Other concerns that were addressed include economic, technical, institutional, schedule, environmental, and health and safety issues. The technical, environmental, and nonproliferation analyses supporting the ROD are documented in three DOE reports [DOE-TSR 96, DOE-PEIS 96, and DOE-NN 97, respectively].

At the request of OFMD, a team of analysts from the Amarillo National Resource Center for Plutonium (ANRC) provided an independent evaluation of the alternatives for plutonium that were considered during the evaluation effort. This report outlines the methodology used by the ANRC team.

This methodology, referred to as multi-attribute utility theory (MAU), provides a structure for assembling results of detailed technical, economic, schedule, environment, and nonproliferation analyses for OFMD, DOE policy makers, other stakeholders, and the general public in a systematic way. The MAU methodology has been supported for use in similar situations by the National Research Council, an agency of the National Academy of Sciences.[1]

It is important to emphasize that the MAU process does not lead to a computerized model that actually determines the decision for a complex problem. MAU is a management tool that is one component, albeit a key component, of a decision process. We subscribe to the philosophy that the result of using models should be insights, not numbers.

The MAU approach consists of four steps: (1) identification of alternatives, objectives, and performance measures, (2) estimation of the performance of the alternatives with respect to the objectives, (3) development of value functions and weights for the objectives, and (4) evaluation of the alternatives and sensitivity analysis. These steps are described in the following sections.

1.1 Identification of the Alternatives, Objectives, and Performance Measures

The process of selecting the best alternative(s) for the disposition of surplus weapons-grade plutonium was a two-stage effort: an initial screening followed by a more detailed analysis of the alternatives that met the minimum screening requirements. The Screening Phase identified eleven alternatives to be studied in the Evaluation Phase. The nine objectives used in the screening process are the starting point for this evaluation. The screening process objectives are: (1) resistance to theft and diversion by unauthorized parties, (2)

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

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, and (9) additional benefits. In the Evaluation Phase, some primary objectives were further defined in terms of secondary objectives with more narrowly-defined meanings. For example, the primary objective of Environment, Safety, and Health was further defined in terms of three secondary objectives: Human Health and Safety, Natural Environment, and Socioeconomic effects.

Performance measures have been developed for each of the objectives to quantify how well a particular alternative satisfies the objective. Some of these measures use natural scales such as cost (dollars), time (years), and environmental impacts (acres of land). Other measures require specially constructed descriptive scales, and the performance of each alternative is assessed in terms of these scales using expert judgment.

1.2 Estimation of the Performance of the Alternatives With Respect to the Objectives

The next step is to obtain estimates of the performance of each alternative on each measure. These performance estimates are used to develop a table that summarizes the overall performance of each alternative with respect to each measure. Each entry in this table may be a single number, or may be a range or probability distribution if there is substantial uncertainty regarding the performance of the alternative in terms of the measure. The ANRC cooperated with DOE in conducting a series of assessment meetings with independent technical experts to generate the data in the table.

1.3 Development of Value Functions and Weights for the Objectives

This step creates a value model based on the objectives using a two-step process. First, a value function is generated for each of the performance measures. This function quantifies the level of satisfaction associated with different values of the performance measure. Second, a weight is assigned to each of the value functions so that a weighted sum of the functions can be computed. The "weights" are assessed so that they represent the decision-maker's willingness to make "tradeoffs" between different performance measures (e.g., a trade-off between cost and schedule). The weighted sum of the product of the weights times the value function scores for an alternative provides a single figure of merit that may be used for comparison and ranking of alternatives.

The ANRC cooperated with DOE in conducting a series of meetings with policy experts and decision-makers to assess the weights and determine the specific forms of the value functions. Note that weights may reflect policy and value judgments, rather than technical judgments about performance that are assessed in the previous step. The separation of these two types of judgments is one of the advantages of the methodology.

1.4 Evaluation of the Alternatives and Sensitivity Analysis

Finally, this aggregate value model may be used to determine an overall ranking of each of the alternatives, or rankings on subsets of the measures that relate to specific objectives such as resistance to Theft or Operational Effectiveness. A sensitivity analysis is conducted to determine if this ranking is robust relative to reasonable changes in model parameters reflecting different technical estimates or policy judgments.

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1. BACKGROUND

In 1994 and 1995, the Department of Energy - Office of Fissile Materials Disposition (OFMD) conducted a screening study of a large number of technologies that could be used for the disposition of surplus plutonium [DOE-SCR 95]. This screening process was supported by the development of screening criteria to identify alternatives that best achieve the fissile nuclear material long-term storage and disposition goals of the U.S. Government as articulated in the President's Nonproliferation and Export Control Policy of September 1993 and the January 1994, “Agreement between the United States and Russia on Nonproliferation of Weapons of Mass Destruction and their Means of Delivery.” The analysis was also consistent with the analytical framework established by the National Academy of Sciences in their study on disposition of surplus plutonium [NAS 94].

The Screening Phase was the first in a two-phase effort to support a final record of decision (ROD) in a manner consistent with the National Environmental Policy Act (NEPA). During this screening process, criteria for the evaluation of the alternatives were established, and alternatives that would perform very poorly on one or more of the criteria were eliminated from further consideration. Of the 37 options considered for plutonium disposition, ten passed the Screening Phase and were found to be reasonable for further consideration and more detailed characterization. As the Evaluation Phase for the ten alternatives for plutonium disposition evolved, two or more variants of some of the original alternatives were identified. As a result, a total of 14 alternatives (including the variants and the “do nothing” alternative) were considered reasonable candidates for plutonium disposition.

The purpose of this report is to define the model and the methodology that were used in the Evaluation Phase of this process to support the selection of a technology for the disposition of surplus weapons grade 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 the decision 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.

1.1 EVALUATION PHASE PROCESS

The challenge of the second phase of the analysis was to refine the definitions of the alternatives to provide more details regarding their likely operating and performance characteristics, and to determine a model or models that will aggregate measures of these characteristics to support the selection of a technology for the disposition of surplus plutonium. At the request of OFMD, a team of analysts from the Amarillo National Resource Center for Plutonium (ANRC) provided an independent evaluation of the alternatives for plutonium disposition that were considered during the Evaluation Phase effort. The ANRC is supported by a consortium of three universities: Texas A&M University System, Texas Tech University, and The University of Texas System, and funds a research program in which two of its seven focus areas is dedicated to the investigation of issues related to the storage and disposition of plutonium.

The ANRC evaluation project involved personnel from The University of Texas at Austin and Texas A&M University. This team became involved with OFMD in May 1995, which marked the approximate beginning of the Evaluation Phase effort. During the summer of

1995, members of the ANRC team met on numerous occasions with OFMD personnel, and with three alternative teams: scientists from the National Laboratories (Lawrence Livermore, Los Alamos, Oak Ridge, and Sandia) and TRW, Inc., who were organized according to the three major types of alternatives under consideration: reactors, immobilization, and borehole alternatives. The OFMD also arranged interviews for ANRC with representatives of the National Security Council, the Department of State, and the White House Office of Science and Technology. Meetings were also held with representatives of TetraTech, a private consulting firm responsible for the Programmatic Environmental Impact Statement (PEIS) [DOE-PEIS 96].

The proposed evaluation methodology developed by the ANRC team was reviewed during meetings with OFMD personnel, and also by the ANRC Senior Technical Review Group (STRG) at a meeting in Washington, D.C. in November 1995. In addition, the proposed methodology was presented in public forums at the American Nuclear Society Annual Meetings in November 1995 and June 1996, and at the International Meeting on Military Conversion and Science "Utilization of the Excess Weapon Plutonium: Scientific, Technological and Socio-Economic Aspects," in Como, Italy in March 1996.

A major objective of the initial stages of this evaluation effort was to determine the performance measures that would be used to evaluate the disposition alternatives, and this was accomplished during Fall 1995. The alternative teams and TetraTech provided a preliminary set of estimates for these performance measures for the plutonium disposition alternatives that were under consideration. The ANRC team used these preliminary estimates to develop an evaluation of the alternatives, and provided these results to OFMD and to representatives of the alternative teams in the form of a pre-decisional draft, and in summary form at the monthly meetings of the OFMD team in Washington, D.C. on November 15, and December 15, 1995.

These preliminary performance estimates were refined during 1996, and this information was communicated to the ANRC team. The evaluation of the alternatives was updated as new information became available. Although this final evaluation report was completed after the ROD, the rankings of the alternatives that were reported to OFMD in early 1996 did not change significantly as estimates of the performance measures were refined. This analysis is intended to provide additional insights regarding the strategy for plutonium disposition that was announced in the ROD.

The process described here is illustrated in Figure 1.

1.2 EVALUATION PHASE METHODOLOGY

The appraisal process used by the ANRCP team in the Evaluation Phase consists of a more detailed examination of these thirteen alternatives using a logical and formal evaluation methodology. This methodology, referred to as multi-attribute utility theory (MAU), provides a structure for assembling results of detailed technical, economic, schedule, environment, and nonproliferation analyses for OFMD, DOE policy-makers, other stakeholders, and the general public in a systematic way. The MAU methodology has been supported for use in similar situations by the National Research Council, an agency of the National Academy of Sciences.[2]

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

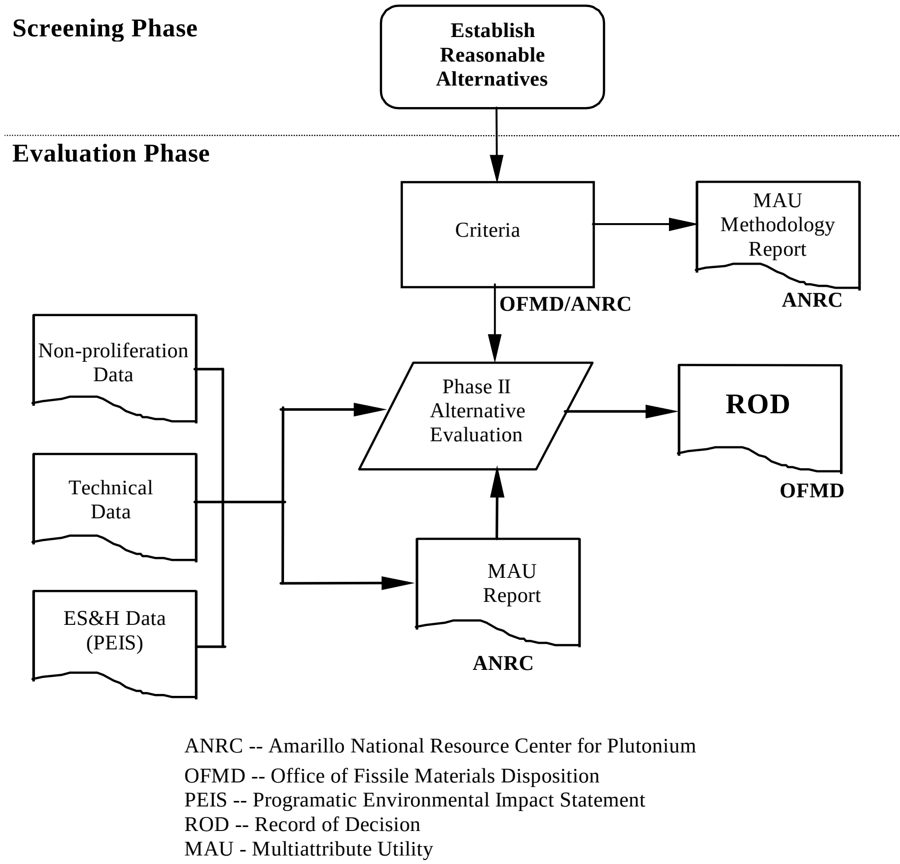

Figure 1: Phases of ROD

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 an electricity generation facility (Keeney, 1980), choosing among vendors for the 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).

An MAU analysis of alternatives explicitly identifies the objectives that are used to evaluate the alternatives for the disposition of surplus plutonium, and helps to identify those alternatives that perform well on a majority of these objectives, with a special emphasis on those objectives that are considered to be relatively more important. In order to carry out the analysis, some facts regarding each of the alternatives are required, and in some cases some assumptions will be needed to estimate the performance of the alternatives on the objectives. As an example, different assumptions may lead to optimistic and pessimistic cost and schedule estimates for the alternatives.

Value judgments are also required for the evaluation of the alternatives. These value judgments determine the relative desirability of different levels of performance of alternatives on the same objective, and the relative desirability of different levels of performance on different objectives. Different policy-makers and stakeholders may have different sets of value judgments, which complicates the task of identifying a preferred set of alternatives.

The MAU analysis can provide a ranking of alternatives for a given set of facts, assumptions, and value judgments. The results of this analysis are traceable; that is, a careful scrutiny of the analysis will show how the combination of facts, assumptions, and value judgments leads to a specific ranking of alternatives. For example, it will be possible to conclude that Alternative A is ranked higher than Alternative B because the facts and assumptions led to the estimate that A performed better than B on one or more objectives that were considered relatively more desirable based on the value judgments.

The primary purpose of the MAU analysis is to explore how robust the rankings of the alternatives are for reasonable combinations of facts, assumptions, and value judgments. Normally, this analysis highlights those alternatives that tend to perform relatively well on many objectives, as well as those that may be superior on several objectives but relatively weak on others. This same analysis will also highlight those alternatives that consistently perform poorly on the objectives. The MAU analysis can also focus on a single alternative, and determine the set of facts, assumptions, and value judgments that would be required to make it rank among the most and/or least preferred alternatives.

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 noted earlier, thirteen reasonable alternatives for the disposition of plutonium were identified as a result of the screening process. In addition, the screening criteria have formed the basis for defining the objectives that are used in this 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 on the overall goal or on a subset of relevant measures, such as a subset of goals relating to environmental impacts. A sensitivity analysis is typically conducted to determine if these rankings are 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 will aide in summarizing the critical information needed for an evaluation of alternatives, and providing 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, this decision analysis process will emphasize the support of the decision-makers charged with the responsibility for the selection of an alternative, 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.

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2. IDENTIFICATION OF ALTERNATIVES AND OBJECTIVES

2.1 ALTERNATIVES

Table 1 provides a concise list of the thirteen disposition alternatives considered in the analysis. Five alternatives were identified which would use surplus plutonium to fabricate mixed oxide fuel (MOX) for nuclear reactors that generate electric power. The spent fuel from these reactors would ultimately be placed in a geologic repository. Six other alternatives would require the immobilization of the surplus plutonium materials in borosilicate glass, ceramics or metal alloy castings; additional radionuclides would be added to provide a radiation barrier to inhibit recovery and reuse. This material would be transferred to the Federal waste management system. Two disposal alternatives involving the placement of plutonium in a borehole were considered to be reasonable, one of them requiring immobilization in an inert matrix and the other utilizing direct emplacement. For additional details regarding these alternatives, see the DOE technical summary report [DOE-TSR 96].

2.2 OBJECTIVES AND MEASURES

The next step in the application of MAU is the development of a "hierarchy" of objectives, sub-objectives, and measures. This hierarchy organizes the primary evaluation criteria, or objectives, into subsets of related measures to aid in communicating the results of the analysis to the decision-makers and other stakeholders. The analysis took advantage of the efforts of the screening process that identified nine objectives for the purpose of eliminating obviously inferior alternatives. Although the objectives for screening alternatives are not identical to those used in the MAU modeling efforts, they provided a useful starting point for the determination of the MAU objectives.

Objectives are often broad statements of goals. Typically two or more sub-objectives 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 sub-objectives may be decomposed further into other sub-objectives, and so on, until a sufficient level of detail is reached to allow measures to be identified.

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

A preliminary set of measures proposed by a team from Lawrence Livermore National Laboratory (LLNL) was a useful reference point for this effort (Edmunds, Koopman and Myers, 1995). We have also reviewed 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 [NAS 94, NAS 95], and for previous studies evaluating technologies and sites for tritium supply and recycling (Decision Insights, 1995).

2.2.1 Objectives

The objectives for any decision provide the basis for evaluating the relative desirability of available alternatives.

Table 1: Disposition Alternatives

REACTOR ALTERNATIVES	
Existing Light Water Reactors, Existing Facilities	MOX fuel fabrication plant built in an existing building at a DOE site, MOX irradiated in existing privately-owned commercial reactors.
Existing Light Water Reactors, Greenfield Facilities	A new co-located pit disassembly/conversion and MOX fabrication facility built at a DOE site, MOX irradiated in existing privately-owned commercial reactors.
Partially Completed Light Water Reactors	Commercial LWRs on which construction had been halted would be completed and operated by DOE.
Evolutionary Light Water Reactors	New LWRs would be built and operated by DOE.
CANDU Reactors	MOX fuel fabricated at a U.S. facility would be transported to one or more Canadian commercial heavy water reactors and irradiated.
VITRIFICATION ALTERNATIVES	
Vitrification Greenfield	Surplus plutonium would be mixed with glass and radioactive materials at a new facility to form homogeneous borosilicate glass logs.
Vitrification Can-in-Canister	Surplus plutonium would be mixed with non-radioactive glass and poured into small cans. These small cans would be placed in larger canisters, which are then filled with radioactive waste glass.
Vitrification Adjunct Melter	Surplus plutonium would be mixed with glass and radioactive materials in a supplemental melter facility to form homogeneous borosilicate glass logs.
Ceramic Greenfield	Surplus plutonium would be mixed with a ceramic and radioactive materials at a new facility to form homogeneous ceramic disks. These disks would be placed in a canister.
Ceramic Can-in-Canister	Surplus plutonium would be mixed with non-radioactive ceramic materials to form sintered ceramic pellets. These pellets would be placed in larger canisters filled with radioactive waste glass.
Electrometallurgical Treatment	Surplus plutonium would be immobilized with radioactive glass-bonded zeolite.
DIRECT DISPOSAL ALTERNATIVES	
Deep Borehole (Immobilization)	Surplus plutonium would be immobilized with ceramic pellets and placed in a borehole.
Deep Borehole (Direct Emplacement)	Surplus plutonium would be converted to a suitable form and placed in a deep borehole.

As described earlier, the potential objectives for the evaluation of alternatives for the disposition of surplus plutonium were initially developed based on the objectives articulated in Presidential policies and in international agreements, as well as the recommendations of the National Academy of Sciences study on this topic [NAS 94, NAS 95]. These statements of objectives were made public in a series of twelve Scoping Meetings held at twelve different locations across the country from August to October 1994. Members of the public were invited to provide input on the validity and importance of these objectives, and to suggest additional criteria that should be considered.

Objectives used 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. Environment, 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.

This list of objectives served the screening process well, and also provided an excellent starting point for this next phase of the analysis.

For this phase the nine objectives have been modified and 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 2.

At this highest level of this hierarchy, three major categories of objectives are identified:

1. Non-proliferation which include 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 is defined as cost effectiveness (Objective 5 from the original list of nine).

3. Environment, 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.

This reorganization of the objectives from the screening report simplifies the task of creating a value model, and particularly the assessments of weights on the objectives. In addition, this simplified structure provides a natural means for translating the insights from the model to OFMD and other interested parties.

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 analysis. Technical viability was originally included in the analysis until discussions with technical experts demonstrated that these concerns could be naturally represented as uncertainty concerning the cost and time associated with completion of the disposition mission.

Public and institutional acceptance was a major concern in the screening process, and the basis for the elimination of many of the alternatives that were originally considered. All of the alternatives shown in Table 1 have satisfied this criterion for the purposes of screening. Further, the other objectives that have been selected for this effort are based on meeting public concerns. Therefore, an alternative selected based on the other eight objectives should 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 measures of the Environment, Safety, and Health objective, as we shall discuss.

Also, the objective of additional benefits has been deleted for this phase of the analysis. 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 objective.

As previously mentioned, Figure 2 represents the highest level of the objectives for selecting a plutonium disposition alternative. Figures 3a, 3b and 3c 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 2, 3a, 3b and 3c. First, the major purpose of these diagrams, particularly Figure 2, is to assist interested parties in "making sense" of an evaluation of alternatives based on the thirty-seven detailed performance measures. The reorganization of the objectives as shown in this hierarchy is neither unique nor fixed. It may be altered in order to provide additional insights. 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 2 and 3a) indicate five distinctly different areas of concern. The first sub-objective is to minimize the opportunities for theft of the materials by unauthorized parties (hereafter referred to as Theft). Safeguards and Security experts indicated that 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, and if the form of the material is not "attractive" to potential thieves because of size, radioactivity, or other concerns.

The second sub-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 (hereafter referred to as Diversion). Providing adequate accessibility safeguards and measurement capability will allow an alternative to satisfy international inspection standards and will provide assurance that diversion by the host nation is not taking place.

The third sub-objective, Irreversibility, 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 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 sub-objective is concerned with fostering International Cooperation with the U.S. disarmament and nuclear non-proliferation goals. This objective focuses on Russian Cooperation and U.S. policy regarding the Civil Use of Plutonium.

The fifth sub-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 disposition once it has begun. Timeliness influences both international cooperation and the "window of vulnerability" of the material.

An alternative will be considered operationally effective (Figures 2 and 3b) if it has low cost. The cost of an alternative considers Life-cycle Costs and initial Investment Costs separately. This reflects some stakeholders views that up-front costs may be important independently due to difficulty in obtaining funding approval for more costly projects. Revenues resulting from by-products such as electric power may offset some of the Life-cycle Costs.

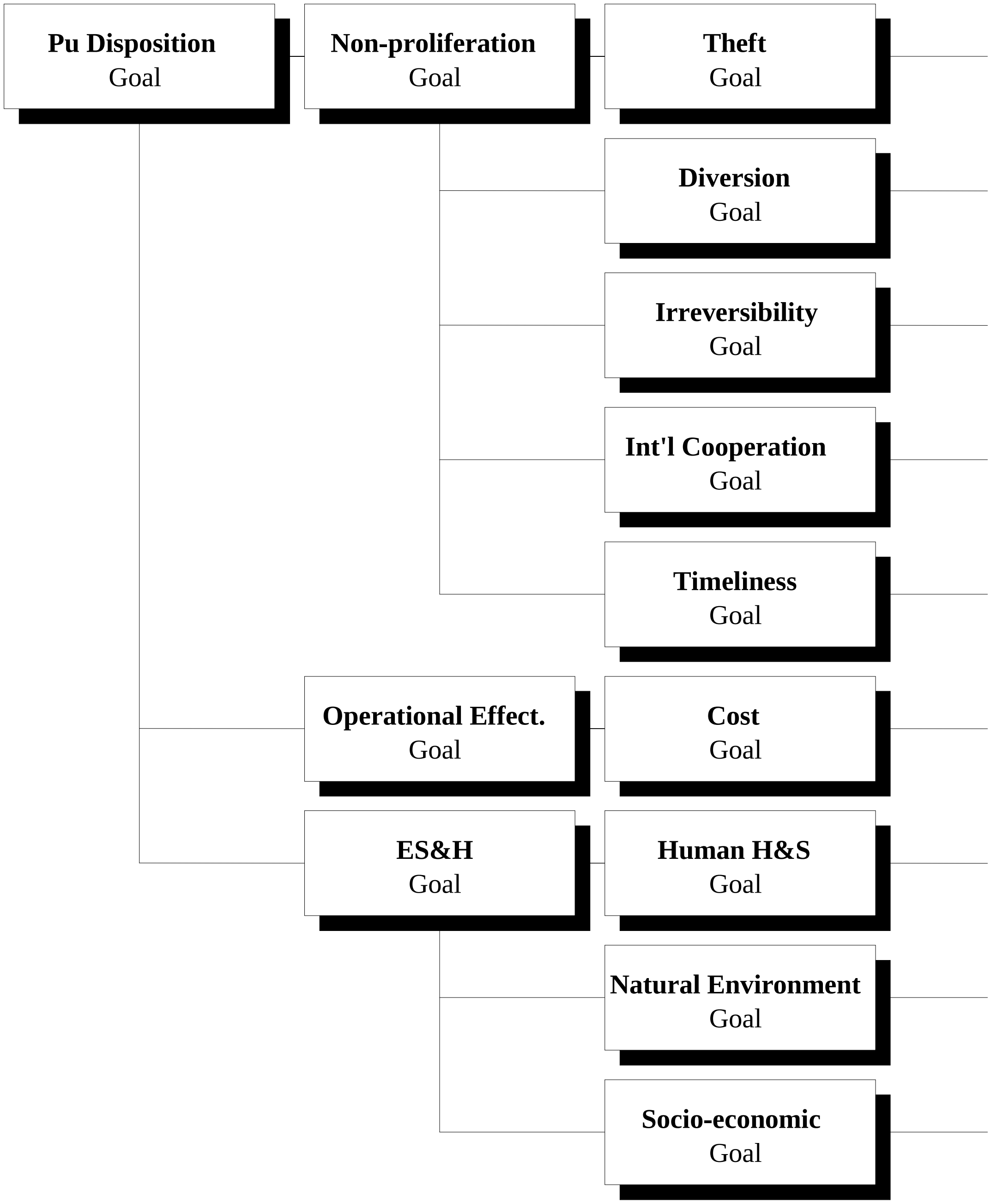

Figure 2: High Level Objectives for Plutonium Disposition

The potential for cost sharing with other related projects may also be considered to offset costs.

Protecting the environment, human safety, and human health has three sub-objectives (Figures 2 and 3c). The first focuses on 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 intersite transportation activities.

Environmental protection is the second sub-objective. This objective measures direct incremental impacts on animal species and on the international stockpile of nuclear waste.

Table 2 also includes a list of some "means" objectives, which are not fundamental objectives, but that list ways of accomplishing our fundamental objectives. For example, the means objectives of minimizing air and water pollution may contribute to the objectives of minimizing public health risks and also of minimizing impacts on species and habitats. However, the degree to which the achievement of these means objectives will impact the fundamental objectives will be evaluated in the technical analysis of each alternative [DOE-PEIS 96]. Therefore, they are not included in the list of objectives for the purpose of this evaluation.

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 benefit should be maximized. These socio-economic impacts also relate to the original screening objective of encouraging public acceptance of the alternative, particularly in the local communities that would be directly affected by the construction and operation of a disposition alternative.

Several other secondary objectives of the plutonium disposition effort clearly do exist, and some of them are listed in Table 2. Many of these secondary objectives were identified in the interaction with public groups during the screening process. However, differences in the performance of alternatives on these secondary objectives should not be sufficient to significantly alter a ranking of the alternatives based on the major objectives that have otherwise been identified.

These secondary objectives may be viewed as "bonus points" that might be added or subtracted if the analysis of the alternatives based on the three primary objectives shown in Figure 2 is very close. For example, if two alternatives were otherwise virtually tied based on the evaluation using the three major categories of objectives, then aesthetic appeal might be used as a "tie-breaker" to select the alternative that is considered more visually attractive.

Finally, process objectives suggest ways of designing the procedure to be used to gather information from decision-makers and public stakeholders. A process that is open to scrutiny and that includes public participation may enhance the chances for public acceptability of the results. Therefore, these objectives have influenced our activities, but are not listed as objectives to be used for evaluating particular alternatives in the formal decision analysis.

2.2.2 Measures

In order to evaluate the alternatives, a measure or a set of measures is needed for each of the objectives shown in Figures 3a, 3b and 3c. These measures have been 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. In developing our set of recommended measures, we have benefited from the rich discussions of

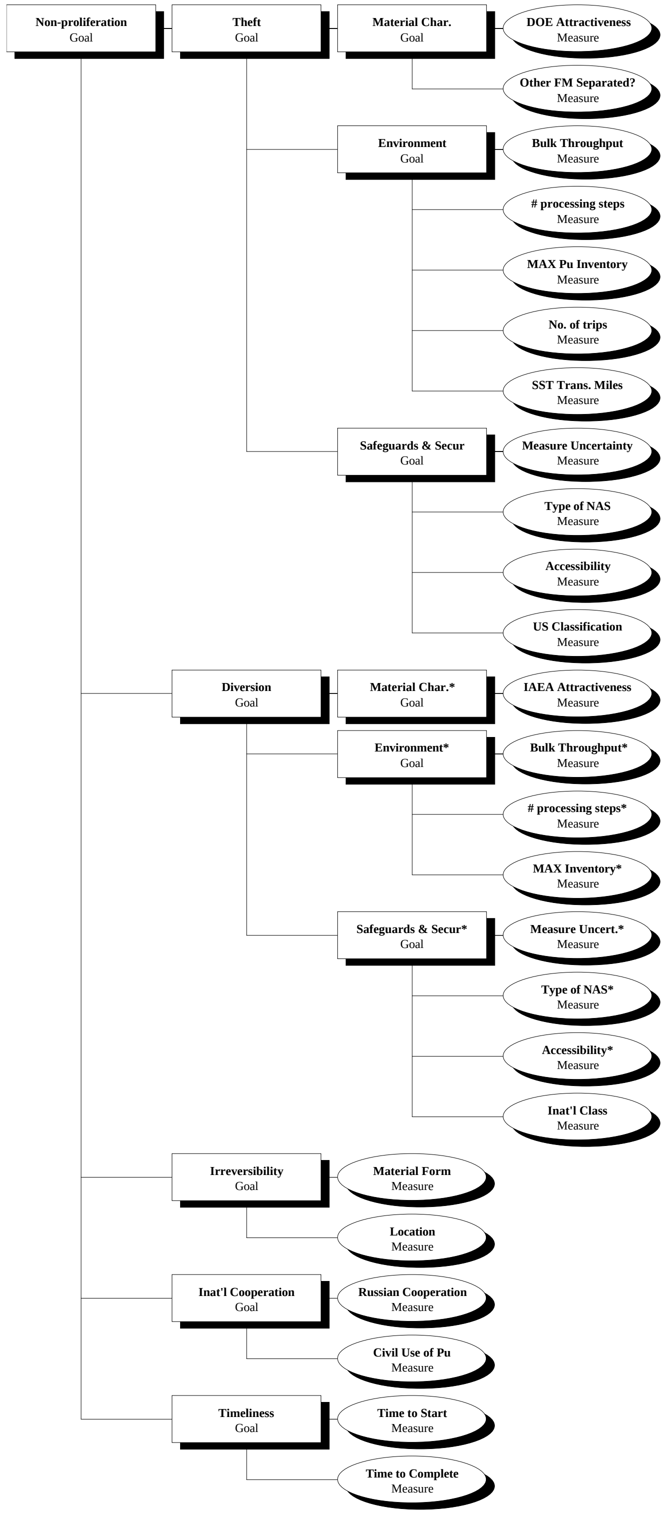

Figure 3a: Detail for Non-proliferation Objective

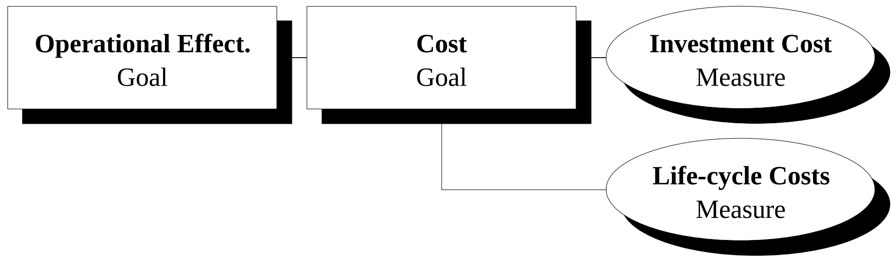

Figure 3b: Detail for Operational Effectiveness Objective

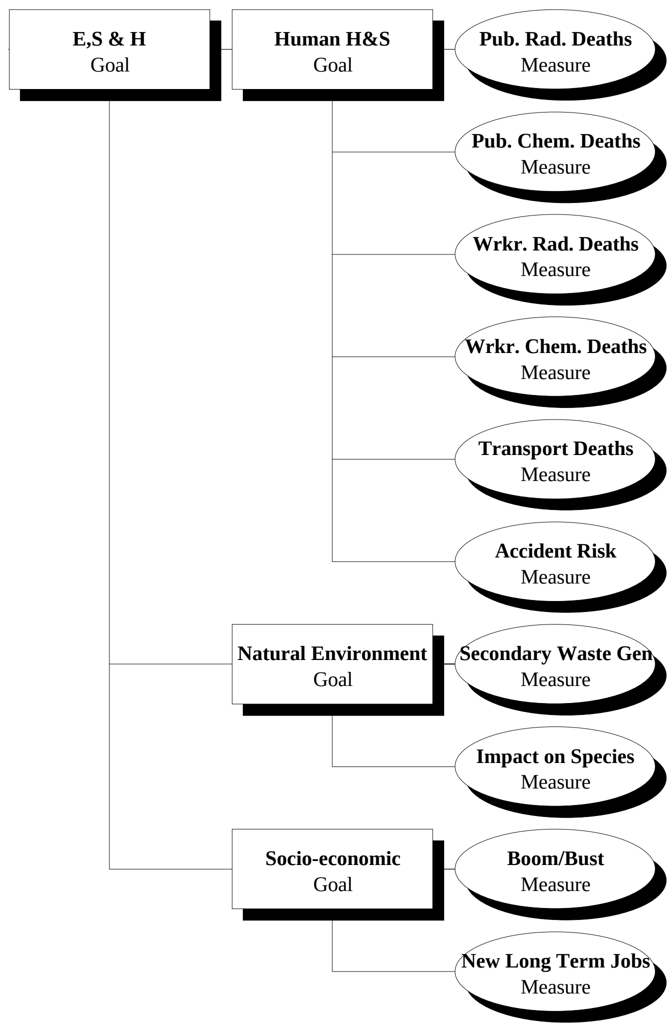

Figure 3c: Detail for Environment Safety and Health Objective

Table 2: Examples of Other Objectives

Secondary Fundamental Objectives
Reduce need for international transportation of plutonium.
Consistency with international effort to provide U.S. leadership.
Provide energy for future generations.
Minimize cost of energy to the consumer.
Provide flexibility to reverse program if the need arises.
Promote technology development.
Reduce dependency on foreign oil.
Minimize negative aesthetic impacts of the facilities.
Means Objectives
Maximize geologic stability for disposal site.
Minimize air pollution.
Minimize water pollution.
Process Objectives
Use best information available.
Involve relevant public and stakeholder groups in a constructive manner.
Educate the public.

the original nine objectives in the screening report (OFMD, 1995), from the preliminary set of measures suggested by the Lawrence Livermore National Laboratory team (Edmunds, Koopman and Myers, 1995), and from the measures proposed for evaluating technologies and sites for tritium supply and recycling (Decision Insights, 1995).

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."

The set of measures for the objectives is shown in Table 3. When logically reasonable, we selected natural measures, such as cost, time, lives lost, and number of animal species that are impacted, to associate with the objectives. However, when no relevant and/or natural scales are closely linked to an objective, such as maximizing the likelihood of Russian cooperation, we have worked with experts to construct a measure to indicate different levels of achievement.

Table 3: Objectives and Measures

NON-PROLIFERATION OBJECTIVES Resistance to Theft by Unauthorized Parties	
OBJECTIVE	**MEASURE**
Attractiveness of the material	Constructed scale based on DOE order 5633.3B
Inventory of other, fissile materials	Presence of other fissile material (Yes/No)
Throughput of disposition process	MT of bulk throughput per year
Security of the disposition environment concerning process accessibility	# processing steps
Maximum plutonium inventory of the material process	Maximum Pu inventory
Risk due to transportation exposure	SST trips (per kg. Pu)
Risk due to transportation exposure	SST miles per alternative
Accounting accuracy of material process	% material difference
Type of nuclear accounting system	Exponential scale biased toward “Item” (% time “Item”)
Accessibility of material in process	Constructed scale based on accessibility of Pu, accessibility of container, and special handling requirements
Classification of material in process	Constructed scale based on security classification of material (Yes or No)
Resistance to Diversion by Host Nation (International Verification and Acceptance)	
Attractiveness of the material	Constructed scale based on expert opinion of IAEA classification
Appeal to IAEA of the throughput of disposition process	MT of bulk throughput per year
Appeal to IAEA of the disposition environment concerning process accessibility	# processing steps
Appeal to IAEA of the maximum amount of plutonium material process	Maximum Pu inventory
Appeal to IAEA of the accounting methods in place	% material difference
Appeal to IAEA of the type of nuclear accounting system	Exponential scale biased toward “Item” (% time “Item)
Appeal to IAEA of the accessibility of material in process	Constructed scale based on accessibility of Pu, accessibility of container, and special handling requirements
Appeal to IAEA of the security classification of material in process	Constructed scale based on security classification of material (Yes or No)
Irreversibility of Final Form	
Irreversibility relative to NAS attractiveness rating	Constructed scale based on attractiveness: A, B, C, D, E per DOE order 5633.3B or IAEA eligible for termination
Irreversibility relative to the location of the plutonium	Constructed scale based location: borehole, geologic repository or in process

Table 3: Objectives and Measures (Con't)

NON-PROLIFERATION OBJECTIVES (continued) International Cooperation and Compliance	
OBJECTIVE	**MEASURE**
Impact a US alternative would have in influencing Russian disposition activities	Constructed scale based on factors considered desirable by Russia and influence of US choices
Do not encourage the civil use of plutonium	Constructed scale based on expert opinion
Timeliness	
Time to start disposition activities	Time between Record of Decision and the start of disposition activities
Time to complete disposition activities	Time between start of disposition and completion of disposition mission
OPERATIONAL EFFECTIVENESS OBJECTIVES **Costs**	
Investment costs	Investment costs -- $M
Life-cycle costs	Discounted life-cycle costs -- $M (R&D, startup, O&M, decontamination and decommissioning)
ENVIRONMENT, SAFETY AND HEALTH OBJECTIVES **Protect Human Health and Safety**	
OBJECTIVE	**MEASURE**
Public H&S risks, operations, radiological exposure	Expected number of public fatalities resulting from exposure to radionuclides during operations
Public H&S risks, operations, chemical exposure	Expected number of public fatalities from exposure to chemicals during operations
Worker H&S risks, operations, radiological exposure	Expected number of worker fatalities resulting from exposure to radionuclides during operations
Worker H&S risks, operations, chemical exposure	Expected number of worker fatalities from exposure to chemicals during operations
H&S risks, transportation	Expected number of fatalities from intersite transportation
Accident risks	Expected number of fatalities in a severe accident
Protect the Natural Environment	
Impacts on secondary waste management	Equivalent cubic yards of incremental waste generated
Impacts on biological species (terrestrial and aquatic)	Number of endangered or threatened species that could be affected
Socio-Economic Benefits	
Boom/bust employment losses	Percent decrease in local employment relative to peak employment
Sustained increase in employment	Number of permanent new jobs created in the local area

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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 Table 4, where performances of three hypothetical alternatives are evaluated on five measures and 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.

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 performance estimates with respect to these measures, DOE conducted a series of assessment meetings focusing on the major objectives. Members of the Safeguards and Security (S&S) team played a major role in evaluating the performance of the alternatives on the non-proliferation objective. Three two-day meetings were held at Sandia-Albuquerque to define the measures and scales associated with Safeguards and Security issues.
The data necessary to evaluate the International Cooperation goal was provided by several smaller meetings with individuals DOE identified as experts in Russian technologies and policies. We also benefited greatly from conversations and meetings with the OFMD group.

The Operational Effectiveness data was provided by the three alternative teams. The three alternative team leaders met to define the technical maturity issues and to maintain common standards and definitions across technologies. All cost data were processed using a common methodology and assumptions based on input provided by the alternative teams.

Environment, Safety and Health data requirements were generated by the analysis necessary to develop the required Programmatic Environmental Impact Statement (PEIS) for the project [DOE-PEIS 97]. Several meetings were held with personnel responsible for the PEIS to ensure the data were consistent with the objectives of the evaluation effort.

Table 4: 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

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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 Table 4, some measures may be represented by probability distributions while some are expressed as point estimates. Some measure are in dollars and some are in acres of land, 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 2. 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 4 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 is small in comparison to the DOE 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 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"[3].

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

[3] This is an exact quote from the assessment meeting with the S&S team.

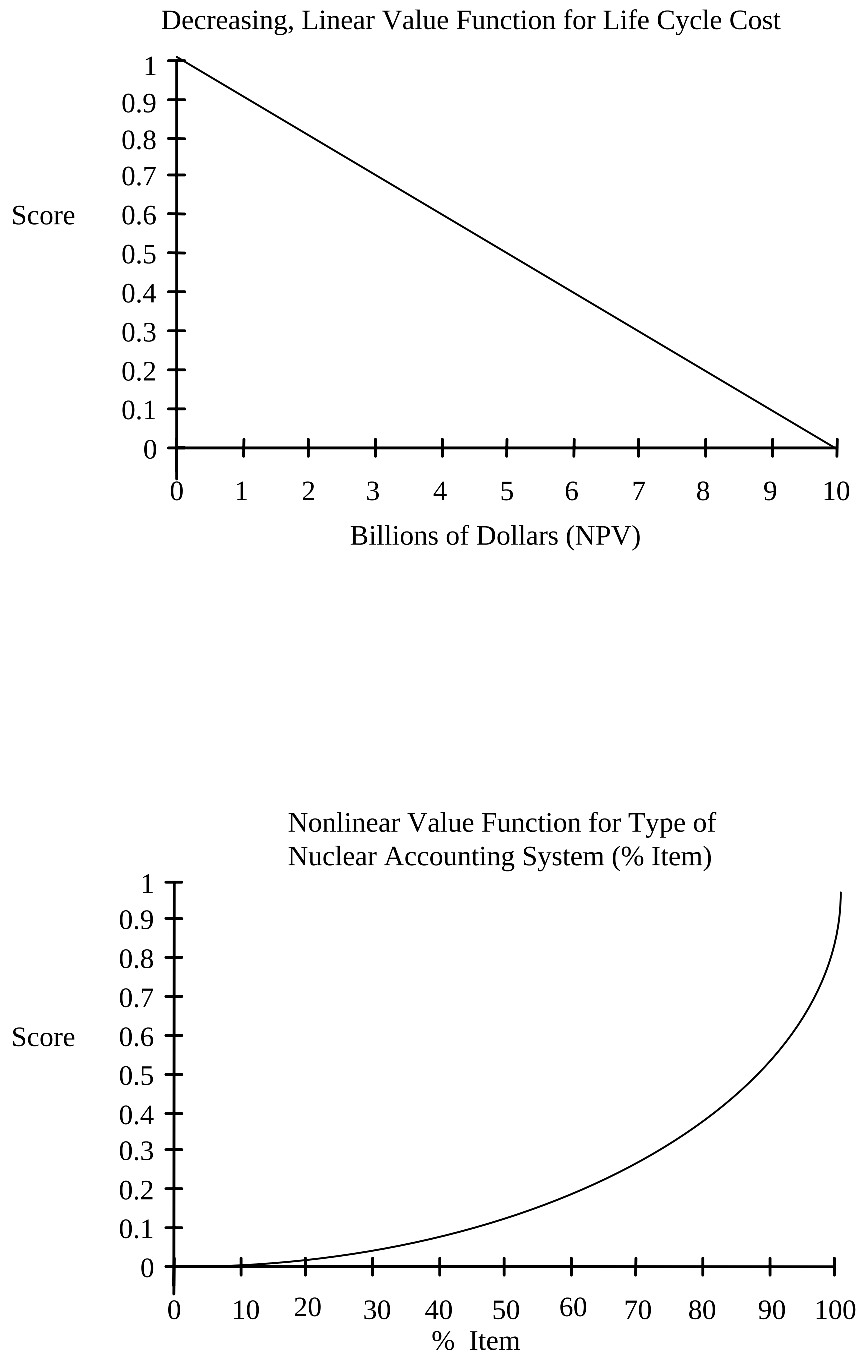

Figure 4: Two-Example Value Functions

checks" can be used to ensure that the responses are meaningful. These assessment protocols are also scripted to minimize biases in the responses and 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 providethe 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 the S&S experts who attended the "measure assessment" meeting described in Section 3. Some weights were obtained during this series of meetings as a part of the effort to measure performance on the major objectives.

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 will be obtained in interviews with persons identified by the Office of Fissile Materials Disposition. The individuals involved may include OFMD personnel, members of the Interagency Working Group, and other members of the DOE or other agencies concerned with issues related to this project.

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:

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

where $u_i(\cdot)$ 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:

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

where $u_i(\cdot)$ 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 was based on information collected from DOE personnel and other stakeholders. 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 Table 4) 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 2. 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 2. 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 Table 5.

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 Alternative C 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 objectives used in the Screening Phase report [DOE-SCR 95]. Comparisons among objectives and sub-objectives at different levels in the hierarchy may also be used to provide additional insights.

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.

Table 5: Example of Evaluation Phase Aggregation

	MAJOR CATEGORIES		
	Non-proliferation	Operational Effectiveness	Environment, Safety, and Health
Alternative A	0.7	0.3	0.7
Alternative B	0.5	0.8	0.1
Alternative C	0.4	0.3	0.4

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

5.2 SENSITIVITY ANALYSIS

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

Figure 5 provides an example of the first type of sensitivity analysis based on the hypothetical scores in Table 5. 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.

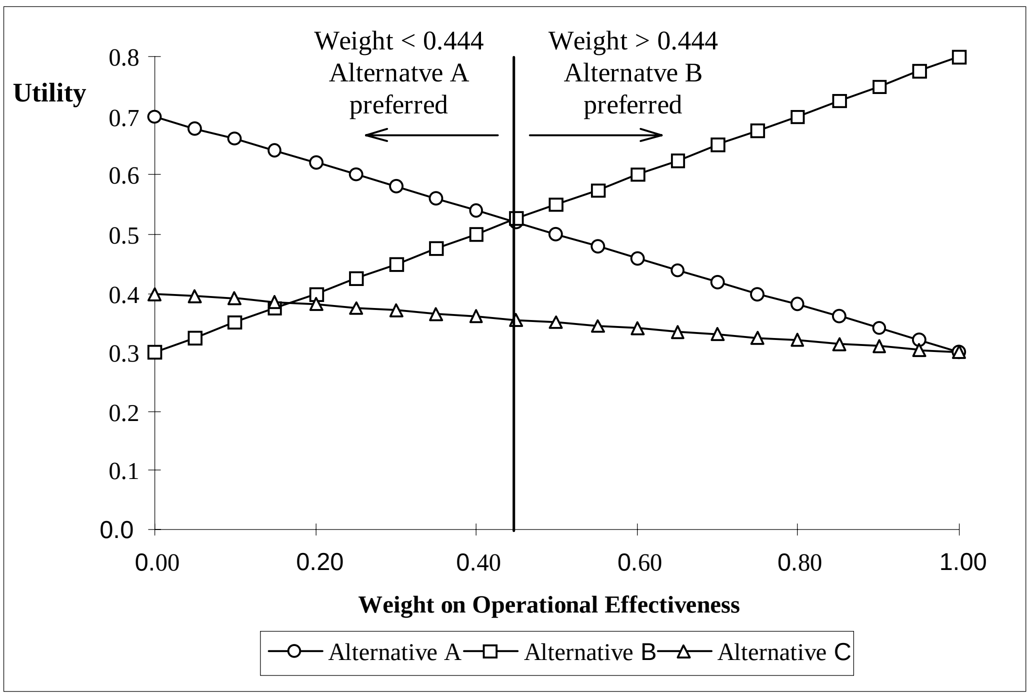

Figure 5: Example of Sensitivity Analysis on “Weights”

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