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Amarillo National
Resource Center for Plutonium

A Higher Education Consortium of The Texas A&M University System,
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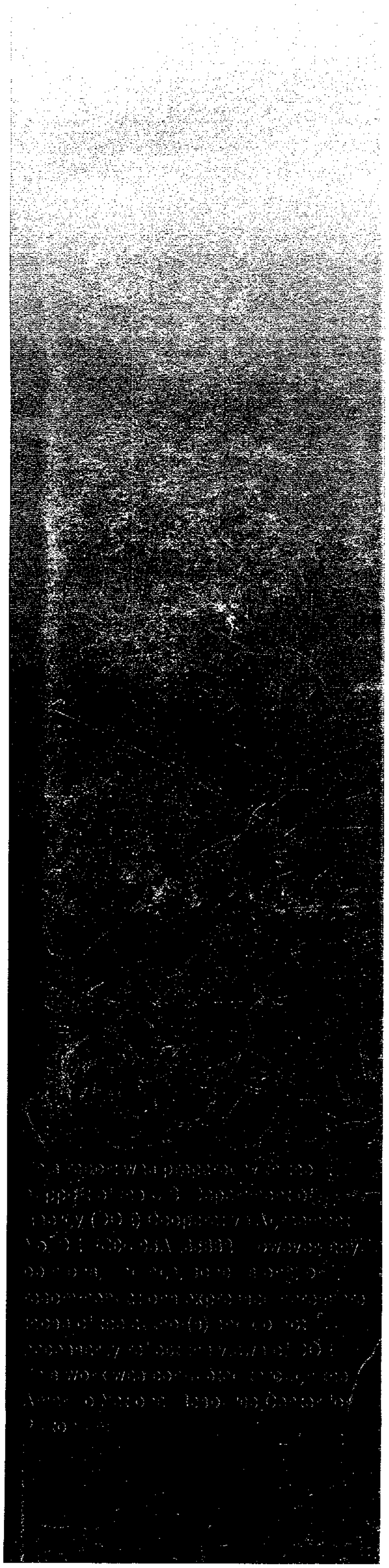

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Evaluation of Alternatives for the Disposition of Surplus Weapons-Usable Plutonium

April 1997

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Evaluation of Alternatives for the Disposition of Surplus Weapons-Usable Plutonium

Submitted by the
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Executive Summary

The Department of Energy - 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]. The disposition alternatives evaluated by DOE are shown in the following table.

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

IMMOBILIZATION 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 ceramic and radioactive materials at a new facility to form homogeneous ceramic disks. These disks would be placed in large canisters.
- Ceramic Can-in-Canister
  - Surplus plutonium would be mixed with non-radioactive ceramic materials to form 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.

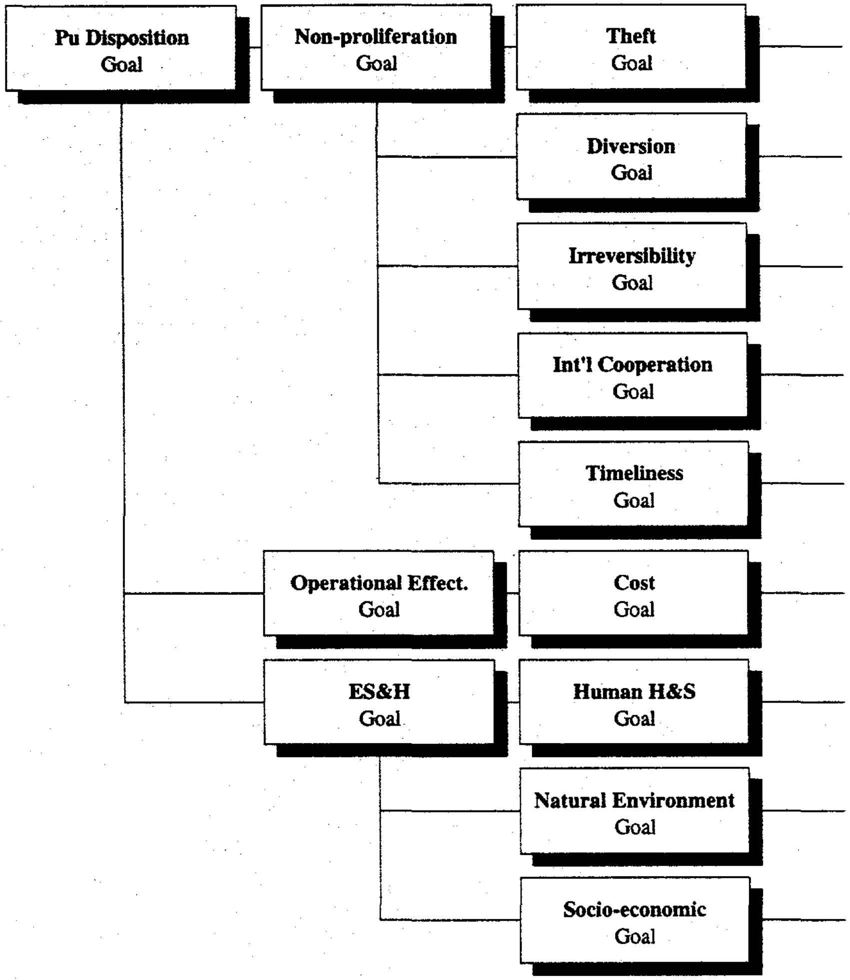
DIRECT DISPOSAL ALTERNATIVES
Deep Borehole (Immobilization) Surplus plutonium would be immobilized with ceramic pellets and placed in a borehole.
Deep Borehole (Direct Emplacement) Surplus plutonium would be converted to a suitable form and placed in a deep borehole.

The analysis reported here was conducted in parallel with these DOE technical, environmental, and nonproliferation analyses. It uses a logical and formal methodology, referred to as multiattribute utility (MAU) theory, to provide a structure for combining these considerations to facilitate an integrated evaluation of the alternatives by decision makers. The data are a collection of system performance estimates and value or policy judgments that reconcile conflicting objectives through the use of explicit tradeoffs. This framework is used to identify critical information for the evaluation, and to help make the basis of decisions transparent to stakeholders. The framework is also used to evaluate the sensitivity of decisions to the individual value judgments and alternative performance estimates. This sensitivity analysis provides an assessment of the overall robustness of decisions. It is important to emphasize that the MAU process implemented here does not provide a computerized model that actually determines *the* decision for plutonium disposition. This analysis is intended to provide additional insights regarding the evaluation of the alternatives, and to assist in understanding the rationale for the choice of the alternatives that were recommended in the ROD.

The goals or objectives included in the MAU model are derived from criteria developed in the screening process [DOE-SCR 95]. In the MAU model, they are arranged in a hierarchy, as shown in the following figure. This hierarchical structure was chosen to facilitate the specification of a value model and the communication of insights from the model to the OFMD and other interested parties. This hierarchy emphasizes three major objectives for the plutonium disposition effort, which are labeled Non-proliferation; Operational Effectiveness; and Environment, Safety and Health (ES&H), respectively.

As shown in the figure, the Non-proliferation objective is further subdivided into the five sub-objectives: Theft (minimize the opportunities for theft of the materials by unauthorized parties), Diversion (maximize the resistance of the disposition alternative to the diversion of the plutonium by the host nation during processing, and provide an internationally verifiable and acceptable process), Irreversibility (maximize the difficulty of recovering the material after disposition has been completed), International Cooperation (foster international cooperation with the U.S. disarmament and nuclear non-proliferation policy), and Timeliness (minimize the time required for the disposition effort to begin and to complete the disposition mission).

Objectives Hierarchy for Plutonium Disposition Decision

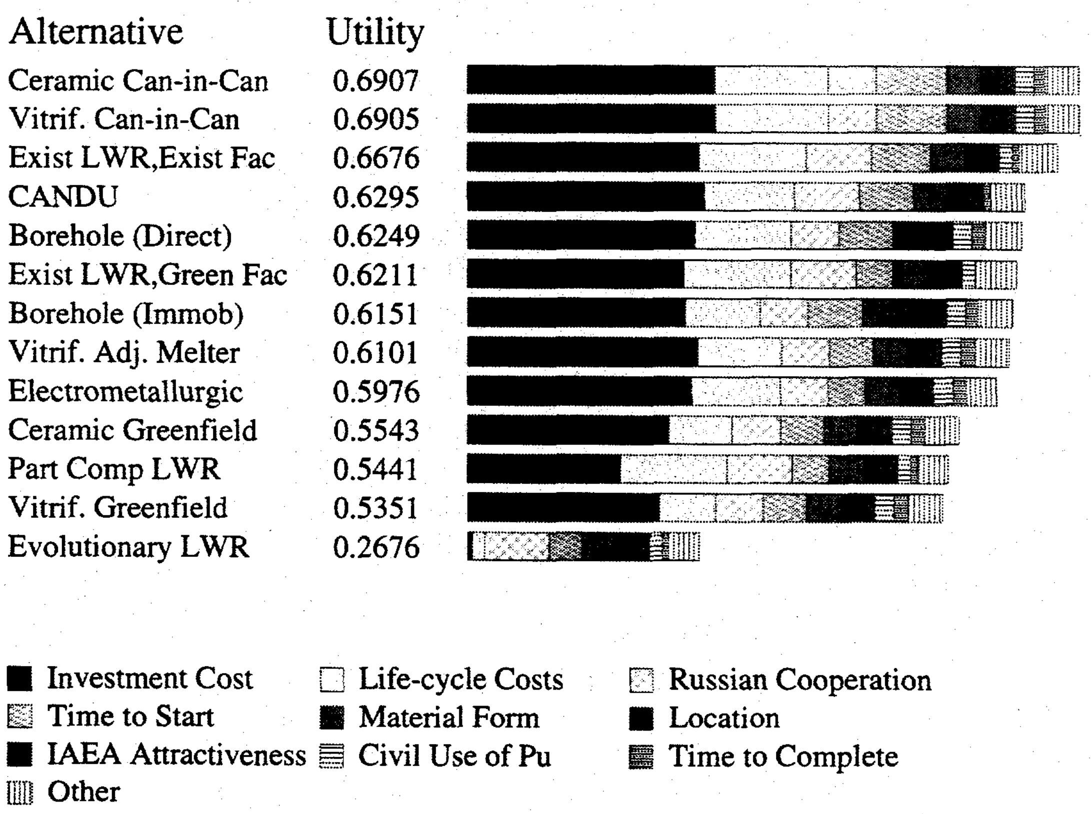


The second major objective shown in the figure, Operational Effectiveness, includes the Investment and Life-cycle costs associated with an alternative. The third objective; Environment, Safety, and Health; is made up of the following three sub-objectives: Human Health and Safety (minimize the incremental health impacts to the public and workers), Natural Environment (minimize the incremental impact on the natural habitat at the sites), and Socio-economic (minimize the incremental adverse impacts to the human environment).

Each sub-objective on the right-hand-side of the figure is further specified in terms of one or more of thirty-seven measures that are included in the model (e.g., Life-cycle Costs, Time to Start, Material Form). Scores of an alternative on these measures determine to what extent implementation of the alternative would satisfy the objectives. Scores for individual measures are weighted and summed to generate a composite score that reflects the overall desirability of the alternative. The model is constructed so that higher overall scores indicate a more desirable alternative.

The MAU model was used to evaluate five reactor, six immobilization, and two borehole alternatives under a base case set of facts, assumptions, and value judgments, and for variations in assumptions and value judgments about this base case. The *stacked bar graph* shown in the following figure provides a useful tool for summarizing the scores of these alternatives with respect to the measures. The overall score, labeled "Utility" in the figure, is a weighted sum of scores for the thirty-seven measures associated with the three objectives discussed previously. The stacked bars shown in the figure are segmented to show the relative contributions of these scores for each alternative. For example, the third segment for the existing LWR alternative is wider than the corresponding segment for the vitrification can-in-can alternative. This indicates that the existing LWR scores higher than the vitrification can-in-can alternative on the Russian cooperation measure. The weights used to generate the following figure were established by OFMD personnel and by a review of previous DOE studies, and are presented as a base case.

Ranking for Pu Disposition Goal



Some key insights of the analysis are as follows:

1) both the vitrification and ceramic can-in-can alternatives achieve high overall scores based to a large extent on low cost and early start times
2) the existing LWR alternative scores higher than the CANDU alternative due to its lower life cycle cost and concerns regarding the civil use of plutonium in CANDU reactors

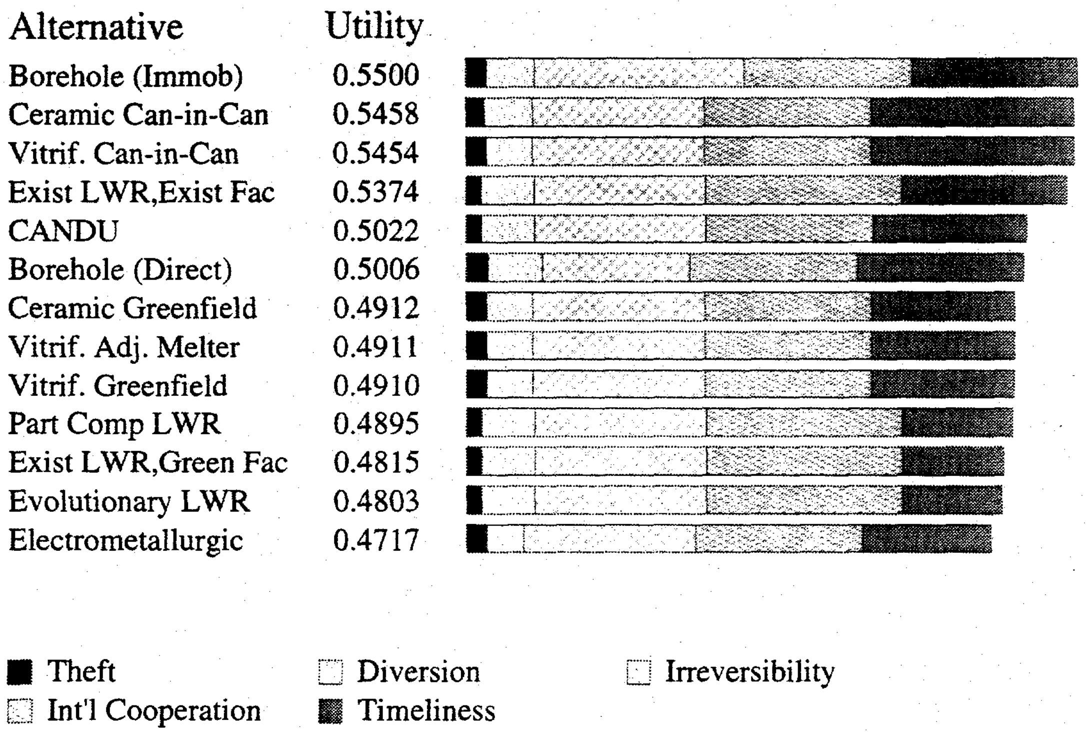
3) existing LWR and CANDU reactor alternatives score higher than new or partially complete reactor alternatives due to cost and schedule advantages
4) the boreholes and vitrification adjunct melter alternatives achieve moderate scores
5) the greenfield and electrometallurgical immobilization alternatives achieve low scores due to high life costs
6) reactor alternatives score high in terms of cooperation with Russia, but score low in terms of encouraging the civil use of plutonium — the two effects tend to offset one another
7) a hybrid alternative that includes existing LWRs and can-in-can immobilization would score well on both Russian cooperation and time to start

This base case ranking of the alternatives was subjected to a series of sensitivity analyses. These analyses included the examination of the effects of varying the weights on the performance measures of the alternatives, and on the three major objectives of Non-proliferation; Operational Effectiveness; and Environment, Safety, and Health. Although some changes in the rankings were observed under extreme combinations of changes in the underlying MAU evaluation model, the general pattern of the rankings shown above proved to be extremely robust. In particular, the two can-in-can immobilization, existing LWR, and CANDU alternatives are generally ranked among the top four or five alternatives. Three of these four alternatives were recommended for further development and examination in the ROD. The fourth, CANDU, was recommended as a back-up alternative should negotiations with Russia lead to joint disposition activities in Canada.

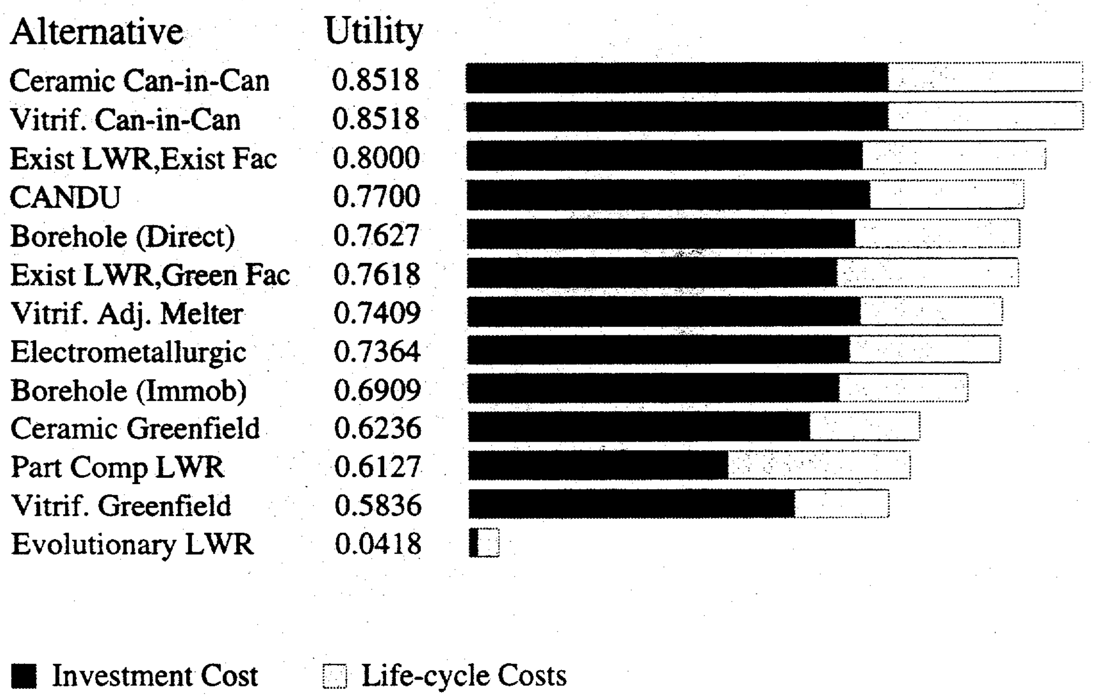
The seventh insight listed indicates that an immobilization-LWR "hybrid" alternative may offer advantages based upon the analysis in this deterministic model. The technological and institutional *uncertainties* associated with all of the alternatives also suggest that a hybrid strategy may be advantageous. Intuitively, the reason for pursuing this hybrid strategy of multiple options is to hedge against the risks associated with such considerations as technology development, contract negotiations, and negotiations with Russia and other nations. One example of the advantage offered by this intuitively appealing approach is illustrated in the body of the report by focusing on one issue of uncertainty, Russian Cooperation. The analysis shows that pursuit of a hybrid strategy is optimal under a reasonable range of possible assumptions about Russian negotiating positions.

Rankings are also presented with respect to each of the three major objectives. The stacked bar graph for the first of these objectives, Non-proliferation, is shown in the following figure. The overall Non-proliferation score is comprised of scores for measures associated with each of the five sub-objectives discussed previously. As indicated by the data in the figure, the borehole with immobilized material scores the highest due to its characteristics relative to Irreversibility. The deep geologic isolation and ceramic material form make the material difficult to recover relative to the other alternatives. However, the timeliness advantage of the can-in-can immobilization alternatives and the international cooperation advantage of the exiting LWR alternative almost compensate for the lower scores on Irreversibility, so that the composite scores of these alternatives are almost as high as that for the borehole with immobilized material. Theft and Diversion sub-objectives do not appear to be major discriminators among the alternatives.

Ranking for Non-proliferation Goal



The stacked bar graph for the Operational Effectiveness objective is shown in the following figure. Investment Cost appears to be a major discriminator. The can-in-can immobilization alternatives and existing reactor alternatives, which save money by utilizing existing facilities, receive the highest utility scores. In addition, the high investment costs required to construct the Evolutionary LWR severely penalize this alternative.

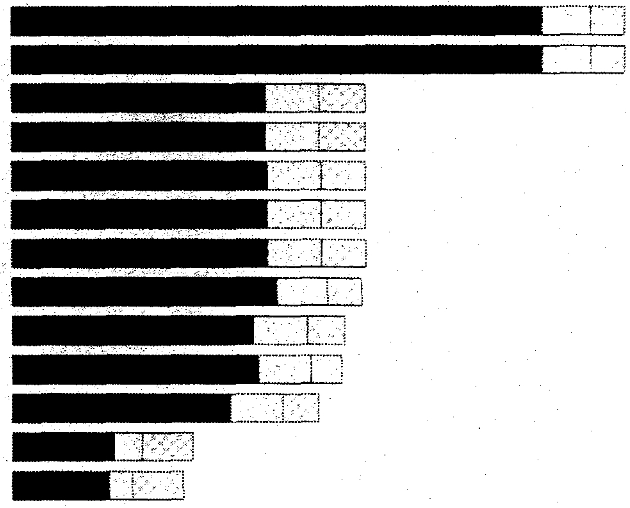


Ranking for Operational Effect. Goal

A stacked bar graph for the Environment, Safety, and Health objective is shown in the last figure. As indicated by the data in the figure, existing reactors outperform all other alternatives because switching from a uranium to a MOX fuel cycle would lower the expected number of fatalities to both workers and the public. This is because the use of MOX fuel would eliminate the need for the more hazardous operations required to mine and process the displaced uranium fuel [DOE-PEIS, pg. 4-978]. The Partially Complete LWR alternative and the Evolutionary LWR alternative are heavily penalized by a relatively large incremental health impact on workers and a relatively high volume of secondary waste generation, since they would represent new operating facilities.

Ranking for ES&H Goal

Alternative	Utility
Exist LWR,Green Fac	0.8490
Exist LWR,Exist Fac	0.8490
Ceramic Greenfield	0.4923
Ceramic Can-in-Can	0.4923
Vitrif. Greenfield	0.4914
Vitrif. Can-in-Can	0.4914
Vitrif. Adj. Melter	0.4914
CANDU	0.4858
Borehole (Direct)	0.4612
Electrometallurgic	0.4587
Borehole (Immob)	0.4254
Evolutionary LWR	0.2513
Part Comp LWR	0.2389



■ Human H&S ☐ Natural Environment ☐ Socio-economic

In conclusion, the two can-in-can immobilization alternatives and the exiting LWR alternative are the most desirable alternatives under a broad range of value judgments regarding the importance of the individual measures.

Evaluation of Alternatives for the Disposition of Surplus Plutonium

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 thirty-seven 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 fourteen alternatives (including the variants and the "do nothing" alternative) were considered reasonable candidates for plutonium disposition.

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 (ANRCP) provided an independent evaluation of the alternatives for plutonium that were considered during the Evaluation Phase effort. The ANRCP is supported by a consortium of three universities, The University of Texas at Austin, Texas A&M University, and Texas Tech University, and funds a research program dedicated to the investigation of issues related to the storage and disposition of plutonium.

The ANRCP 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 ANRCP team met on numerous occasions with OFMD personnel, and with the 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 ANRCP 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]. A list of these meetings is included in Appendix A.

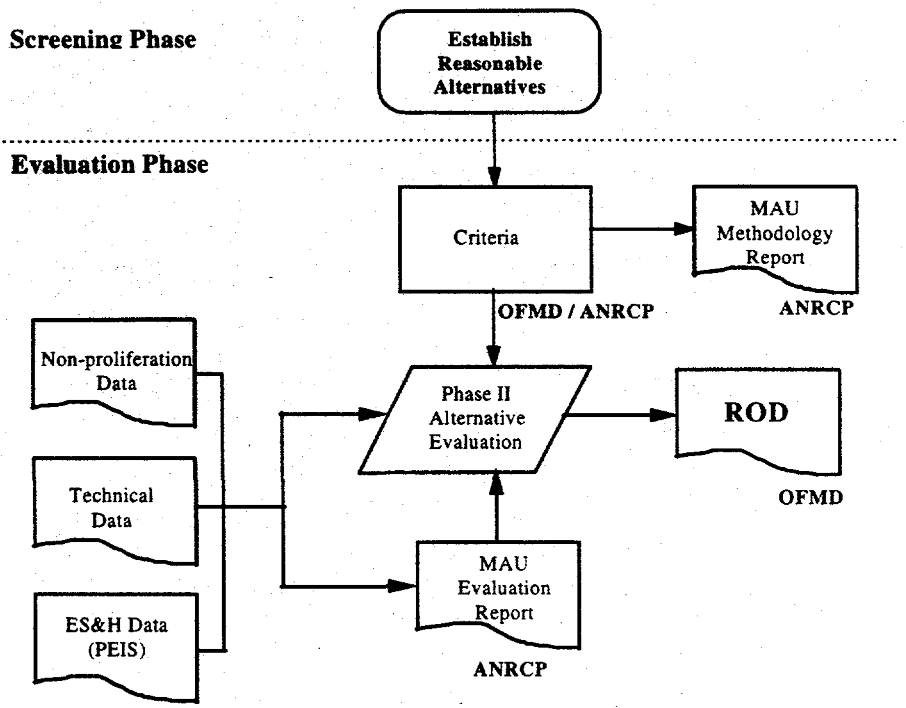
The proposed evaluation methodology developed by the ANRCP team was reviewed during meetings with OFMD personnel, and also by the ANRCP Senior Technical Review Group (STRG) at a meeting in Washington D.C. in November 1995. In addition, the proposed methodology was presented in public forums at the American 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 ANRCP 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 ANRCP 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 above is illustrated in Figure 1.

Figure 1 - Phases of ROD



ANRCP -- Amarillo National Resource Center for Plutonium
OFMD -- Office of Fissile Materials Disposition
PEIS -- Programatic Environmental Impact Statement
ROD -- Record of Decision

1.2 Evaluation Phase Methodology

The Evaluation Phase focused on a comparison of the thirteen "disposition", as opposed to "do nothing", alternatives, based on the assumption that long-term continued storage of U.S. weapons-grade plutonium is not consistent with U.S. policy regarding the proliferation of nuclear weapons. 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 multiattribute 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]

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

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

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).

A 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.

Other than continued storage, the thirteen reasonable disposition alternatives identified in the first phase may be grouped into three categories: reactor alternatives, immobilization alternatives, and borehole alternatives. In addition to an overall comparison and evaluation of these thirteen alternatives, an evaluation of alternatives within each of these alternative categories will be presented. The differences among alternatives within each of these three categories is generally less than differences across categories because alternatives within categories often share common relative strengths and weaknesses.

In the ROD, OFMD has recommended alternatives from two of these categories for further development. Such a strategy provides a contingency in case a common weakness among alternatives in one family proves more difficult to overcome during implementation than is currently forecast. This idea of a parallel implementation strategy using alternatives from two categories was recommended by a complimentary study by the National Academy of Sciences [NAS 94, NAS 95]. In addition to the evaluation of the individual alternatives, an analysis of this strategy of parallel development of two alternatives for the disposition of weapons-usable plutonium is also developed.

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 aide in communicating the results of the analysis to the decision makers and other stakeholders. The analyses 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

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
IMMOBILIZATION 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 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.

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), and for previous studies concerned with the management and disposition of surplus plutonium [NAS 94, NAS 95].

2.2.1 Objectives

The objectives for any decision provide the basis for evaluating the relative desirability of available alternatives. 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 Scoping Meetings held different locations across the country from August to October 1994 [DOE-MD 97]. 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.

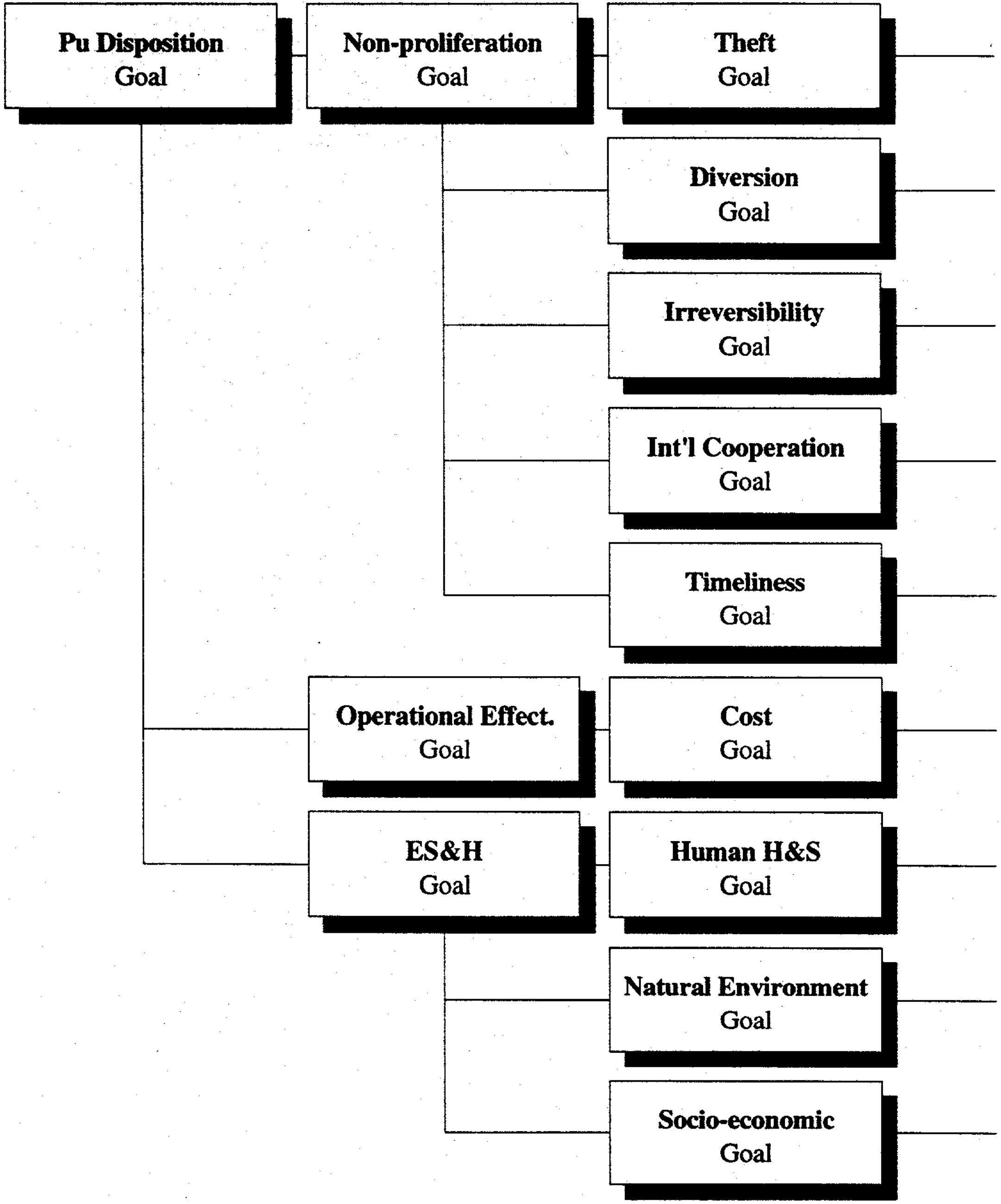
Objectives used for screening the alternatives for the disposition of plutonium were the following:

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.

Figure 2 - High Level Objectives for Plutonium Disposition



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

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 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, as discussed in Section 6. 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.

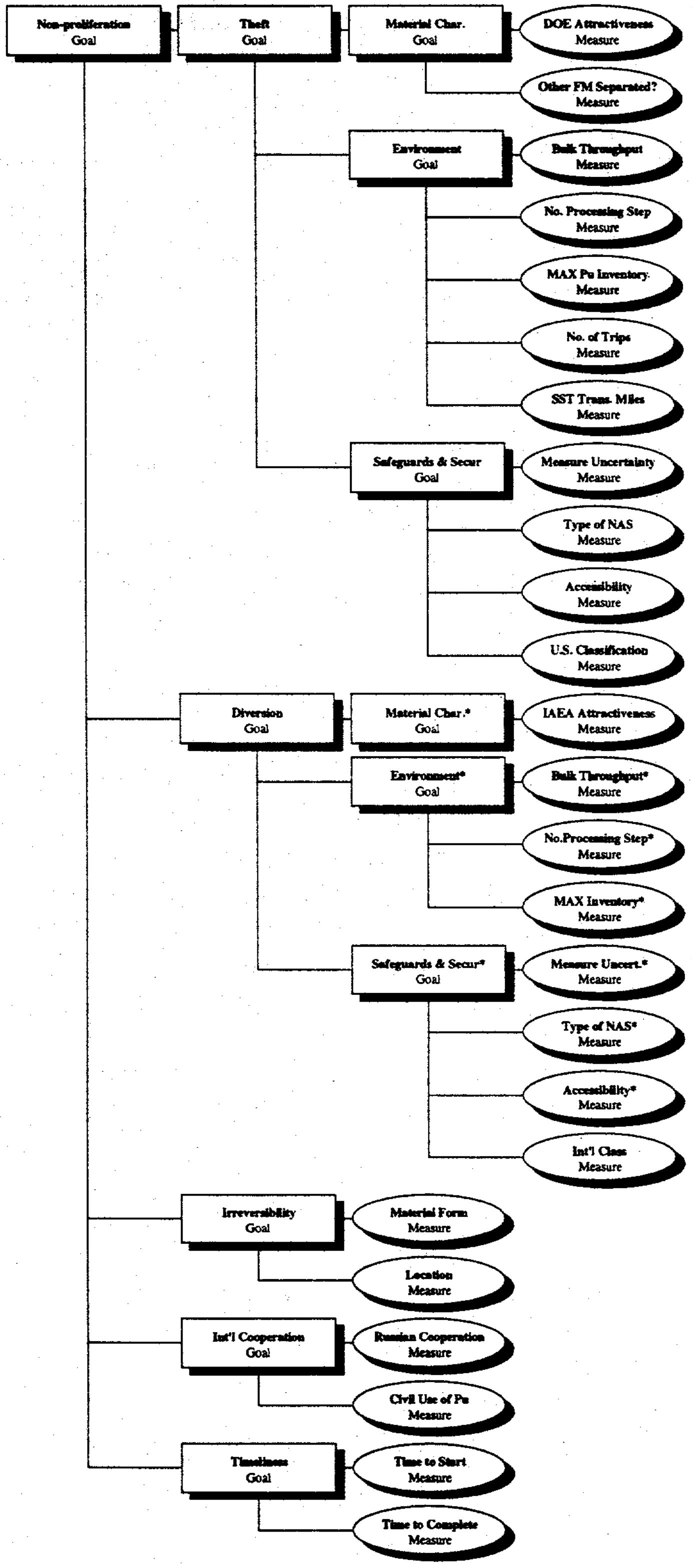
Public and institutional acceptance was a major concern in the screening process and the basis for the elimination of many of the alternatives that were originally considered. All of the alternatives shown in Table 1 have satisfied this criterion for the purposes of screening. Further, the other objectives 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

Figure 3a - Detail for Non-proliferation Objective



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. 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 inter-site transportation activities.

Figure 3b - Detail for Operational Effectiveness Objective

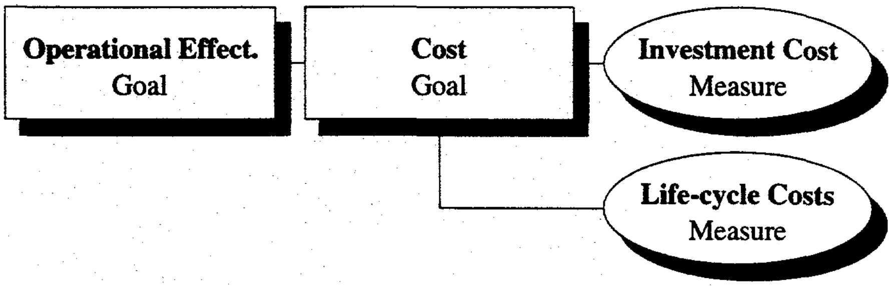
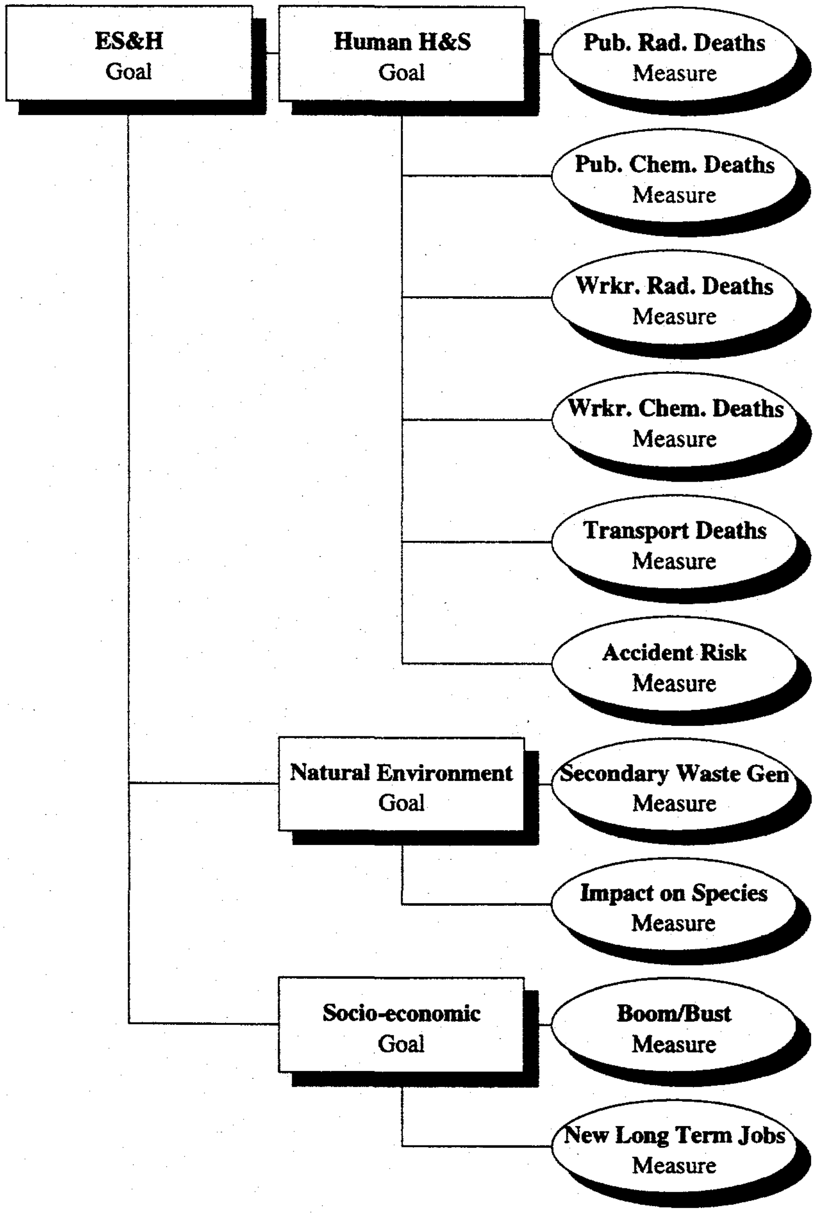


Figure 3c - Detail for Environment Safety and Health Objective



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

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 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.

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.

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.

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

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. In developing the set of recommended measures, we have benefited from the rich discussions of the original nine objectives in the screening report (OFMD, 1995) and from the preliminary set of measures suggested by the Lawrence Livermore National Laboratory team (Edmunds, Koopman and Myers, 1995).

The measure or set of measures associated with an objective should cover all aspects of the objective. In addition, the chosen measures must be relevant for all the alternatives under consideration to ensure consistency and comparability across disposition candidates. 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, natural measures have been selected, such as cost, time, statistical 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 denote different levels of achievement.

Table 3 - Objectives and Measures

Abbreviation Used in Figures and Descriptions	**OBJECTIVE**	**MEASURE**
NON-PROLIFERATION OBJECTIVES		
RESISTANCE TO THEFT BY UNAUTHORIZED PARTIES		
DOE Attractiveness	Attractiveness of the material	Constructed scale based on DOE order 5633.3B
Other FM Separated?	Inventory of other, fissile materials	Presence of other fissile material (Yes/No)
Bulk Throughput	Throughput of disposition process	Metric tons of bulk throughput per year
No. Processing Step	Security of the disposition environment concerning process accessibility	Number of processing steps
MAX Pu Inventory	Maximum plutonium inventory of the material process	Maximum Pu inventory
No. of Trips	Risk due to transportation exposure	Number of Safe and Secure Transports (per kg. Pu)
SST Trans. Miles	Risk due to transportation exposure	Safe and Secure Transport miles per alternative
Measurement Uncertainty	Accounting accuracy of material process	Percentage material difference
Type of NAS	Type of nuclear accounting system	Exponential scale biased toward "Item" (percentage of time "Item")
Accessibility	Accessibility of material in process	Constructed scale based on accessibility of Pu, accessibility of container, and special handling requirements
U.S. Classification	Classification of material in process	Constructed scale based on security classification of material (Yes or No)

Table 3 - Objectives and Measures Continued

Abbreviation Used in Figures and Descriptions	**OBJECTIVE**	**MEASURE**
NON-PROLIFERATION OBJECTIVES continued		
RESISTANCE TO DIVERSION BY HOST NATION (INTERNATIONAL VERIFICATION AND ACCEPTANCE)		
IAEA Attractiveness	Attractiveness of the material	Constructed scale based on expert opinion of IAEA classification
*Bulk Throughput**	Appeal to IAEA of the throughput of disposition process	Metric tons of bulk throughput per year
*No. Processing Step**	Appeal to IAEA of the disposition environment concerning process accessibility	Number of processing steps
*MAX Inventory**	Appeal to IAEA of the maximum amount of plutonium material process	Maximum Pu inventory
*Measurement Uncert.**	Appeal to IAEA of the accounting methods in place	Percentage material difference
*Type of NAS**	Appeal to IAEA of the type of nuclear accounting system	Exponential scale biased toward "Item" (percentage time "Item)
*Accessibility**	Appeal to IAEA of the accessibility of material in process	Constructed scale based on accessibility of Pu, accessibility of container, and special handling requirements
Int'l Classification	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		
Material 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
Material Location	Irreversibility relative to the location of the plutonium	Constructed scale based location – borehole, geologic repository or in process

Table 3 - Objectives and Measures Continued		
Abbreviation Used in Figures and Descriptions	**OBJECTIVE**	**MEASURE**
NON-PROLIFERATION OBJECTIVES continued		
INTERNATIONAL COOPERATION AND COMPLIANCE		
Russian Cooperation	Impact a U.S. alternative would have in influencing Russian disposition activities	Constructed scale based on factors considered desirable by Russia and influence of U.S. choices
Civil Use of Pu	Do not encourage the civil use of plutonium	Constructed scale based on expert opinion
TIMELINESS		
Time to Start	Time to start disposition activities	Time between Record of Decision and the start of disposition activities
Time to Complete	Time to complete disposition activities	Time between start of disposition and completion of disposition mission
OPERATIONAL EFFECTIVENESS OBJECTIVES		
COST		
Investment Cost	Investment cost	Investment costs in millions of dollars
Life-cycle Costs	Life-cycle costs	Discounted life-cycle costs in millions of dollars (R&D, startup, O&M, decontamination and decommissioning)

Table 3 - Objectives and Measures Continued

Abbreviation Used in Figures and Descriptions	**OBJECTIVE**	**MEASURE**
ENVIRONMENT, SAFETY AND HEALTH OBJECTIVES		
PROTECT HUMAN HEATH AND SAFETY		
Pub. Rad.. Deaths	Public H&S risks, operations, radiological exposure	Expected number of public fatalities resulting from exposure to radionuclides during operations
Pub. Chem.. Deaths	Public H&S risks, operations, chemical exposure	Expected number of public fatalities from exposure to chemicals during operations
Wrkr. Rad.. Deaths	Worker H&S risks, operations, radiological exposure	Expected number of worker fatalities resulting from exposure to radionuclides during operations
Wrkr. Chem.. Deaths	Worker H&S risks, operations, chemical exposure	Expected number of worker fatalities from exposure to chemicals during operations
Transport Deaths	H&S risks, transportation	Expected number of fatalities from inter-site transportation
Accident Risk	Accident Risks	Expected number of fatalities in a severe accident
PROTECT THE NATURAL ENVIRONMENT		
Secondary Waste Gen	Impacts on secondary waste management	Equivalent cubic yards of incremental waste generated
Impact on Species	Impacts on biological species (terrestrial and aquatic)	Number of endangered or threatened species that could be affected
SOCIO-ECONOMIC BENEFITS		
Boom/Bust	Boom/bust employment losses	Percent decrease in local employment relative to peak employment
New Long-Term Jobs	Sustained increase in employment	Number of permanent new jobs created in the local area

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.

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. However, since many of the alternatives that would clearly be inferior were eliminated by the screening study, it is unlikely that more than a small subset of the alternatives will be obvious candidates for elimination from further consideration based on the inspection of this matrix.

In order to obtain performance estimates with respect to these measures, the ANRCP cooperated with the DOE in conducting a series of assessment meetings focusing on the major objectives. Members of the DOE 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 on July 6-7, July 31-Aug. 1, and Aug. 16-17 of 1995, to define the measures and scales associated with Safeguards and Security issues.

The data necessary to evaluate the International Cooperation sub-objective 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, engineers and 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 alternatives, and borehole alternatives. The three alternative team leads met 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 96]. Several meetings were held with personnel responsible for the PEIS to ensure the data were consistent with the objectives of the evaluation effort.

A full set of the fundamental data used for the evaluation and analysis is presented in Appendix B. In order to develop a meaningful alternatives-by-objectives (and measures) matrix, additional processing of some of the data in Appendix B was required, primarily to develop measures for the objectives Non-proliferation and Environment, Safety and Health. The resulting alternatives-by-objectives matrix is presented in Section 5 following a more detailed discussion of the measures and the calculations required to generate them.

4. Development of Value Functions

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. The performance measures for some alternatives may be represented by probability distributions or ranges, while some are expressed as point estimates. Some measures are in dollars and one is in numbers of endangered species, 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 Figures 2, 3a, 3b, and 3c. The use of utility theory ensures that any recommendation reflects:

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

The first and second issues will be addressed in this section; the third in Section 6. For a more detailed presentation of these topics see Keeney and Raiffa (1976) and von Winterfeldt and Edwards (1986).

4.1. Multiattribute Utility Functions

In order to obtain an overall evaluation for each disposition alternative on a higher level objective, an aggregation model may be used 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 multiple criteria, 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 $u_i(\cdot)$ 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:

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

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).

In this analysis of the thirteen alternatives for the disposition of plutonium, the additive model (1) will be used to aggregate the results of the evaluation effort. This model is chosen because the independence assumptions that justify the use of the additive model are reasonable for this analysis due to the relationships among the objectives and measures, and because the results of the analysis are easier to interpret when the additive model is used. However, a sensitivity analysis has been carried out in Section 8.1 with the multiplicative model (2) to ensure that the results are not altered in a significant way by the use of the additive model (1).

For a more detailed discussion of the assumptions underlying these two models, see Keeney and Raiffa (1976).

4.2 Value Functions for Non-proliferation objectives

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.

In this section, the measures shown previously in Table 3 are explained in more detail, and the value function associated with each measure is described. This discussion will be grouped in the same fashion as the objectives hierarchy shown in Figures 2, 3a, 3b and 3c. The approach used to aggregate the measures of Theft and Diversion and the methodology used to provide scores for the Environment, Safety and Health measures will also be discussed.

4.2.1 Value Functions for Theft

The measures shown in Figure 3a under the sub-objectives Theft, Diversion and Irreversibility were developed during a series of two day meetings at Sandia National Laboratories in Albuquerque, NM with Safeguards and Security (S&S) team members from Sandia, Lawrence Livermore, and Los Alamos National Laboratories. For each of these measures, the S&S team cooperated with a joint ANRCP/DOE team in developing a value function to score the performance of an alternative. Many of the measures and scales used for the sub-objective Theft also apply to the sub-objective Diversion. This "double counting" is consistent with the judgments of the S&S team because these repeated measures have different interpretations under the different goals.

For example, the measure Measurement Uncertainty appears under both sub-objectives. In the case of Theft, this measure captures the ability of the host nation to detect a material difference that may indicate a theft has occurred, while the same measure is interpreted as the ease with which an outside inspector can verify the quantity of plutonium in process under the sub-objective Diversion. Scales that apply for measures that are members of both sub-objectives will be noted as they are presented.

Theft - Material Characteristics
DOE Attractiveness

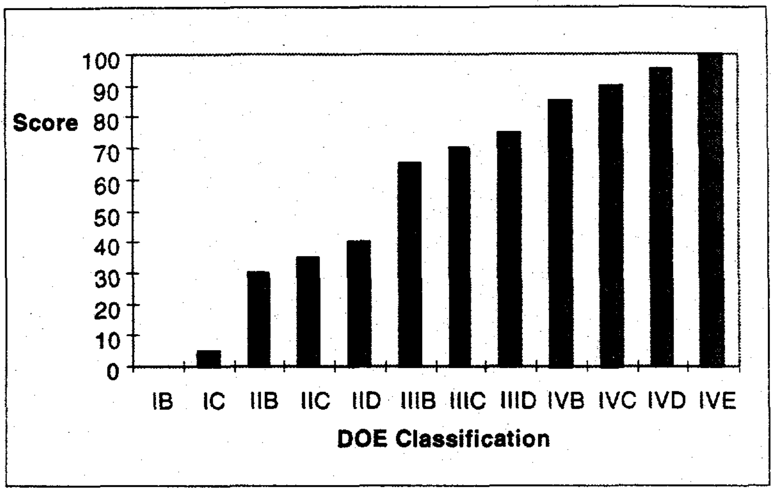
Table 4 presents DOE Attractiveness, a measure of the desirability of the material in process at a facility from the perspective of a potential thief, defined by DOE Order 5633.31. The twelve DOE Attractiveness categories range from IV-E to I-B. This measure only applies to the objective Theft.

Table 4 - Attractiveness Levels from DOE Order 5633.31

		Safeguards Category (I = greatest concern) Versus Quantity of Contained Material (kg.)			
		Pu or U-233			
Type of Material	**Attractiveness Level**	**I**	**II**	**III**	**IV**
Weapons	A	Any quantity is Category I			
Pure Products	B	> 2	0.4 - 2	0.2 - 0.4	< 0.2
High-grade materials	C	>6	2 - 6	0.4 - 2	< 0.4
Low-grade materials	D	NA	> 16	3 - 16	< 3
All other materials	E	Any reportable quantity is Category IV			

The value function scores corresponding to each level of DOE Attractiveness were assigned by the S&S team, and are shown in Figure 4.

Figure 4 - Scale for DOE Attractiveness



Other Separated Fissile Materials

Other Separated Fissile Materials is a simple scale: if there are no separated fissile materials, the facility scores a 100; otherwise, it scores a zero. The reasoning behind this scale was that the presence of fissile materials other than plutonium or U-235 could possibly be used as a diversion path. This measure only applies to the objective Theft.

Theft - Environment

Bulk Throughput

Bulk Throughput measured in metric tons per year is another indicator of the degree to which the process can be monitored. The higher the throughput of plutonium in bulk form (e.g. powder), the harder it will be to accurately monitor and measure the plutonium in process at the facility. It should be noted that an alternative that has zero Bulk Throughput at a facility may or may not have high throughput in the form of discrete physical units known as "items" (e.g., pits). The S&S team felt that items were much easier to monitor, so there was less risk associated with high item throughput.

Bulk Throughput applies to both Theft and Diversion. Figure 5 is the value function scale used to score a facility's annual level of Bulk Throughput. The range of Bulk Throughput is 0 to 7 metric tons per year.

Number of Processing Steps

The measure Number of Processing Steps, not including receiving and/or shipping, is used in both Theft and Diversion. A processing step was defined as an action or activity that involves a form change of greater than one percent in the physical or chemical properties of the material. This measure captures the complexity of the processing at a facility. The outcome for an alternative is the sum of the processing steps at each facility.

Figure 6 is a graphic depiction of the value function scale used to score the Number of Processing Steps for an alternative. The range of Number of Processing Steps is 1 to 35.

Figure 5 - Value Function for Bulk Throughput

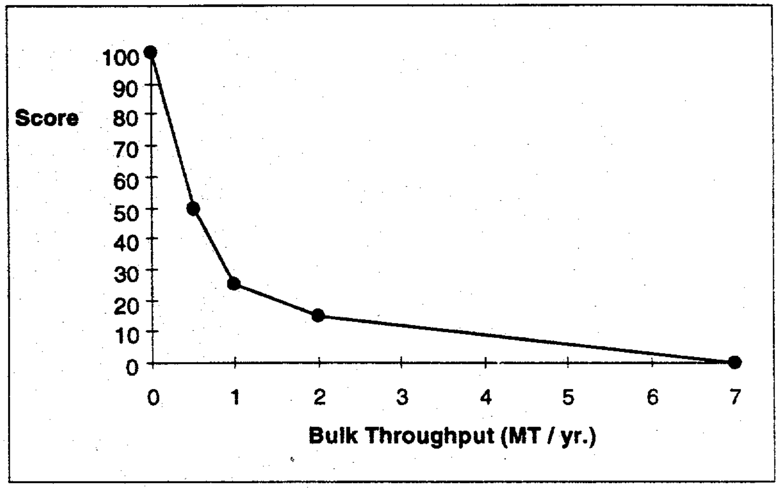
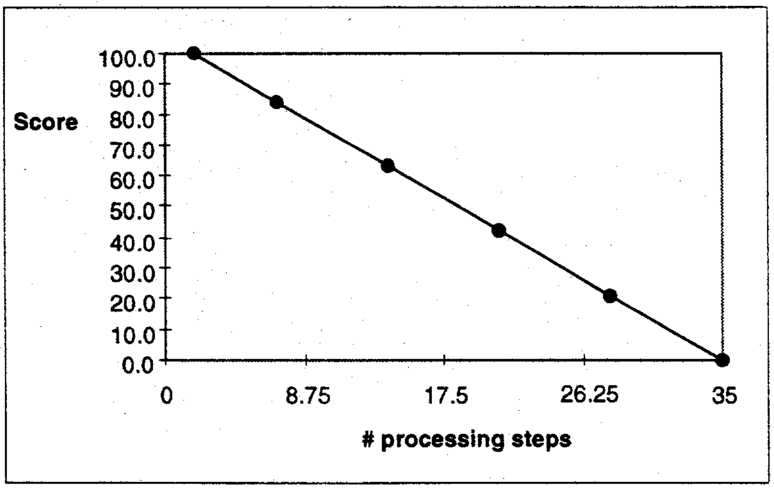


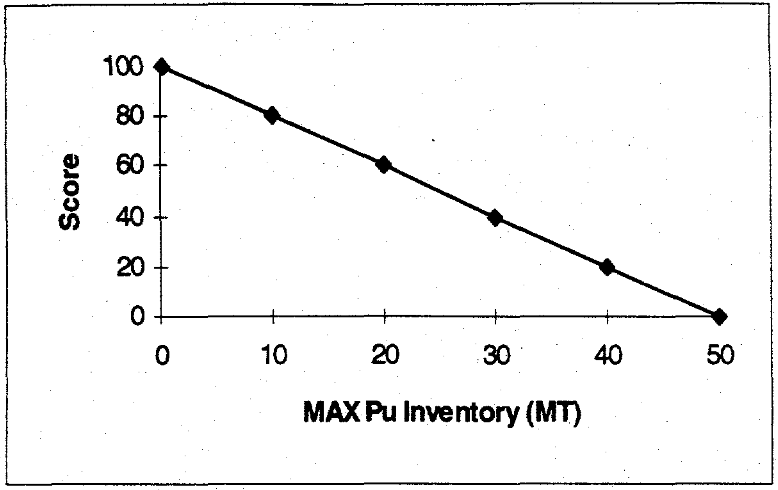
Figure 6 - Value Function for Number of Processing Steps



Maximum Plutonium Inventory

Maximum Plutonium Inventory was selected as a measure for two reasons. First, the S&S team felt that the more plutonium on hand, the more attractive the facility is as a target for theft. Second, the measure also relates to the complexity of the processes in a facility. Maximum Plutonium Inventory appears as a measure for both Theft and Diversion, and in both cases ranges from 0 to 50 MT. Figure 7 depicts the value function for scoring Maximum Plutonium Inventory.

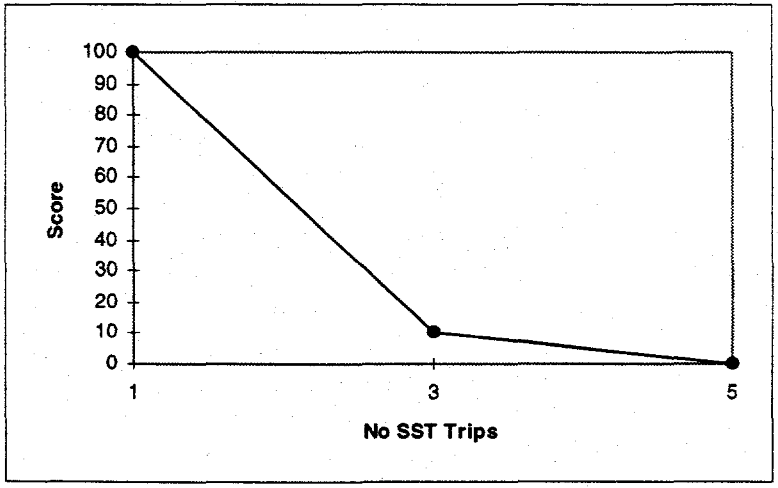
Figure 7 - Value Function for Maximum Plutonium Inventory



Number of SST Trips

Two measures were designed to measure the degree to which an alternative was susceptible to theft during inter-site transportation. The first, number of safe and secure transports (SSTs), was selected because the S&S team felt that the risk from theft was greatest when SST cargoes were loaded and unloaded, so the number of these events was important. The S&S team estimated that an alternative would have between 1 and 5 safe and secure transports.

Figure 8 - Value Function for Number of SST Trips

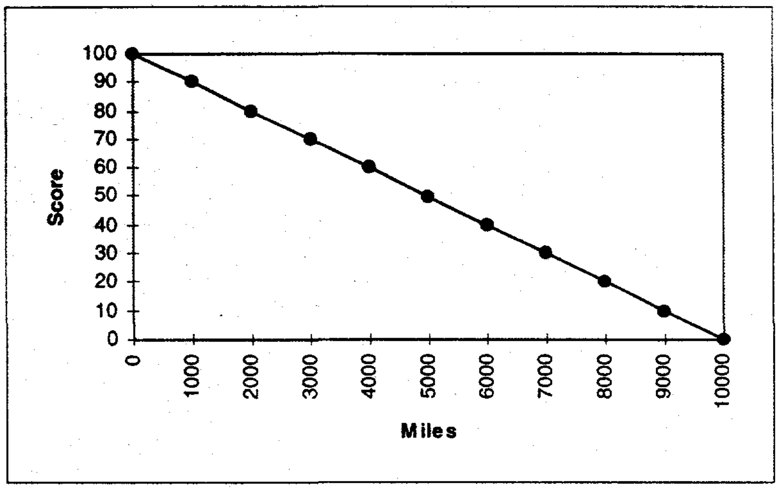


SST Transport Miles

The total number of SST miles was chosen as a second measure to reflect the notion that the longer plutonium is in transport, the higher the risk of theft. The S&S team estimated between 0 and 10,000 SST Transport Miles per disposition alternative.

Both SST measures are defined for a unit quantity of plutonium. These two measures only apply to Theft, and their value functions are presented in Figures 8 and 9, respectively. Note that these measures reflect the number of times each kg. of plutonium is transported and how far it is moved.

Figure 9 - Value Function for Total Number of SST Miles



Theft - Safeguards and Security
Measurement Uncertainty

The S&S team felt that Measurement Uncertainty was important for two reasons. It relates to Theft by allowing the U.S. to detect a theft if one were to occur. Measurement Uncertainty is important with regard to Diversion because low Measurement Uncertainty makes it easier for outside inspectors to determine if diversion is taking place.

As shown in Figure 10, Measurement Uncertainty ranges from 0% to 100%. This value function reflects a judgment that it is extremely important to reduce Measurement Uncertainty to less than 5%.

Type of Nuclear Accounting System

Figure 11 depicts the value function scale for the Type of Nuclear Accounting system (NAS) utilized at a facility. This measure is included in both Theft and Diversion because item accounting is easier to implement and may deter a theft or diversion attempt due to the speed with which the attempt would be recognized. The scale is defined over the percentage of time that item accounting can be used for a kg. of plutonium at the facility, ranging from 0 to 100% item accounting. A facility with 50% item accounting also utilizes bulk accounting 50% of the time.

Figure 10 - Value Function for Measurement Uncertainty

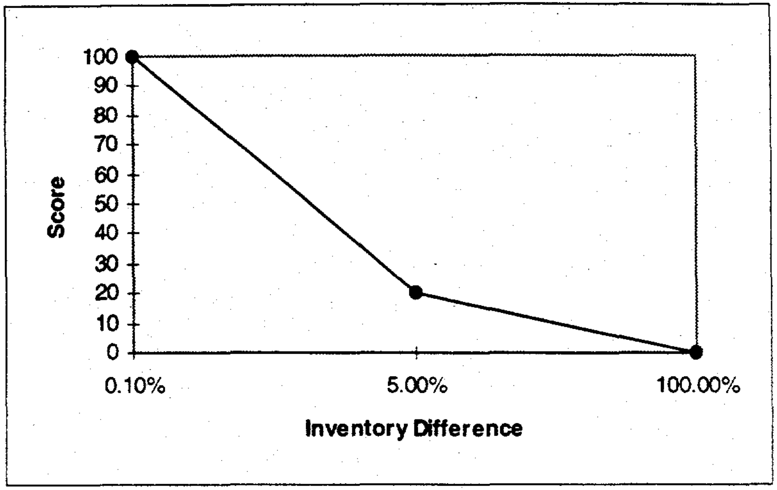
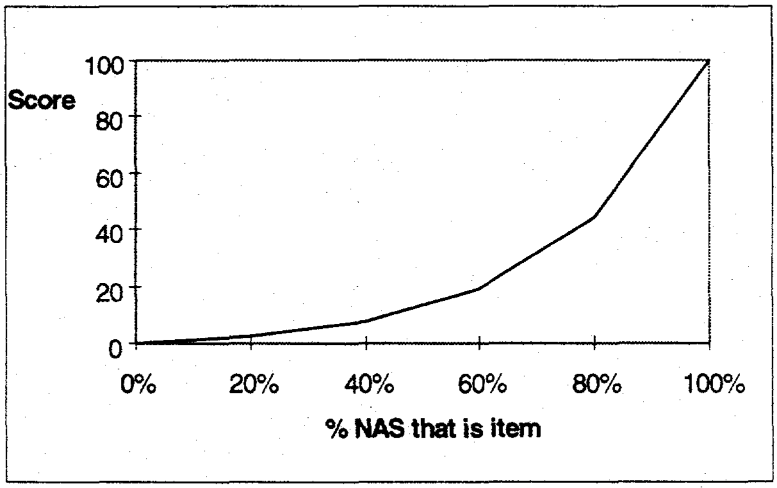


Figure 11 - Value Function for Type of Nuclear Accounting System



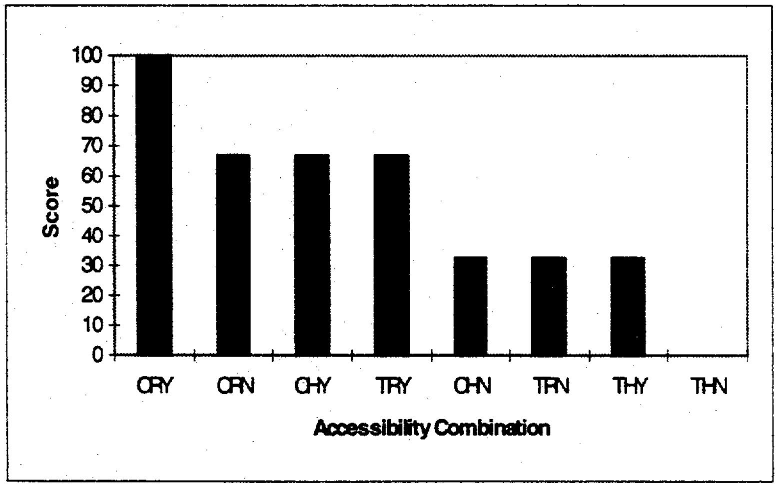
Accessibility of Plutonium

Accessibility of Plutonium is a measure used for both sub-objectives, Theft and Diversion. The measure is really a combination of three factors: the accessibility of the plutonium in process, the accessibility of the "container", and whether special handling equipment is required to move the plutonium. Table 5 is a representation of the eight possible combinations of these three "sub-measures". The actual measure used for a facility was a three letter acronym describing the facility. For example, CRY, the best case for Accessibility of Plutonium, represents a facility where the plutonium is in a tamper indicating container (C), the plutonium requires robotics to handle (R), and special handling equipment is required to move the plutonium/container (Y). The value function scores for all eight combinations are presented in Figure 12.

Table 5 - Combinations for Accessibility of Plutonium "Sub-measures"

Accessibility of Pu touchable Pu (T) tamper-indicating container (C)		*Accessibility of Container* hands on container (H) remote / robotics (R)		*Special Equipment to Move Pu* yes (Y) no (N)	
Measure	Score	Measure	Score	Measure	Score
C	1	R	1	Y	1
C	1	R	1	N	0
C	1	H	0	Y	1
C	1	H	0	N	0
T	0	R	1	Y	1
T	0	R	1	N	0
T	0	H	0	Y	1
T	0	H	0	N	0

Figure 12 - Value Function for Accessibility of Plutonium



U.S. Classification

U.S. Classification of the plutonium and/or the form of the plutonium being processed at a facility is used as a measure for the sub-objective Theft. The S&S team felt that if the material were classified, it would be more likely to be a target for theft, and classified information, as well as material, would be at risk. This measure is also important for the sub-objective Diversion, because it may preclude the application of International Atomic Energy Agency (IAEA) safeguards on certain materials.

The scale for this alternative is simple: a facility with classified material scores a zero, while a facility with unclassified material scores a 100. The same measure is used for

International Classification of the plutonium. The idea is that classified material is less likely to be eligible for inspection by outside parties.

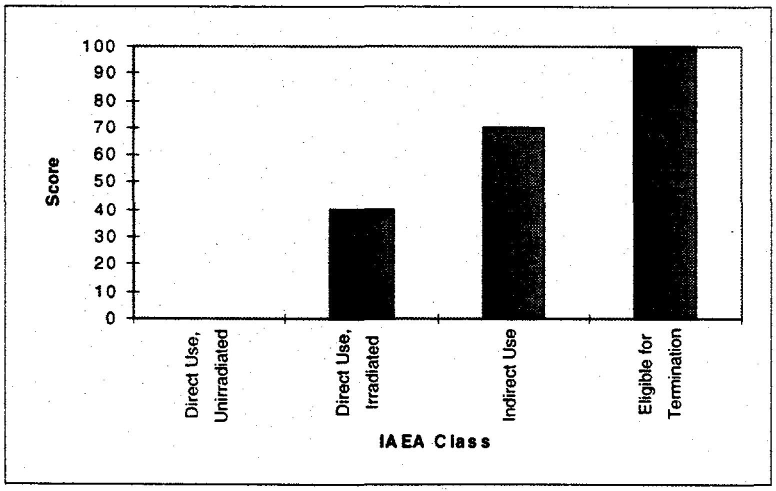
4.2.2 Value Functions for Diversion

Many of the measures and scales used to represent the sub-objective Diversion were also used for Theft. We will now describe the measure and value function that is unique to the Diversion sub-objective.

Diversion - Material Characteristics
IAEA Attractiveness

IAEA Attractiveness is similar in spirit to DOE Attractiveness except there is an international perspective. If a facility scores well on this measure, the International Atomic Energy Agency (IAEA) will be less concerned about the threat of diversion by the host nation because the material in process is difficult to reuse in a weapons program. In fact, some processes may be eligible for termination of IAEA safeguards. The range for this measure (see Figure 13) is direct-use, unirradiated material to material eligible for termination of IAEA safeguards.

Figure 13 -Value Function for IAEA Attractiveness



All other measures in Diversion are similar in definition and have the same value functions as the measures of the same name discussed under Theft.

4.2.3 Value Functions for Irreversibility

The measures and value functions for Irreversibility were also developed by the S&S team. The two measures relating to irreversibility issues are Material Form and the Material Location of the final disposition environment. Material Form is defined per DOE order 5633.3B ranging from E to B (see Table 4). Material Location is a three level scale; from best to worst, disposition in a borehole, disposition in a repository, plutonium in process or no disposition. Figures 14 and 15 represent the value functions for these two measures.

Figure 14 - Scale for Final Material Form

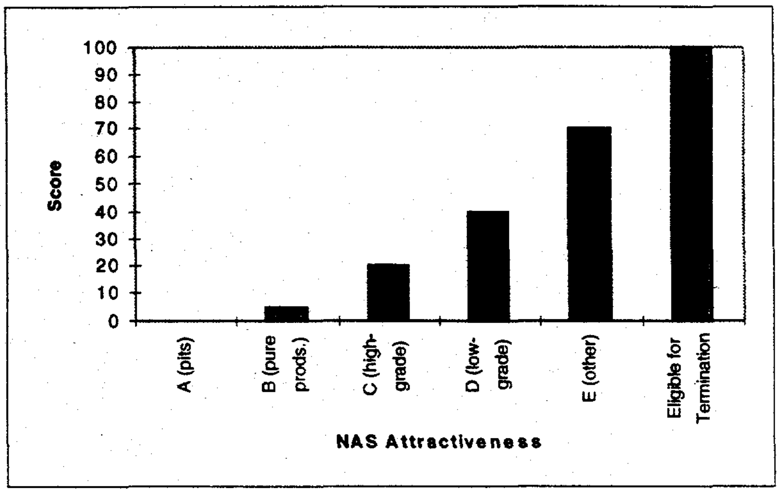
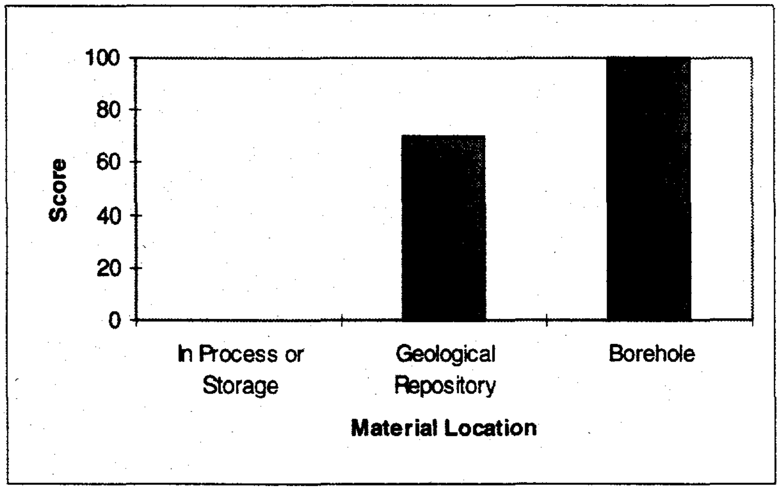


Figure 15 - Scale for Final Material Location



4.2.4 Value Functions for International Cooperation

This objective considers cooperation with Russia and with other countries separately. These measures and scores were developed by State Department, White House Office of Science and Technology, and OFMD personnel. Since the subject matter is sensitive, we will limit our discussion to a presentation of the final results.

Russian Cooperation

The development of a measure for the sub-objective maximize cooperation with Russia required a constructed scale. The resulting value function scores are based on expert opinion and were assigned directly to the alternatives. For example, the reactor alternative Existing Light Water Reactor was assigned a score of 50. In general, the reactor alternatives received somewhat higher scores than the immobilization and borehole alternatives because the experts judged that the Russians were more likely to adopt similar disposition alternatives, and therefore more likely to cooperate with their U.S. counterparts.

Do not encourage the Civil Use of Plutonium
In September 1993, the Clinton Administration issued the following statement regarding the United States policy towards the Civil Use of Plutonium[2]:

> The United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes.

The immobilization and borehole disposition alternatives are clearly consistent with, and in fact promote this policy. Although the reactor alternatives would involve development of a MOX fuel fabrication infrastructure, the following facts are also relevant for this assessment: 1) the disposition program will use plutonium that is derived from weapons production, as opposed to plutonium produced in civil reactors; 2) the program does not involve separation of additional plutonium from spent fuel; 3) the MOX fuel fabrication and storage facilities are dedicated facilities that are to be used only for the plutonium disposition mission; 4) reactor alternatives may in fact discourage the use of plutonium by demonstrating that it is more expensive to burn MOX fuel than LEU fuel; and 5) the cost of a MOX fuel fabrication plant is small compared to the cost of the additional facilities required for reprocessing spent fuel, so there will still be a large economic barrier to recycling spent fuel in the United States.

Although none of the alternatives are believed to constitute a violation of this policy, some alternatives support the policy to a greater or lesser extent than others. A rank ordering of the alternatives with the respect to the degree with which they support the policy are presented in Table 6. The value function scores for the individual alternatives were assigned by expert opinion and are shown in Table 7.

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[2] White House Fact Sheet. Nonproliferation and Export Control Policy, September 27, 1993.

Table 6 - Alternative Scores for Civil Use of Plutonium
1) BOREHOLE ALTERNATIVES - send the clearest policy signal that the surplus plutonium will not be used in the commercial nuclear power industry
2) IMMOBILIZATION ALTERNATIVES - also send a policy signal that plutonium will not be used in the commercial nuclear power industry
3) LWRS WITH GOVERNMENT OWNED MOX FABRICATION FACILITIES - government ownership provides assurance that the MOX fuel fabrication facilities will be shut down when the plutonium disposition mission is complete
4) CANDU REACTORS WITH U.S. GOVERNMENT OWNED MOX FABRICATION FACILITIES - use of heavy water reactor technology is less preferred than LWR technologies due to nonproliferation concerns (e.g. on-line refueling, man-portable fuel assemblies, closer to weapons grade plutonium isotopics)

4.2.5 Value Functions for Timeliness

Time to Start

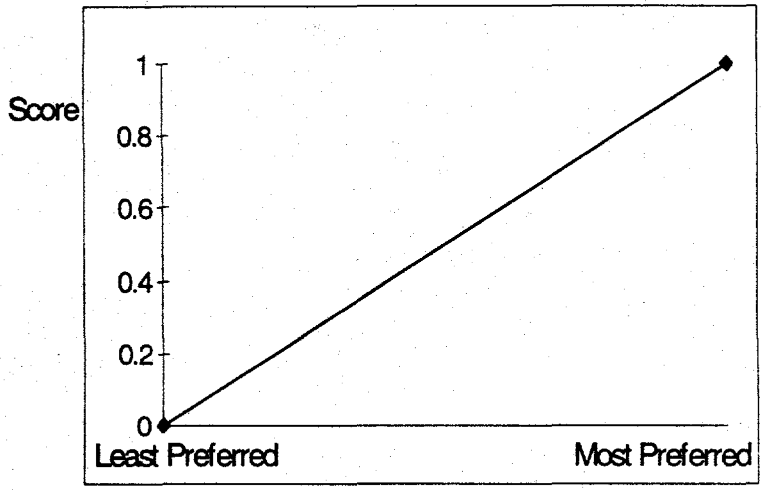
The Time to Start of disposition for an alternative corresponds to the time between the ROD and the point at which plutonium is made as inaccessible as spent fuel. For the alternatives under consideration, these dates are: 1) date of reactor start up with the first MOX fuel assemblies, or 2) date first immobilized waste form with radiation barrier is produced, or 3) date first canister or ceramic material containing plutonium is placed in a borehole. Note that Time to Start refers to the time from the ROD that an infrastructure that can support a continuous steady-state campaign to complete the disposition mission is available. The date for test or demonstration activities to dispose of a few kgs., or even a few hundred kgs., would not be considered the start year for disposition. Time to Start ranges from the most preferred 7 to 14 years.

The value function associated with the Time to Start measure is linear between the least preferred and most preferred outcomes, 14 and 7 years respectively. An example of such a linear value function is provided in Figure 16.

Time to Complete

The Time to Complete refers to the duration of the disposition activities from the start year to the time when the disposition of the last quantity of plutonium has been completed according to the same standard defined in the Time to Start measure (i.e., the last kg. of plutonium achieves the spent fuel standard). The estimated Time to Complete disposition ranges from 9 to 18 years, with earlier completion preferred. The corresponding value function was determined to be linear over this range, as illustrated in Figure 16.

Figure 16 - Example of a Linear Value Function



4.3 Value Functions for Operational Effectiveness Objectives

Investment Cost

Investment Cost refers to the undiscounted, constant dollar cost of designing, building, and licensing facilities. Operation, maintenance, and decommissioning costs are not included in this measure. The Investment Cost range from $580 to $6880 million and the value function was determined to be linear.

Life-cycle Cost

Life-cycle Cost is the value of all discounted cash flows for the alternative. These costs include capital, operations, maintenance, and decommissioning expenditures. These costs may be offset by discounted cash flows of incremental revenue streams from the sale of electricity generated by an alternative. Life-cycle Costs range from $1050 to $3660 million, and the corresponding value function was determined to be linear (e.g., see Figure 16).

4.4 Value Functions for Environment, Safety, and Health (ES&H) Objectives

The ES&H data utilized in the evaluation of the disposition alternatives were based on the analysis carried out for the PEIS. In a some cases, it was necessary to refine or manipulate these estimates. These exceptions will be noted. All of the corresponding value functions are linear over the ranges that are defined.

4.4.1 Value Functions for Human Health and Safety Objectives

Public Radiation Fatalities

This measure refers to the expected value of the number of additional human fatalities in the general population that will be caused by radiation exposure that can be attributed to implementation of the alternative over its operating lifetime. The radiation exposure is assumed to occur under normal operating conditions, as opposed to accident conditions. Note that for this and the other human health and safety measures, the term "expected value" is used in the statistical sense, and refers to probability times consequence. The range for this measure is -1 to 1, where negative numbers represent lives that are saved. These saved lives would be realized if an existing reactor alternative were utilized because the fabrication and burning of MOX fuel creates less of a risk to the public than the current usage of uranium [DOE-PEIS 96 pgs. 4-977 – 4-980].

Public Chemical Fatalities

This measure refers to the expected value of the number of additional human fatalities in the general population caused by chemical exposure that can be attributed to implementation of the alternative over its operating lifetime. The chemical exposure is assumed to occur under normal operating conditions, as opposed to accident conditions. Public chemical fatalities are between 0 and 1 for all alternatives considered here.

Worker Radiation Fatalities

This measure refers to the expected value of the number of additional human fatalities in the worker population caused by radiation exposure that can be attributed to implementation of the alternative over its operating lifetime. The radiation exposure is assumed to occur under normal operating conditions, as opposed to accident conditions. The range for this measure is -13 to 9, where negative numbers represent lives that are saved.

These saved lives would be realized if an existing reactor alternative were utilized because the fabrication and burning of MOX fuel creates less of a risk to the workers than the mining, milling, processing, enrichment, and fabrication of uranium fuel. The uranium that would be displaced by the MOX fuel must be mined, transported, and processed. This sequence of actions is estimated to be inherently more risky for workers that the production of MOX fuel from weapons-usable plutonium [DOE-PEIS 96 pgs. 4-977 – 4-980].

Worker Chemical Fatalities

This measure refers to the expected value of the number of additional human fatalities in the worker population caused by chemical exposure that can be attributed to implementation of the alternative over its operating lifetime. The chemical exposure is assumed to occur under normal operating conditions, as opposed to accident conditions. Worker Chemical Fatalities are between 0 and 1 for all alternatives considered here.

Transportation Fatalities

Implementation of an alternative will require shipment of plutonium to various storage and disposition facilities. There is a risk of accidents during transport. The measure refers to the expected value of the number of fatalities caused by accidents during transportation (e.g., fatalities attributed to truck accidents on highways). Transportation fatalities are between 0 and 3 for all alternatives.

Accident Risk

This measure refers to the expected value of the number of additional human fatalities in the worker and general populations that will be caused by a design basis accident for the alternative. This measure is between 0 and 1 for all alternatives.

4.4.2 Natural Environment Objective

Impact on Species

Facilities may be built at sites that contain habitats of endangered species. There is a possibility that the species may be adversely affected by construction and operation of the facilities. This measure refers to the number of endangered species that are known to exist at the site where facilities will be built, somewhere between 0 and 8.

Secondary Waste Generation

This measure refers to the volume, in cubic yards, of additional low level radioactive waste generated by the alternative that can be attributed to the plutonium disposition mission. Note that if a currently operating reactor were used for burning MOX fuel, little incremental waste would be generated by the switch from uranium to MOX fuel. The alternatives considered would add between 0 and 4,000 equivalent cubic yards to the nation's low level waste facilities.

4.4.3 Socio-economic objective

The measures for socio-economic benefits/detriments are related to the original Screening Phase objective Public and institutional acceptance. These two measures capture some of the public concerns as they relate to the local economy.

Boom/Bust

A rapid economic expansion to accommodate construction of facilities followed by a sharp reduction in economic activity may have an adverse impact on the local community. The local community would have to build additional housing, schools, and infrastructure to accommodate the expansion, and might not have the tax base to pay for the additional infrastructure after the economic contraction occurs. The Boom/Bust measure attempts to capture this impact by using the ratio of the change in jobs over the total number of jobs in the area (i.e., (peak jobs-long-term jobs)/job base). The range is 0% to 5%, and higher values of this statistic are less desirable than lower values.

New Long-term Jobs

In contrast to the short term economic impulse described above, New Long-term Jobs are considered desirable. This measure refers to the number of long-term jobs (10 years or greater) created for the community by the alternative. The estimated number of sustainable jobs associated with an alternative ranges from a most preferred 3,000 to 0.

4.5 Aggregation of Measures for Theft and Diversion

Once the measures outlined in Table 3 and the value functions described in the previous sections were defined for Theft and Diversion, the analysis was ready to proceed. However, the majority of measures and scales are defined for a processing *facility* rather than an end-to-end disposition alternative. Most of the thirteen alternatives considered have four such facilities, so the remaining question was: How should a single score, or distribution of scores, for each alternative for each measure be generated?

Three approaches were used for this evaluation. The first was based on the notion that a chain is only as strong as its weakest link. This "weak link by facility" approach applied all the weights and scales to determine which of the facilities required by an alternative provided the largest risk of theft. Then the measure levels for that facility (for all theft measures) were used for the alternative being evaluated. The same process was repeated for Diversion.

The second approach is referred to as the average utility approach. Each facility that makes up an alternative was scored for each measure. Then the measure scores were combined using a weighted average to give a facility measure. Next, the scores for the facilities required by an alternative were aggregated using a weighted average. The "weight" used for aggregation across the facilities was a function of the number of processing steps at the facility. The S&S team felt that the number of processing steps was an important measure of the need of a facility for safeguards against theft and for international assurances that diversion was not taking place. Therefore, the more processing steps at a facility, the higher that facility's weight should be when aggregating across facilities. The amount of time that plutonium spent at each facility was also considered to be important, but this information was not available for development of weighting functions.

After reviewing the initial modeling efforts, the S&S team requested a third model. Their idea was to build an absolute worst case based on the worst score for each measure across facilities. While this model represents no real facility or process, it does provide a worst case analysis.

4.6 Aggregation of ES&H measures across facilities and sites

As noted above, each alternative consists of a number of different facilities. The reactor alternatives include a pit disassembly/conversion facility, a MOX fuel fabrication facility, and a reactor facility. The immobilization alternatives include a pit disassembly/conversion facility and an immobilization facility. The deep borehole alternatives include a pit disassembly/conversion facility, an immobilization facility for the immobilized borehole alternative, and a borehole site with emplacement facilities.

Each of the facilities in an alternative would have different ES&H impacts at different sites. To properly evaluate an alternative, a single value is required for each measure. Consequently, siting assumptions for the facilities had to be made, and ES&H impacts for an alternative had to be aggregated for all of the facilities.

5. Alternatives by Objectives Matrix and Scores

The alternatives by objectives (and measures) matrix described in Section 3 is shown in Table 7, along with the corresponding scores for the performance of each alternative on each of the measures. These scores were determined from the value functions described above. For example, the Existing LWR, Existing Facilities alternative was assigned a category of IB on the measure DOE Attractiveness, which receives a corresponding score of 0.00 from the DOE Attractiveness value function scale shown in Figure 4.

The measure outcomes for the Theft and Diversion sub-objectives shown in Table 7 were computed based on the "weak link by facility" approach described in Section 4.5. Corresponding measure outcomes for the Theft and Diversion sub-objectives based on the average utility approach and on the worst case approach are shown in Appendix C. All other outcomes for the alternatives and the corresponding scores would be identical to those shown in Table 7 for the two additional cases shown in Appendix C.

The data in Table 7 will be used as the "base case" for the evaluation of the alternatives for the disposition of plutonium. An extensive sensitivity analysis will explore whether different assumptions regarding, for example, the calculation of the measure outcomes for the Theft and Diversion objectives, would result in significantly different conclusions regarding the relative desirability of the alternatives.

Before proceeding with a formal analysis of the data in Table 7, it may be useful to inspect the un-aggragated data in order to develop some insights regarding the relative strengths and weaknesses of the alternatives. This review will be organized according to the hierarchy of objectives and measures shown in Figure 2.

5.1 Non-proliferation Data

The non-proliferation objective includes several important sub-objectives. The alternatives differ significantly in terms of their performance on these sub-objectives.

5.1.1 Theft and Diversion Data

An inspection of Table 7 indicates that the alternatives, in general, do not differ a great deal on the sub-objectives of Theft and Diversion. As discussed above, the results shown in Table 7 for these measures are based on the concept of the "weak link" facility; that is, the outcomes and scores are determined from the facility that provided the largest threat of theft and/or diversion. All of the alternatives require a "pit disassembly" facility as the first step in processing the weapons-usable plutonium, and this facility was identified as a common "weak link", which explains the fact that all of the alternatives have the same outcomes and value function scores on some of the Theft and Diversion measures in Table 7.

However, notable differences do exist among the alternatives for some of these measures. For example, the number of processing steps required by the reactor alternatives are larger than the numbers for the immobilization and borehole options, and the latter receive higher value function scores on these measures as a consequence. Also, the Borehole (Direct) alternative has more Measurement Uncertainty than the other

Table 7 - Alternatives by Objectives Matrix with Scores

	Non-proliferation						
	Theft						
	Material Characteristics		Environment				
	DOE Attractiveness	*Other FM Separated?*	*Bulk Throughput*	*No. Processing Steps*	*MAX Pu Inventory*	*No. of Trips*	*SST Trans Miles*
Exist LWR, Exist Fac	IB	Y	5	22	0.5	4	5300
	0.0000	0.0000	0.0600	0.3824	0.9908	0.0500	0.4700
Part. Comp. LWR	IB	Y	5	22	0.5	4	4700
	0.0000	0.0000	0.0600	0.3824	0.9908	0.0500	0.5300
Exist LWR, Green Fac	IB	Y	5	22	0.5	3	3900
	0.0000	0.0000	0.0600	0.3824	0.9908	0.1000	0.6100
Evolutionary LWR	IB	Y	5	22	0.6	4	4450
	0.0000	0.0000	0.0600	0.3824	0.9888	0.0500	0.5550
CANDU	IB	Y	5	22	0.5	4	5350
	0.0000	0.0000	0.0600	0.3824	0.9908	0.0500	0.4650
Vitrif. Greenfield	IB	Y	5	13	5	2	5000
	0.0000	0.0000	0.0600	0.6471	0.9007	0.5500	0.5000
Vitrif. Can-in-Can	IB	Y	5	13	5	2	5000
	0.0000	0.0000	0.0600	0.6471	0.9007	0.5500	0.5000
Vitrif. Adj. Melter	IB	Y	5	13	2	2	5000
	0.0000	0.0000	0.0600	0.6471	0.9608	0.5500	0.5000
Ceramic Greenfield	IB	Y	5	13	5	2	5000
	0.0000	0.0000	0.0600	0.6471	0.9007	0.5500	0.5000
Ceramic Can-in-Can	IB	Y	5	15	2	2	5000
	0.0000	0.0000	0.0600	0.5882	0.9608	0.5500	0.5000
Electrometallurgical	IB	Y	4	15	2	2	1700
	0.0000	0.0000	0.0900	0.5882	0.9608	0.5500	0.8300
Borehole (Direct)	IB	Y	5	6	2	2	3500
	0.0000	0.0000	0.0600	0.8529	0.9608	0.5500	0.6500
Borehole (Immob)	IB	Y	5	11	2	2	3500
	0.0000	0.0000	0.0600	0.7059	0.9608	0.5500	0.6500

Table 7 - Alternatives by Objectives Matrix with Scores Continued

	Non-proliferation							
	Theft				Diversion			
	Safeguards & Security				Material Char*	Environment*		
	Measure Uncertainty	*Type of NAS*	*Access-ibility*	*U.S. Classif-ication*	*IAEA Attract-iveness*	*Bulk Through-put**	*No. Process-ing Step**	*MAX Inventory**
Exist LWR, Exist Fac	0.80%	30%	THN	Y	DUU	5	22	0.5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.9908
Part. Comp. LWR	0.80%	30%	THN	Y	DUU	5	22	0.5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.9908
Exist LWR, Green Fac	0.80%	30%	THN	Y	DUU	5	22	0.5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.9908
Evolutionary LWR	0.80%	30%	THN	Y	DUU	5	22	0.6
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.9888
CANDU	0.80%	30%	THN	Y	DUU	5	22	0.5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.9908
Vitrif. Greenfield	0.80%	30%	THN	Y	DUU	5	13	5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.9007
Vitrif. Can-in-Can	0.80%	30%	THN	Y	DUU	5	13	5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.9007
Vitrif. Adj. Melter	0.80%	30%	THN	Y	DUU	5	13	5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.9007
Ceramic Greenfield	0.80%	30%	THN	Y	DUU	5	13	5
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.9007
Ceramic Can-in-Can	0.80%	30%	THN	Y	DUU	5	15	0.04
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.5882	1.0000
Electrometallurgical	0.85%	30%	THN	Y	DUU	4	15	25
	0.8776	0.0433	0.0000	0.0000	0.0000	0.0900	0.5882	0.5004
Borehole (Direct)	1.60%	30%	THN	Y	DUU	5	6	2
	0.7551	0.0433	0.0000	0.0000	0.0000	0.0600	0.8529	0.9608
Borehole (Immob)	0.80%	30%	THN	Y	DUU	5	11	2
	0.8857	0.0433	0.0000	0.0000	0.0000	0.0600	0.7059	0.9608

Table 7 - Alternatives by Objectives Matrix with Scores Continued

	Non-proliferation							
	Diversion				Irreversibility		International Cooperation	
	Safeguards & Security*							
	*Measure Uncert.**	*Type of NAS**	*Accessibility**	*Int'l Class*	*Material Form*	*Material Location*	*Russian Cooperation*	*Civil Use of Pu*
Exist LWR, Exist Fac	2%	30%	THN	Y	E	R	50.2	70
	0.7714	0.0433	0.0000	0.0000	0.7000	0.7000	0.5020	0.7000
Part. Comp. LWR	2%	30%	THN	Y	E	R	50.2	70
	0.7714	0.0433	0.0000	0.0000	0.7000	0.7000	0.5020	0.7000
Exist LWR, Green Fac	2%	30%	THN	Y	E	R	50.2	70
	0.7714	0.0433	0.0000	0.0000	0.7000	0.7000	0.5020	0.7000
Evolutionary LWR	2%	30%	THN	Y	E	R	50.2	70
	0.7714	0.0433	0.0000	0.0000	0.7000	0.7000	0.5020	0.7000
CANDU	2%	30%	THN	Y	E	R	50.2	10
	0.7714	0.0433	0.0000	0.0000	0.7000	0.7000	0.5020	0.1000
Vitrif. Greenfield	20%	50%	THN	N	E	R	37.3	95
	0.1684	0.1192	0.0000	1.0000	0.7000	0.7000	0.3730	0.9500
Vitrif. Can-in-Can	20%	50%	THN	N	E	R	37.3	95
	0.1684	0.1192	0.0000	1.0000	0.7000	0.7000	0.3730	0.9500
Vitrif. Adj. Melter	20%	50%	THN	N	E	R	37.3	95
	0.1684	0.1192	0.0000	1.0000	0.7000	0.7000	0.3730	0.9500
Ceramic Greenfield	15%	50%	THN	N	E	R	37.3	95
	0.1789	0.1192	0.0000	1.0000	0.7000	0.7000	0.3730	0.9500
Ceramic Can-in-Can	20%	50%	THN	N	E	R	37.3	95
	0.1684	0.1192	0.0000	1.0000	0.7000	0.7000	0.3730	0.9500
Electrometallurgical	15%	50%	THN	N	E	R	37.3	95
	0.1789	0.1192	0.0000	1.0000	0.7000	0.7000	0.3730	0.9500
Borehole (Direct)	3%	30%	THN	Y	C	B	37.3	100
	0.5265	0.0433	0.0000	0.0000	0.2000	1.0000	0.3730	1.0000
Borehole (Immob)	10%	30%	THN	N	E	B	37.3	100
	0.1895	0.0433	0.0000	1.0000	0.7000	1.0000	0.3730	1.0000

Table 7 - Alternatives by Objectives Matrix with Scores Continued

	Non-proliferation		Operational Effectiveness	
	Timeliness		Cost	
	Time to Start	*Time to Complete*	*Investment Cost*	*Life-cycle Costs*
Exist LWR, Exist Fac	9	15	980	1220
	0.7333	0.3333	0.8600	0.6950
Part. Comp. LWR	13	15	3050	1210
	0.4667	0.3333	0.5643	0.6975
Exist LWR, Green Fac	13	18	1380	1240
	0.4667	0.1333	0.8029	0.6900
Evolutionary LWR	14	14	6880	3660
	0.4000	0.4000	0.0171	0.0850
CANDU	10	14	870	1660
	0.6667	0.4000	0.8757	0.5850
Vitrif. Greenfield	12	9	2030	2550
	0.5333	0.7333	0.7100	0.3625
Vitrif. Can-in-Can	7	11	580	1050
	0.8667	0.6000	0.9171	0.7375
Vitrif. Adj. Melter	12	9	1020	1830
	0.5333	0.7333	0.8543	0.5425
Ceramic Greenfield	12	9	1810	2330
	0.5333	0.7333	0.7414	0.4175
Ceramic Can-in-Can	7	11	580	1050
	0.8667	0.6000	0.9171	0.7375
Electrometallurgical	13	9	1190	1710
	0.4667	0.7333	0.8300	0.5725
Borehole (Direct)	10	10	1110	1500
	0.6667	0.6667	0.8414	0.6250
Borehole (Immob)	10	10	1350	2050
	0.6667	0.6667	0.8071	0.4875

Table 7 - Alternatives by Objectives Matrix with Scores Continued

	Environment, Safety and Health					
	Human Health and Safety					
	Pub. Rad. Deaths	*Pub. Chem. Deaths*	*Wrkr. Rad. Deaths*	*Wrkr. Chem. Deaths*	*Transport Deaths*	*Accident Risk*
Exist LWR, Exist Fac	-3.50E-01	4.70E-09	-1.30E+01	7.40E-06	1.33E+00	2.80E-01
	0.6750	1.0000	1.0000	1.0000	0.5577	0.7197
Part. Comp. LWR	3.90E-01	4.70E-09	8.90E+00	7.40E-06	1.33E+00	2.80E-01
	0.3050	1.0000	0.0045	1.0000	0.5577	0.7197
Exist LWR, Green Fac	-3.50E-01	4.70E-09	-1.30E+01	7.40E-06	1.33E+00	2.80E-01
	0.6750	1.0000	1.0000	1.0000	0.5577	0.7197
Evolutionary LWR	3.90E-01	4.70E-09	8.90E+00	7.40E-06	1.33E+00	3.42E-04
	0.3050	1.0000	0.0045	1.0000	0.5577	0.9997
CANDU	4.12E-04	4.70E-09	1.48E+00	7.40E-06	6.77E-01	3.22E-04
	0.4998	1.0000	0.3418	1.0000	0.7743	0.9997
Vitrif. Greenfield	2.52E-06	4.70E-09	1.42E+00	7.40E-06	1.17E+00	1.98E-06
	0.5000	1.0000	0.3445	1.0000	0.6097	1.0000
Vitrif. Can-in-Can	2.52E-06	4.70E-09	1.42E+00	7.40E-06	1.17E+00	1.98E-06
	0.5000	1.0000	0.3445	1.0000	0.6097	1.0000
Vitrif. Adj. Melter	2.52E-06	4.70E-09	1.42E+00	7.40E-06	1.17E+00	1.98E-06
	0.5000	1.0000	0.3445	1.0000	0.6097	1.0000
Ceramic Greenfield	2.45E-06	4.70E-09	1.47E+00	7.40E-06	1.19E+00	1.91E-06
	0.5000	1.0000	0.3423	1.0000	0.6030	1.0000
Ceramic Can-in-Can	2.45E-06	4.70E-09	1.47E+00	7.40E-06	1.19E+00	1.91E-06
	0.5000	1.0000	0.3423	1.0000	0.6030	1.0000
Electrometallurgical	1.20E-02	4.70E-09	1.86E+00	7.40E-06	1.24E+00	2.28E-06
	0.4940	1.0000	0.3245	1.0000	0.5863	1.0000
Borehole (Direct)	2.46E-06	4.70E-09	1.97E+00	7.40E-06	1.36E+00	2.05E-06
	0.5000	1.0000	0.3195	1.0000	0.5475	1.0000
Borehole (Immob)	2.46E-06	4.70E-09	2.42E+00	7.40E-06	2.16E+00	1.92E-06
	0.5000	1.0000	0.2991	1.0000	0.2797	1.0000

Table 7 - Alternatives by Objectives Matrix with Scores Continued

	Environment, Safety and Health			
	Natural Environment		Socio-economic	
	Impact on Species	*Secondary Waste Gen*	*Boom/Bust*	*New Long-term Jobs*
Exist LWR, Exist Fac	1	2151	0.0%	1792
	0.8750	0.4623	1.0000	0.5973
Part. Comp. LWR	1	3425	0.6%	2622
	0.8750	0.1438	0.8800	0.8740
Exist LWR, Green Fac	1	2151	0.0%	1792
	0.8750	0.4623	1.0000	0.5973
Evolutionary LWR	1	3231	1.0%	2622
	0.8750	0.1923	0.7920	0.8740
CANDU	1	1998	0.0%	1792
	0.8750	0.5005	1.0000	0.5973
Vitrif. Greenfield	1	1859	0.0%	2300
	0.8750	0.5353	1.0000	0.7667
Vitrif. Can-in-Can	1	1859	0.0%	2300
	0.8750	0.5353	1.0000	0.7667
Vitrif. Adj. Melter	1	1859	0.0%	2300
	0.8750	0.5353	1.0000	0.7667
Ceramic Greenfield	1	1859	0.0%	2402
	0.8750	0.5353	1.0000	0.8007
Ceramic Can-in-Can	1	1859	0.0%	2402
	0.8750	0.5353	1.0000	0.8007
Electrometallurgical	1	1900	0.0%	1625
	0.8750	0.5250	1.0000	0.5417
Borehole (Direct)	1	1850	0.0%	1884
	0.8750	0.5375	1.0000	0.6280
Borehole (Immob)	1	1888	0.0%	1822
	0.8750	0.5280	1.0000	0.6073

alternatives under the Theft sub-objective. In general, the immobilization and borehole options indicate more Measurement Uncertainty under the Diversion sub-objective. This is explained by the fact that international verification of the disposal of the plutonium becomes more difficult once it is immobilized in glass, ceramics, or metal alloy castings, and protected by a radiation barrier. It should also be noted that, in general, Measurement

Uncertainty is larger for the Diversion sub-objective than for Theft within each alternative. This difference is due to the potential difficulty associated with infrequent inspection of a continuous process by international verification authorities.

Other differences do appear in Table 7 for individual alternatives on some of the other Theft and Diversion measures.

5.1.2 Irreversibility Data

There are two measures associated with the sub-objective Irreversibility, Material Form and Material Location. All of the alternatives except for the Borehole (Direct) have the same final material form category of E, which corresponds to a form less desirable to the host nation than low-grade radioactive waste products. The form of the material associated with the Borehole (Direct) alternative is category C, which corresponds to high-grade radioactive waste, and would be relatively more desirable as a target for reuse by the host nation. As a result, the corresponding value function score for the Borehole (Direct) alternative is lower (0.2) on the measure Material Form than the scores of the other alternatives (0.7).

The final disposition of the material will be located in a repository (the reactor and immobilization alternatives) or a borehole (the borehole alternatives). The borehole location is considered less accessible for purposes of reuse of the material by the host nation, and so the two borehole alternatives receive higher value function scores on this measure.

5.1.3 International Cooperation Data

The alternatives were assigned scores directly on the measures Russian Cooperation and Civil Use of Plutonium. The reactor alternatives received somewhat higher scores on the measure Russian Cooperation than the immobilization or borehole alternatives. The reasoning of the experts was that the Russians were more likely to adopt a reactor option for the disposal of their weapons-usable plutonium, and so they would be more likely to cooperate with U.S. efforts if similar strategies were being followed. Section 9 extends the analysis of U.S. - Russian interactions.

In contrast, the immobilization and borehole alternatives received higher scores on the measure Civil Use of Plutonium. The rationale for these ratings was that these alternatives would be less likely to encourage, or be perceived to encourage, the civil use of plutonium in the U.S. and in other countries.

5.1.4 Timeliness Data

The measures associated with the sub-objective Timeliness are the Time to Start and the Time to Complete. All of the alternatives are forecasted to start between 7 and 14 years from the ROD. As the value function scores indicate, early start times are considered highly desirable for the project.

In general, the Time to Complete for the immobilization and borehole options are shorter than for the reactor options.

5.2 Operational Effectiveness Data

The lowest Base Investment Costs of $580 million are estimated for the Vitrification Can-in-Canister and the Ceramic Can-in-Canister alternatives. The highest Investment Cost estimates are associated with the new and partially completed reactor alternatives. The Evolutionary LWR alternative would have an initial Investment Cost estimated to be $6,880 million, and the Investment Cost for the completion of a Partially Completed LWR is estimated to be $3,050 million. The range of Investment Costs for the remaining alternatives is from $870 million to $2,030 million.

The Base Life-cycle Costs estimates actually vary less than the initial Investment Costs. The lowest Life-cycle Costs are estimated to be $1,050 million for the Vitrification Can-in-Canister and the Ceramic Can-in-Canister options. The highest forecasted Life-cycle Cost of $3,660 million is estimated for the Evolutionary LWR alternative.

5.3 Environment, Safety and Health Data

The Environment, Safety and Health (ES&H) measures are associated with the sub-objectives Human Health and Safety, Natural Environment, and Socio-economic. The outcomes for the alternatives represent *incremental* changes in expected impacts in these categories as a result of the selection of each alternative.

5.3.1 Human Health and Safety Data

The Human Health and Safety outcomes shown in Table 7 represent estimated impacts for the operating lives of the alternatives. For example, the use of MOX fuel in a Partially Completed LWR is estimated to result in 0.039 (3.9E-01) additional expected deaths to the public in areas surrounding the facilities as a result of exposure to radiation over the operating life of the project, which is estimated to be 15 years as shown in Table 7. This expected increase in fatalities is extremely small, and would be virtually indistinguishable relative to other causes of death among the public.

The expected numbers of incremental deaths from radiation, chemical exposures, and transportation accidents are extremely small for both the public and workers from all sources except for one category: incremental expected worker deaths from exposure to radiation and other industrial hazards which range from -13 to 8.9 (-1.3E+01 to 8.9E+00). The use of MOX fuel in an existing LWR (using existing facilities or greenfield) is estimated to prevent 13 additional expected worker deaths due to the displacement of the need for additional uranium, which is mined and processed under circumstances that are relatively hazardous. For a detailed discussion of these estimates, see the PEIS [DOE-PEIS 96 pg. 4-977 – 4-980].

In contrast, the Partially Completed LWR and the Evolutionary LWR alternatives have an expected number of incremental Worker Radiation Fatalities of 8.9, primarily because these alternatives would introduce a new operating reactor into the system rather than changing the fuel source for existing reactors. Finally, the expected worker deaths from radiation associated with the immobilization and borehole options are primarily the result of the required pit disassembly facilities, which are common to all of the alternatives.

5.3.2 Natural Environment

The alternatives do not differ in terms of their potential impacts on endangered species. The Partially Completed and the Evolutionary LWR alternatives are estimated to produce more secondary waste than the other alternatives, but the range of estimated incremental waste generated only ranges from 1,792 to 3,425 equivalent cubic yards.

5.3.3 Socio-economic

The Boom/Bust ratios for the alternatives shown in Table 7 do not show a large variation (from 0 to 1%). Similarly, the estimated range of 1,625 to 2,622 New Long-term Jobs created is not great, with the larger numbers of estimated new jobs associated with the Partially Completed and Evolutionary LWR alternatives.

5.4 Summary

In summary, a review of Table 7 shows some key differences among the alternatives, but many similarities as well. These similarities should not be surprising. For example, two of the reactor alternatives are simply "variants" of a basic concept (e.g., the two existing LWR alternatives), and these variants would be expected to have similar or even identical outcomes on the majority of the measures. Likewise, some of the immobilization alternatives are "variants", as are the two borehole alternatives.

Key differences do occur on many of the measures, however. As noted above, the immobilization alternatives tend to have fewer processing steps than the reactor alternatives, which provides some advantage relative to the objective of minimizing the threat of theft. But the immobilization alternatives tend to have greater Measurement Uncertainty, which makes them more difficult to verify regarding the objective of ensuring against diversion of plutonium by the host country. The reactor alternatives are judged to have some advantage in increasing the chances of Russian cooperation, but may not be as appealing as the immobilization and borehole alternatives from the standpoint of U.S. policy regarding the Civil Use of Plutonium.

The Vitrification and Ceramic Can-in-Can alternatives offer the earliest forecasted start times, and the immobilization alternatives generally have shorter times to completion. Costs vary with no obvious patterns among families of alternatives. Likewise, the ES&H measures vary somewhat from alternative to alternative, but clear patterns are difficult to discern with one notable exception.

Careful inspection of Table 7 indicates that the Vitrification Adjunct Melter alternative "dominates" the Vitrification Greenfield alternative. These two alternatives differ on only three measures, Investment Cost, Life-cycle Cost, and Maximum Plutonium Inventory under the Theft sub-objective, and Vitrification Adjunct Melter is preferred on all three.

The evaluation of the alternatives cannot be completed without value judgments that make "tradeoffs" between the performances of alternatives on the different measures. These "tradeoffs" can be translated into numerical "weights" on the value function scores associated with the measures, and used to aggregated these scores as weighed averages to provide rankings of the alternatives on the objectives and sub-objectives, and to provide additional insights regarding the alternatives.

6. Tradeoffs and Weights

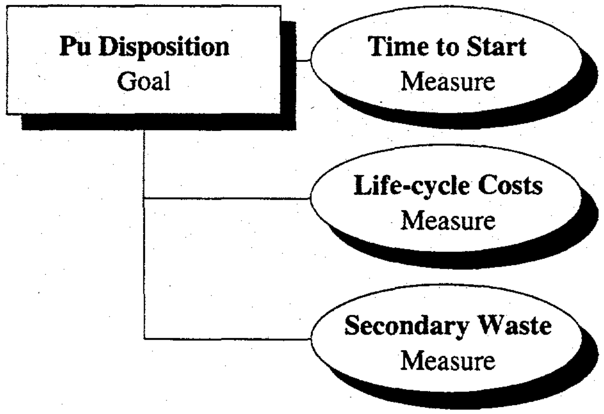
Each objective, sub-objective, and measure in the attribute hierarchy is given a weight. These weights reflect the value tradeoffs among objectives (or sub-objectives and measures within objectives), and are dependent on the ranges of the outcomes considered in the analysis.

The assessment of tradeoffs requires the decision maker to respond to choices between two hypothetical alternatives. For an analysis with an additive MAU model (1) and n measures, n-1 tradeoffs are required to uniquely determine the weights. Before the tradeoffs assessed from the project participants are presented, a simple hypothetical example will be provided to aide in understanding these results.

6.1 Example of tradeoff procedure

Assume that the selection of a disposition alternative is a function of only three measures: Time to start, Life-cycle Costs and incremental Secondary Waste Generated. The first step in completing the analysis would be to define the hierarchical structure of the model. With only three measures, this task is quite easy; see Figure 17.

Figure 17 - Example Model Structure



The accurate calculation of the weights for the measures requires the use of the value functions that have been assessed over the ranges of the measures. For this example, we will use the three value functions corresponding to these measures as defined in Section 4. Now the weights for the simple example shown in Figure 17 can be determined by two tradeoff questions. Each of these tradeoffs can be made between any two measures in the analysis, as algebra is all that is necessary to convert the tradeoffs to weights.

The tradeoff assessment procedure requires that ranges are specified for the performance levels on each measure. For the value functions defined in Section 4, Time to Start ranges from 5 to 20 years, Life-cycle Costs range from $0 to $4000 million (NPV), and between 0 and 4,000 cubic yards of low-level waste will be generated. Notice that these ranges are wider than the ranges of the actual performance levels for the alternatives on these measures, as shown in Table 7. It is not necessary for the ranges used to define the value functions to match the ranges of values for the performance levels of the actual alternatives. As long as the ranges used in the tradeoff procedure are wide enough to include the performance measure levels of the actual alternatives, the procedure will result in appropriate weights.

Next, the decision maker may be asked to consider a hypothetical alternative that achieves only the worst levels of performance on two measures, say an alternative with a Time to Start of 20 years and a secondary waste production of 4,000 cubic yards. Holding the levels of performance on the other measures constant (in this example, holding the level of performance constant on the measure Life-cycle Cost), the decision maker is asked to judge whether it would be more important to improve the level of performance on the measure Time to Start from 20 years to the best value of 5 (recall that the range for the measure Time to Start is 5 to 20 years, and a shorter Time to Start is more desirable), or to improve the measure Secondary Waste Generation from 4,000 to 0 cubic yards. As an example, a decision maker might decide it would be more important to reduce the Time to Start from 20 to 5 years than to decrease Secondary Waste Generation from 4,000 to 0 cubic yards.

This response indicates that the weight that will (should) be determined for the measure Time to Start will be larger than the weight for Secondary Waste Generation. In a similar manner, suppose the decision maker responds that it is more important to reduce the Time to Start from 20 to 5 years for a hypothetical alternative than to reduce Life-cycle Costs from $4000 million to $0, and that it would be more important to reduce the Life-cycle Cost from $4000 million to $0 than to decrease Secondary Waste Generation from 4,000 to 0 cubic yards. These responses imply that the weight for the measure Time to Start will be larger than the weight for Life-cycle Costs, and the weight for Life-cycle Costs will be larger than the weight for Secondary Waste Generation.

The decision maker is then presented with two hypothetical alternatives with identical levels of performance on all measures (in this case, on Secondary Waste Generation) except for the following two measures:

	Alternative I	Alternative II
Time to Start	5	20
Life-cycle Costs ($M)	$4,000	0

Notice that Alternative I has the best Time to Start and the worst Life-cycle Cost while Alternative II has the worst Time to Start and the best Life-cycle Cost. Based on the earlier response that it would be more important to improve performance on Time to Start from its worst to its best value than to improve Life-cycle Costs, the decision maker should prefer Alternative I to Alternative II.

If one alternative is preferred to the other, the decision analyst aides the decision maker in adjusting the measures until the alternatives are indifferent to each other. In this case, Alternative II would be improved by reducing the Time to start from its worst value of 20 years until a point of indifference is reached. For example suppose that the decision maker is indifferent between the following alternatives:

Measure Number	Measure	Alternative I	Alternative II
1	Time to Start	5	8
2	Life-cycle Costs ($M)	$4,000	0

This response provides the information necessary to determine the ratio of the weights for the measures Time to Start and Life-cycle Costs. Using an additive MAU function (1), this trade-off above implies the following equality (recall that all other measures are held constant at the same level so that they "cancel out" on both sides of the equation):

$$w_1 u_1(5) + w_2 u_2(4000) = w_1 u_1(8) + w_2 u_2(0)$$

The single attribute utility functions are scaled so that $u_i\left(x_i^*\right) = 1$, where x_i^* is the "best" result on measure i, and $u_i\left(x_{i*}\right) = 0$, where x_{i*} is the "worst" value for measure i. Therefore, $u_1(5) = 1$ for Time to start, and $u_2(4000) = 0$ and $u_2(0) = 1$ for Life-cycle Costs. Finally, since the value function for Time to Start is linear (Section 4.2.5),

$u_1(8) = \left[\dfrac{20-8}{20-5}\right] = 0.8$. Therefore, we have $w_1 = 0.8 w_1 + w_2$, or $w_1 = 5 w_2$.

The decision maker would then move on to the next tradeoff using a similar elicitation procedure. Suppose the decision maker is indifferent between the following hypothetical alternatives:

Measure Number	Measure	Alternative I	Alternative II
2	Life-cycle Costs ($M)	0.1	0
3	Secondary Waste Gen.	0	1

This tradeoff implies that the decision maker would be willing to pay $100,000 to dispose of one cubic yard of secondary waste. As before we can simplify the equality implied by this tradeoff to determine that

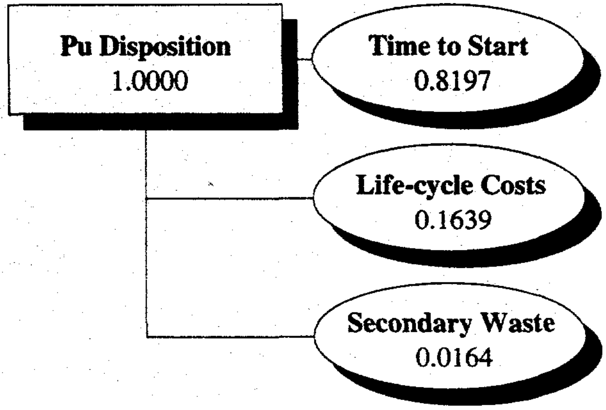
$$w_2 u_2(0.1) + w_3 u_3(0) = w_2 u_2(0) + w_3 u_3(1)$$

which gives $0.999975 w_2 + w_3 = w_2 + 0.99975 w_3$, or $w_2 = 10 w_3$.

The scaling convention for weights associated with MAU theory requires that the sum of the three weights is one. This requirement along with the ratios between two pairs of weights determined above allows the appropriate weights to be calculated by simple algebra, and the result is: $w_3 = 0.016393,\ w_2 = 0.16393,\ and\ w_1 = 0.81965$

Based on these example tradeoffs, Figure 18 presents the weights that would be used in the evaluation of alternatives based on the three measures used in this hypothetical example. For additional details and examples, see Keeney and Raiffa (1976) or von Winterfeldt and Edwards (1986).

Figure 18 - Weights Generated in Example



6.2 Tradeoffs

The actual model, displayed in Figures 2, 3a, 3b and 3c, is much more complicated than the preceding example. First, there are thirty-seven measures in the analysis. Second, it is unlikely that a single individual is qualified to make every tradeoff required; in other words, specialists must be consulted for certain areas. It might also be argued that some of the tradeoffs reflect expert opinion, while others are matters of policy. For these reasons, tradeoffs were made at various levels throughout the hierarchy.

All of the tradeoffs presented in the following sections are presented in the same format used in the simple example of Section 6.1, and represent judgments that Alternative I is *indifferent* to Alternative II. We will begin with the tradeoffs obtained from the Safeguards and Security (S&S) team.

6.2.1 Tradeoffs within Theft

The S&S team provided judgments regarding the measurement of Theft, Diversion and Irreversibility. These judgments were obtained in two different meetings that lasted two days each. First, the appropriate measures for these objectives and their associated value functions were determined, which required the identification of the ranges over which performance levels of the alternatives might vary on each of the measures. Next, the procedure outlined in the previous section was used to determine the correct model weights for the base case. When the tradeoffs were assessed, there were between five and ten participants in the meeting. The assessment procedure continued until group discussion led to a consensus opinion.

To provide focus and to ease assessment, Theft was broken down into three categories: Material characteristics, Environment, and Safeguards and Security as shown in Figure 3a. Tradeoffs were obtained within each of these three areas.

Theft – Material Characteristics

The DOE Attractiveness measure ranged from IV-E (a small amount of non-radioactive waste) to I-A (a large amount of weapons-usable material), while the measure Other Separated Fissile Materials in inventory was a simple "Yes" or "No". The S&S team agreed that it would be much more important to improve the attractiveness measure from its worst value (I-A) to its best value (IV-E) than to change the inventory measure from "Yes" to "No". After discussion, the team agreed that they would be indifferent between the two alternatives below, which implies a larger weight on the attractiveness measure than on the inventory measure.

Measure	*Alternative I*	*Alternative II*
DOE Attractiveness	III-B	IV-E
Other Separated Fissile Materials	No	Yes

Theft – Environment

Four tradeoffs were necessary to determine the weights within the Theft-Environment category of measures. The first two tradeoffs involved choices comparing changes in the measures of the Maximum Plutonium Inventory and the level of throughput of plutonium in bulk form with the Number of Processing Steps. The team determined that they would be willing to increase the Maximum Plutonium Inventory level from 0.1 to 40 MT in order to obtain a reduction in Number of Processing Steps from 5 to 1. That is, they would be indifferent between the two alternatives below (with all other measures equal).

Measure	*Alternative I*	*Alternative II*
No .Processing Steps	1	5
Max Pu Inventory	40 MT	0.1 MT

In a similar manner, the team reasoned that a reduction in the annual throughput of plutonium in bulk form from 1 metric ton to none would be equivalent in terms of impact on the threat of theft to a reduction in Number of Processing Steps from 20 to 1. Again, this tradeoff may be represented by the judgment of indifference between the two alternatives shown below.

Measure	*Alternative I*	*Alternative II*
Bulk Throughput	1 MT / yr.	0.0 MT / yr.
No .Processing Steps	1	20

The next two tradeoffs involved the safe and secure transports (SSTs) of the material. First, a judgment was made that a reduction in the number of SST inter-site trips from 3 to 1 would be roughly equivalent to a reduction in the number of Total SST Miles traveled from 10,000 to 100, as represented by the judgment of indifference between the two alternatives below. This judgment reflects the belief that the threat of theft is higher at the start and end of a trip rather than while the vehicles are in transit, so small reductions in the number of trips would be more beneficial in improving security than relatively large reductions in the number of miles traveled.

Measure	***Alternative I***	***Alternative II***
SST Trips	1	3
Total SST Miles	10,000	100

The final judgment within this category related the number of SST Trips to concerns about the processing environment within the facilities. A reduction in the throughput of plutonium in bulk form from 0.5 to 0 was judged to be equivalent to a reduction in the number of inter-site SST Trips from 5 to 1. Since the range of inter-site SST Trips used in the analysis was from 1 to 5, this tradeoff indicates that the weight on the measure Bulk Throughput will be larger than the weight on the measure of SST Trips. The corresponding indifference judgment is shown below.

Measure	***Alternative I***	***Alternative II***
Bulk Throughput	0.5 MT / yr.	0.0 MT / yr.
SST Trips	1	5

Theft -- Safeguards and Security

A similar approach was used to determine tradeoffs for the measures that were considered to be directly related to safeguards and security concerns. Measurement Bulk Throughput during processing is a major concern for safeguards and security control, since the elimination of this uncertainty makes it possible to detect any theft immediately. Therefore, the S&S team chose to make the required three tradeoffs for this category of measures using Measurement Uncertainty as a common factor in each.

The first tradeoff involved judgments regarding comparisons of changes in Measurement Uncertainty with changes in the Type of Nuclear Accounting System. The latter is measured as the percentage of time that item accounting can be used for a kg. of plutonium at a facility. It seems clear that a desire for item accounting is motivated by the same concern for a reduction in Measurement Uncertainty, since both measures relate to the ability to immediately detect a theft if one should occur. This suggests that these two measures may not be consistent with a preference structure that could be modeled appropriately with an additive MAU model ((1) in Section 4.1), and that a multiplicative preference model ((2) in Section 4.2) might be more appropriate. This observation was the subject of a sensitivity analysis, as discussed in Section 8.1.2.

The tradeoff judgment was that an increase in Measurement Uncertainty from 0.1% to 10% would be offset, in terms of its implications for protection against theft, by a change in the type of accounting system from 100% item to 100% bulk. This judgment is implied by an indifference judgment regarding the two alternatives shown below.

Measure	*Alternative I*	*Alternative II*
Measure Uncertainty	10%	0.1%
Type of NAS	ITEM	BULK

The tradeoff between Measurement Uncertainty and the U.S. Classification of the plutonium was based on the following argument. Although plutonium that is classified is more likely to be a target for theft, the S&S team felt that unclassified material was still an attractive target for potential thieves and that measurement error was always an important concern. Therefore, an increase in Measurement Uncertainty of a small amount, from 0.1% to 1%, would be roughly offset if the material were not classified, in terms of the overall vulnerability of the material to theft.

Measure	*Alternative I*	*Alternative II*
Measure Uncertainty	1%	0.1%
U.S. Classification	UNC	SRD

A tradeoff between Measurement Uncertainty and the Accessibility of Plutonium was considered next. Logically, it seems reasonable to accept some additional Measurement Uncertainty in exchange for ensuring that the plutonium is not accessible to potential thieves. According to the judgment summarized in the table below, an increase of Measurement Uncertainty from 0.1% to 5% could be tolerated if the plutonium were protected in a tamper-indicating container (C), only accessible using remote handling equipment or robotics (R), and required special equipment to move (Y).

Measure	*Alternative I*	*Alternative II*
Measure Uncertainty	5%	0.1%
Accessibility of Pu	CRY	THN

Aggregation within Theft

Once the weights had been determined within each Theft sub-objective using the tradeoff responses shown in the preceding sections, two additional tradeoffs were needed to determine the weights for the sub-objectives Material characteristics, Environment, and Safeguards & Security. To accomplish this, a representative measure was chosen from each sub-objective, and the following additional tradeoffs were obtained from the S&S team.

Theft Sub-objective	*Measure*	*Alternative I*	*Alternative II*
Material Characteristics	DOE Attractiveness	II-C	IV-E
Safeguards & Security	Measure Uncertainty	0.1%	100%

Theft Sub-objective	***Measure***	***Alternative I***	***Alternative II***
Safeguards & Security	Measure Uncertainty	0.1%	10%
Environment	Bulk Throughput	5 MT / yr.	0.0 MT / yr.

The first tradeoff shown above reflects the judgment that concern over Measurement Uncertainty would be eliminated if the form of the material could be changed from DOE Attractiveness level II-C (2-6 kg. of high-grade materials) to attractiveness level IV-E (non-radioactive materials). The second tradeoff is based on a rationale similar to that used in determining the tradeoff between Measurement Uncertainty and item accounting; that is, an increase in Measurement Uncertainty from 0.1% to 10% would be offset in terms of vulnerability to theft if the level of throughput of bulk plutonium could be reduced from 5 metric tons per year to 0.

6.2.2 Tradeoffs within Diversion

For similar reasons, the objective Diversion was decomposed into the same three measures as Theft, as shown in Figure 3a. Many of the measures and sub-objectives associated with Diversion have the same names as similar measures associated with Theft. To aide in distinguishing between the two interpretations, measures associated with Diversion that have the same names as measures associated with Theft end with an "*"; e.g., Material Characteristics is a sub-objective for Theft while Material Characteristics* is a sub-objective for Diversion.

Diversion -- Material Characteristics

There is a single measure, IAEA Attractiveness, for this sub-objective, so no tradeoffs are required within this category.

Diversion -- Environment

Two tradeoffs were required for the environment category of measures, which contains three measures. The measure of Bulk Throughput* is common in the tradeoffs. It is interesting to note that even though these three measures are also used for the evaluation of the alternatives in terms of the vulnerability to theft, the tradeoffs were different when they were considered in terms of the implications for the diversion of the plutonium by the host country.

The first tradeoff shown below implies a willingness to accept an increase from 0 to 0.5 metric tons of Bulk Throughput* in exchange for a reduction in the Number of Processing Steps*, compared to a willingness to accept an increase from 0 to 1.0 metric tons when the concern was theft rather than diversion. The obvious implication is that an increase in Bulk Throughput* creates a more difficult environment for IAEA or other third-party verification that no diversion of the materials has occurred, and this impact is larger with regard to concerns about diversion than about the potential for theft.

Measure	*Alternative I*	*Alternative II*
Bulk Throughput*	0.5 MT / yr.	0.0 MT / yr.
No .Processing Steps*	1	20

The second tradeoff in this category implies a judgment that a reduction in the throughput* of plutonium in bulk form from 1 metric ton per year to 0 would be equivalent in terms of implications for verification to a reduction in plutonium inventory from 40 to 0.1 metric tons.

Measure	*Alternative I*	*Alternative II*
Bulk Throughput*	0.0 MT / yr.	1 MT / yr.
Max Pu Inventory*	40 MT	0.1 MT

Diversion -- Safeguards and Security

The Safeguards and Security category of measures within the Diversion goal has three measures that are identical to those used for the Theft goal, as well as a fourth measure of material attractiveness used for international inspection in place of the DOE Attractiveness measure. Once again, Measurement Uncertainty* is used as the common basis for the tradeoffs.

A change in the Type of Nuclear Accounting System* from 100% item to 100% bulk was judged to have a similar impact on the process of verification to ensure that no plutonium was diverted as a change in the Measurement Uncertainty* from 0.1% to 5%. This same change in the Type of Nuclear Accounting System was paired with a change in Measurement Uncertainty from 0.1% to 10% when theft was the issue. This would imply that Measurement Uncertainty* would have a relatively larger weight compared to the Type of Nuclear Accounting System* within the diversion category than in the theft category.

Measure	*Alternative I*	*Alternative II*
Measure Uncertainty*	5%	0.1%
Type of NAS*	ITEM	BULK

The judgment was made that an increase in Measurement Uncertainty* from 0.1% to only 2% could be offset by a change in the Accessibility of Plutonium* of the material from category THN to CRY. When theft was the consideration, this same change in Accessibility of Plutonium* was compared to a change in Measurement Uncertainty from 0.1% to 5%, showing relatively more of a concern for Measurement Uncertainty* when the issue is diversion and the need to verify the integrity of the process.

Measure	*Alternative I*	*Alternative II*
Measure Uncertainty*	0.1%	2%
Accessibility of Pu*	THN	CRY

Finally, change from classified to unclassified for the measure International Classification* would be worth a very large increase in Measurement Uncertainty* (from 10% to 100%), since classified material is less likely to be available for inspection and verification by the IAEA or other third-party personnel.

Measure	*Alternative I*	*Alternative II*
Measure Uncertainty*	10%	100%
International Classification	SNSI	UNC

Aggregation within Diversion

In order to compare measures across the categories of Material Characteristics, Environment, and Safeguards and Security for Diversion, two additional tradeoffs were required, as was the case for Theft. The first tradeoff shown below between Measurement Uncertainty* and Bulk Throughput* is exactly the same as the judgment made for these measures for Theft. The second tradeoff compares IAEA measures of attractiveness with changes in Measurement Uncertainty*, and the judgment indicates that a change in the level of attractiveness from direct-use unirradiated material to direct-use irradiated material would be comparable to a change in Measurement Uncertainty* from 10% to 0.1%.

Diversion Sub-objective	*Measure*	*Alternative I*	*Alternative II*
Safeguards & Security*	Measure Uncertainty*	0.1%	10%
Environment*	Bulk Throughput*	5 MT / yr.	0.0 MT / yr.

Diversion Sub-objective	*Measure*	*Alternative I*	*Alternative II*
Material Characteristics*	IAEA Attractiveness	Direct Use, Unirradiated	Direct Use, Irradiated
Safeguards & Security*	Measure Uncertainty	0.1%	10%

6.2.3 Irreversibility

In the screening report, Irreversibility was a sub-objective of Diversion. After some discussions with OFMD personnel, Irreversibility was established as separate sub-objective under Non-proliferation. The rationale behind this change was that the measures of Diversion applied to the time period while the material was in process, while the main concern of Irreversibility was the final form and location of the material. The single tradeoff necessary for the Irreversibility sub-objective is provided below. This comparison implies that the value of changing the form of weapons-usable plutonium from "pits" taken from disassembled nuclear weapons to spent fuel would have a similar value, with regard to ensuring irreversibility of the disposition process, as transferring material from in process storage to a geological repository.

Measure	*Alternative I*	*Alternative II*
Material Form	Pits (A)	Spent Fuel (E)
Material Location	Geological Repository	In Process or Storage

6.2.4 International Cooperation

As previously mentioned, the value functions for the measures in International Cooperation were defined by State Department, White House Office of Science and Technology, and OFMD personnel. The tradeoff presented below was provided by OFMD personnel. One implication of this tradeoff is the judgment that ensuring Russian cooperation in disassembling their nuclear weapons is more important than concerns about the implications of the alternatives for the U.S. policy on nonproliferation, and will receive a larger weight within this category. Recall the discussion in Section 4.2.4 which emphasizes the judgment that none of the alternatives considered are in direct conflict with U.S. policy on nonproliferation.

Measure	*Alternative I*	*Alternative II*
Russian Cooperation	100	85
Civil Use of Pu	0	100

6.2.5 Timeliness

The tradeoff for the Timeliness objective was also provided by OFMD personnel. This tradeoff, shown below, clearly indicates a strong preference for alternatives that can start the disposition of the surplus plutonium as quickly as possible. More specifically, the tradeoff implies that OFMD would be willing to extend the time required for the completion of the disposition of all of the surplus plutonium by 15 years in order to start the process 3.5 years earlier.

Measure	*Alternative I*	*Alternative II*
Time to Start	13.5	10
Time to Complete	5	20

6.2.6 Aggregating within Non-proliferation

OFMD provided the following tradeoffs to allow aggregation across the five sub-objectives of Non-proliferation. Once these tradeoffs were specified, the weights within Non-proliferation were uniquely determined. As noted above, Time to Start was considered an important measure for the alternatives, and was selected by the OFMD personnel as a common measure to use in all of these tradeoffs.

Tradeoffs across categories are particularly difficult to make, because the responders must consider implications regarding different but important goals. This emphasizes the importance of a sensitivity analysis of the implications of these tradeoffs, which is provided in Section 8.1.

The first tradeoff shown below compared the implications of an increase in the Time to Start for an alternative with the implications of a change in the measure of DOE Attractiveness on the potential for theft. A relatively large change in the DOE Attractiveness measure was considered equivalent to only a change of one year in the Time to Start for an alternative, again highlighting the emphasis on an early start.

Non-proliferation Sub-objective	*Measure*	*Option I*	*Option II*
Timeliness	Time to Start	11	10
Theft	DOE Attractiveness	IVE	IB

The comparison of the implications of a change in Measurement Uncertainty* for ensuring that no diversion of materials occurs was compared with a change in the Time to Start. A similar judgment to the one shown above indicates a willingness to sacrifice a large change in Measurement Uncertainty* (with regard to its implications for diversion), in order to improve the start time of an alternative by 2 years.

Non-proliferation Sub-objective	*Measure*	*Option I*	*Option II*
Timeliness	Time to Start	12	10
Diversion	Measurement Uncertainty*	0.1%	100.0%

A comparison of the Time to Start with concern for irreversibility is interesting, and indicates a judgment that irreversibility of the process is considered relatively important. Note that a change in the Time to Start of 6 years was judged equivalent to a change in the Material Location from 100% of the material in a borehole to a mix of 55% in process and 45% in a geological repository.

Non-proliferation Sub-objective	*Measure*	*Option I*	*Option II*
Timeliness	Time to Start	16	10
Irreversibility	Material Location	Borehole	55% processing 45%in repository

The final tradeoff between categories within the non-proliferation measures also reveals a judgment that Russian Cooperation is extremely important to the success of the effort. In this tradeoff, only a small decline in the level of Russian Cooperation would be sacrificed in order to gain 6 years in the Time to Start of the disposition effort.

Non-proliferation Sub-objective	*Measure*	*Option I*	*Option II*
Timeliness	Time to Start	16	10
International Cooperation	Russian Cooperation	100	75

6.2.7 Tradeoffs within Operational Effectiveness

Operational Effectiveness is decomposed into only two measures that were compared directly by OFMD personnel in the following indifference tradeoff. This tradeoff implies that a \$1,000 million increase in the initial Investment Costs would be judged equivalent to an increase in total Life-cycle Costs of \$1,000 million, which would be spread over the operating life of the project. In other words a dollar spent on Investment Costs is considered to be equal to a dollar spent on Life-cycle Costs. However, note that some additional weight is given to Investment Cost by thus judgment, since they are also included in the calculation of Life-cycle Costs. This tradeoff provides the necessary information to determine the weights within Operational Effectiveness.

Measure	***Alternative I***	***Alternative II***
Investment Cost (\$M)	1000	0
Life-cycle Costs (\$M)	0	1000

6.2.8 Tradeoffs within Environment, Safety and Health

The majority of the tradeoffs presented above were made with respect to measures that were unique to the OFMD program. These tradeoffs considered measures related to the theft and diversion of weapons-usable plutonium, for example, or policy issues related to Russian Cooperation and U.S. non-proliferation policies. As a result, expert judgment was required to provide the baseline estimates of tradeoffs that give the information necessary to determine the weights on these measures.

In contrast, many different government programs have been subject to evaluations that have involved measures of environmental impacts, and information from these studies can be used to estimate reasonable tradeoffs within this category of measures. For example, Tengs, et al (1994) studied five hundred examples of life-saving interventions, typically U.S. government actions and regulations, to determine the estimated cost per life year saved of these interventions. Previous DOE studies also exist which provide information regarding the tradeoffs between costs and statistical human lives, and between costs and other environmental impacts.

Rather than asking for new expert judgments in this area where previous information is available regarding ES&H tradeoffs, this information from other DOE and government programs was used to determine the weights used in the baseline analysis. This tradeoff information is typically presented in terms of dollars rather than in the format of a comparison between two alternatives as presented in the previous sections. Nevertheless, there is a correspondence between these alternative presentations of tradeoff information. Table 8 presents the information necessary to determine baseline weights for the ES&H measures based on the use of tradeoffs stated in terms of dollars.

Table 8 - Unit Weights for ES&H Measures

	MIN	MAX	RANGE	Unit Price ($M)	Range Price ($M)	Weight
Human H&S						**0.7926**
Public Fatalities Radiation	-1	1	2	10	20.0	0.0528
Public Fatalities Chemical	0	1	1	10	10.0	0.0264
Worker Fatalities Radiation	-13	9	22	10	220.0	0.5812
Worker Fatalities Chemical	0	1	1	10	10.0	0.0264
Fatalities Transport	0	3	3	10	30.0	0.0793
Accident Risk	0	1	1	10	10.0	0.0264
Natural Environment						**0.1268**
Impacts on Species	0	8	8	1	8.0	0.0211
Secondary Waste Generated	0.00	4,000	4,000	0.01	40.0	0.1057
Socio-economic						**0.0806**
Short-term Job Loss	0%	5%	0	10	0.5	0.0013
Long-term Job Creation	0	3,000	3,000	0.01	30.0	0.0793

Table 8 displays the minimum and maximum performance levels used to determine the value functions in this analysis. The actual performance levels of the disposition alternatives fall within these limits. For each measure; the "Range" of the measure is simply the difference between these minimum and maximum levels. The unit price may be interpreted as the amount the decision maker (or public agency) is willing to pay (in millions of dollars) to reduce the level of the measure by one unit. The "Range Price" is the product of the range and the unit price. The ES&H measure weights may then be calculated by dividing the "Range Price" for a measure by the sum of the "Range Prices" for all of the ES&H measures.

For example, Table 8 indicates that up to $10 million would be spent on this program in order to save a statistical human life. Tengs, et. al.(pg. 14) report that the median cost/life-year saved from 34 interventions designed to avert deaths due to occupational hazards was $346,000. Assuming that the affected individual was 40 years of age with a 70 year life expectancy, we arrive at approximately $10 million as the implied cost per death averted, the value used for the baseline analysis in this study. Another reference point is the figure of $5.5 million/life used in the DOE Laboratory Integration Prioritization System Report [DOE-LIPS 95 pg. 3-7] for the evaluation of alternative environmental compliance and restoration projects.

To be consistent with the previous sections, similar tradeoff comparisons can be shown that are determined from the information presented in Table 8.

Human H&S

The tradeoffs regarding human health and safety implied by Table 8 are all presented with Public Fatalities Radiation as the common measure. These tradeoffs highlight the implication of Table 8 that equal weights should be placed on all human lives saved, whether they represent members of the public or workers, and without regard to the cause (e.g., radiation exposure, chemical exposure, transportation accidents, or other accidents).

Measure	*Alternative I*	*Alternative II*
Public Fatalities Radiation	1	0
Public Fatalities Chemical	0	1

Measure	*Alternative I*	*Alternative II*
Public Fatalities Radiation	1	0
Worker Fatalities Radiation	0	1

Measure	*Alternative I*	*Alternative II*
Public Fatalities Radiation	1	0
Worker Fatalities Chemical	0	1

Measure	*Alternative I*	*Alternative II*
Public Fatalities Radiation	1	0
Transportation Fatalities	0	1

Measure	*Alternative I*	*Alternative II*
Public Fatalities Radiation	1	0
Accident Risk	0	1

At first glance, it may not be obvious that the tradeoff information and the unit weights result in the same measure weights. In particular, the tradeoffs indicate that one public fatality from radiation exposure is equivalent to one worker fatality from radiation, yet the weights in Table 8 for these measures are quite different. The reason for this apparent discrepancy is that the tradeoff displayed does not incorporate the fact that the ranges of the two measures are quite different. The weights are determined to accommodate different ranges when the tradeoffs are used to aggregate value function scores.

Some studies have argued that employees are compensated for health risks through their salaries, and accept these risks voluntarily when they agree to employment. Therefore, it would be appropriate to allocate relatively more money to protect the general public from risks. Based on this argument we have adjusted these tradeoffs as a sensitivity analysis to allow for the possibility that society should be willing to spend up to twice as much to reduce the risks of public mortality as it would spend to reduce the risks of worker mortality. This analysis is presented in Section 8.2.4.

Natural Environment

The tradeoffs concerning the measures related to impacts on the natural environment can also be presented using the common measure of Public Fatalities Radiation. This use of a measure from another category provides a basis for easily comparing tradeoffs across categories as well as within them.

The first tradeoff indicates that an increase in 0.8 statistical public fatalities from radiation exposure would be accepted in order to reduce the number of endangered species that are threatened by the construction and operation of an alternative from 8 to 0. Note that this tradeoff is implied by the "unit price" in Table 8 of $1million that would be spent to reduce by 1 the number of endangered species that are threatened. This ratio of $10 million for a human life vs. $1 million for an endangered species is 10 to 1, which corresponds to the ratio of 8 to .8.

Measure	***Alternative I***	***Alternative II***
Public Fatalities Radiation	0.8	0
Impact on Species	0	8

The second tradeoff in this category implies that an increase of 1 statistical fatality would be accepted in exchange for a reduction in the Secondary Waste Generated by an alternative of 1000 cubic yards. Again, this tradeoff is implied by the ratio of the dollar figures shown in Table 8.

Measure	***Alternative I***	***Alternative II***
Public Fatalities Radiation	1	0
Secondary Waste Generated	0 cubic yards	1000 cubic yards

Socio-economic Benefits

The tradeoffs regarding the socio-economic impacts of alternatives are shown below, and again are presented relative to the common measure Public Fatalities Radiation. The implications of these tradeoffs may be interpreted in a similar manner to those associated with the Natural Environment measures.

Measure	***Alternative I***	***Alternative II***
Public Fatalities Radiation	0.05	0
Boom/Bust (Short term job loss)	0%	5%

Measure	***Alternative I***	***Alternative II***
Public Fatalities Radiation	1	0
New Long Term Jobs	1,000 jobs	0 jobs

The use of a common measure in all of these tradeoff statements means that no additional tradeoffs are required to allow aggregation across the categories of the ES&H measures.

6.2.9 Aggregation Across the Three Major Objectives

At this stage, the data necessary to calculate the weights within each of the three major objectives, Non-proliferation, Operational Effectiveness, and ES&H, have been provided. Two additional tradeoffs are required to allow an aggregation across these three objectives to provide a single score for each alternative.

The first of these tradeoffs was provided by OFMD personnel. This tradeoff reflects a judgment that an increase in the Investment Cost from $390 million to $2500 million would be justified if the Time to Start could be reduced from 20 to 5 years.

Major Objective	***Measure***	***Alternative I***	***Alternative II***
Operational Effectiveness	Investment Cost ($M)	390	2500
Non-proliferation	Time to Start	20	5

The second tradeoff reflects the information provided in Table 8 that an additional $10 million would be spent in order to reduce the number of estimated statistical human fatalities by 1.

Major Objective	***Measure***	***Alternative I***	***Alternative II***
Operational Effectiveness	Investment Cost ($M)	0	10
Operational Effectiveness	Public Fatalities Radiation	1	0

6.3 The weights

The tradeoffs presented in the previous sections provide a unique set of measure weights for the evaluation of plutonium disposition alternatives. We now present these final weights in Figures 19, 20a, 20b, and 20c to parallel the measures displayed in Figures 2, 3a, 3b and 3c. The weights in these figures are "local weights". In other words, the weights sum to one within each sub-objective. To find the overall weight an individual measure has within the analysis, simply multiply all the weights through the hierarchy.

Once again, it is important to emphasize that these weights do not represent measures of the relative importance of the corresponding measures. Instead, they are influenced by the ranges over which each of these measures vary, so they should be interpreted within this context.

Figure 19 - High Level Weights

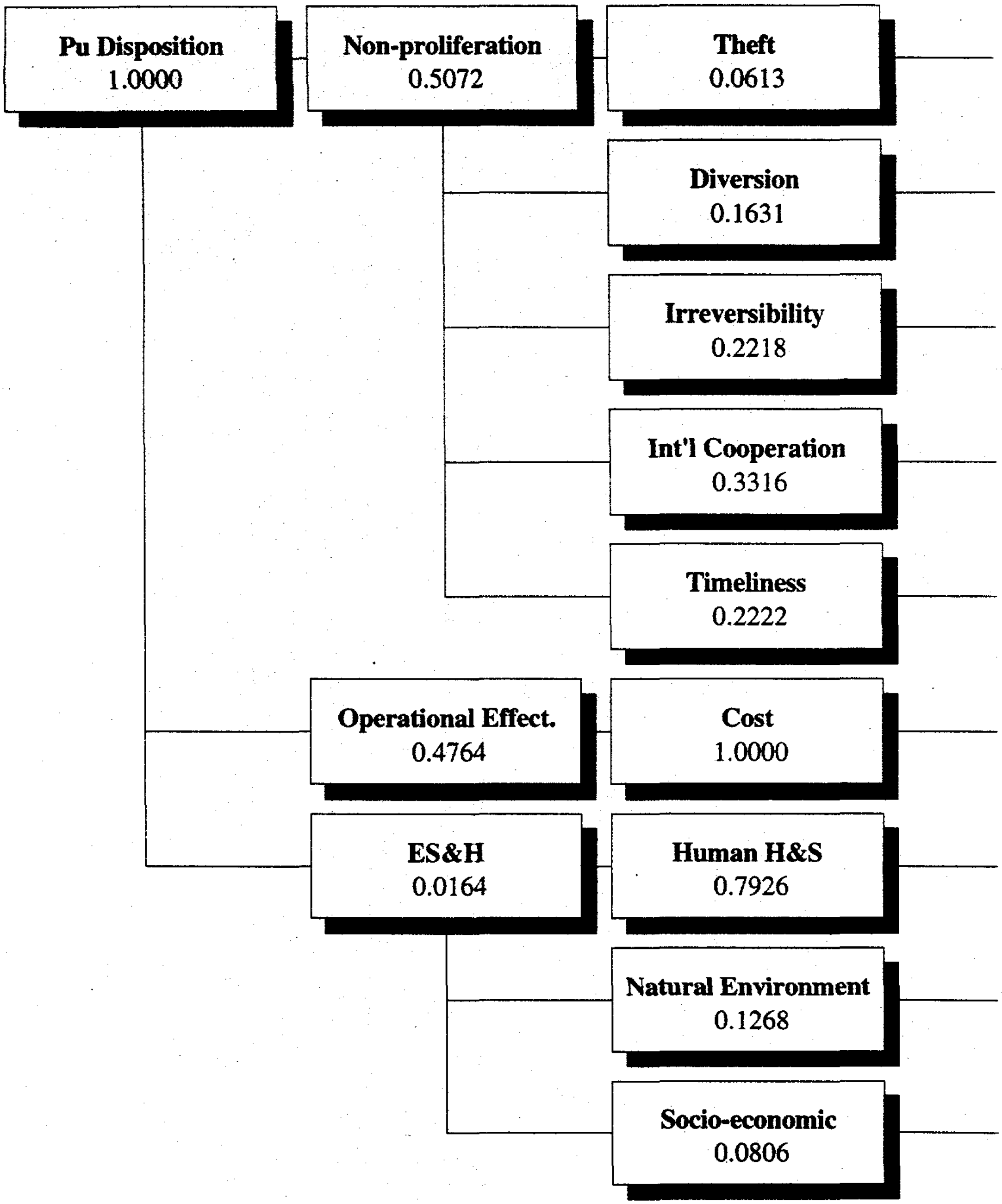


Figure 20a - Non-proliferation Weights

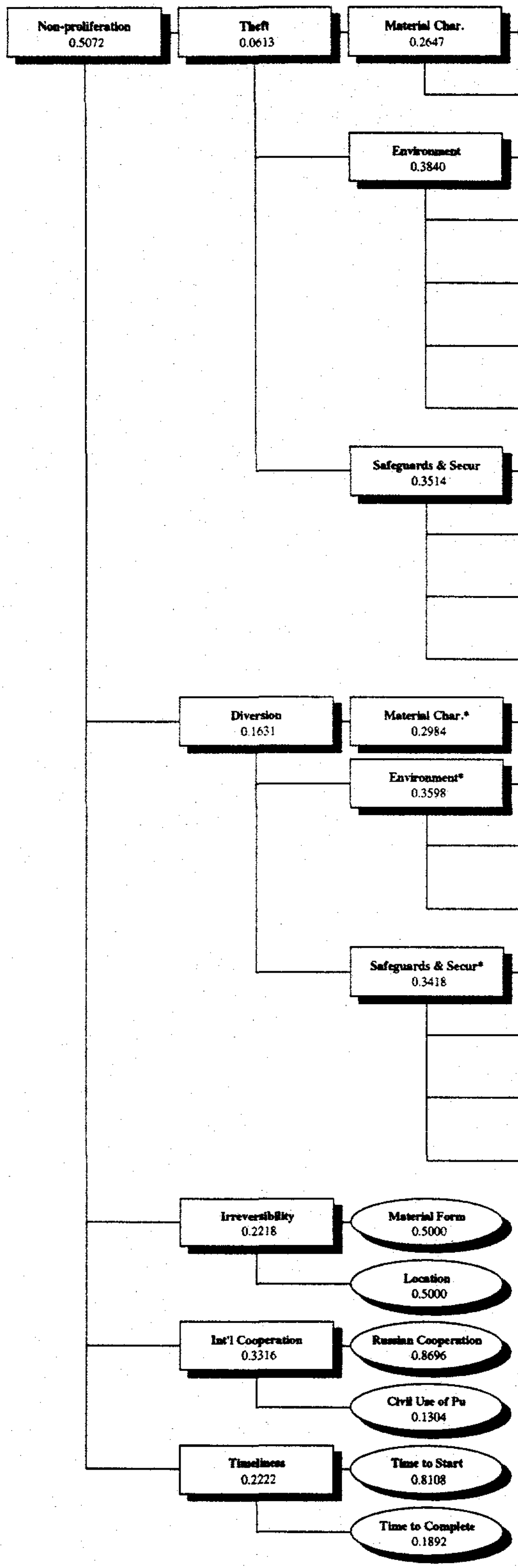


Figure 20b - Operational Effectiveness Weights

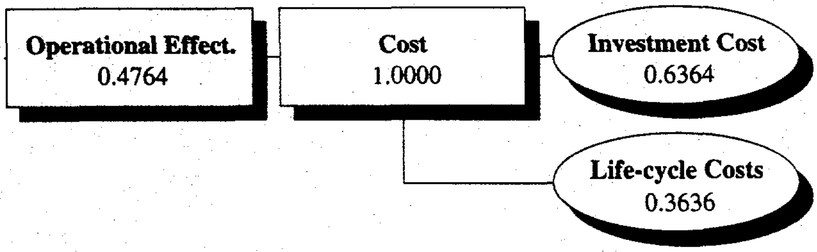
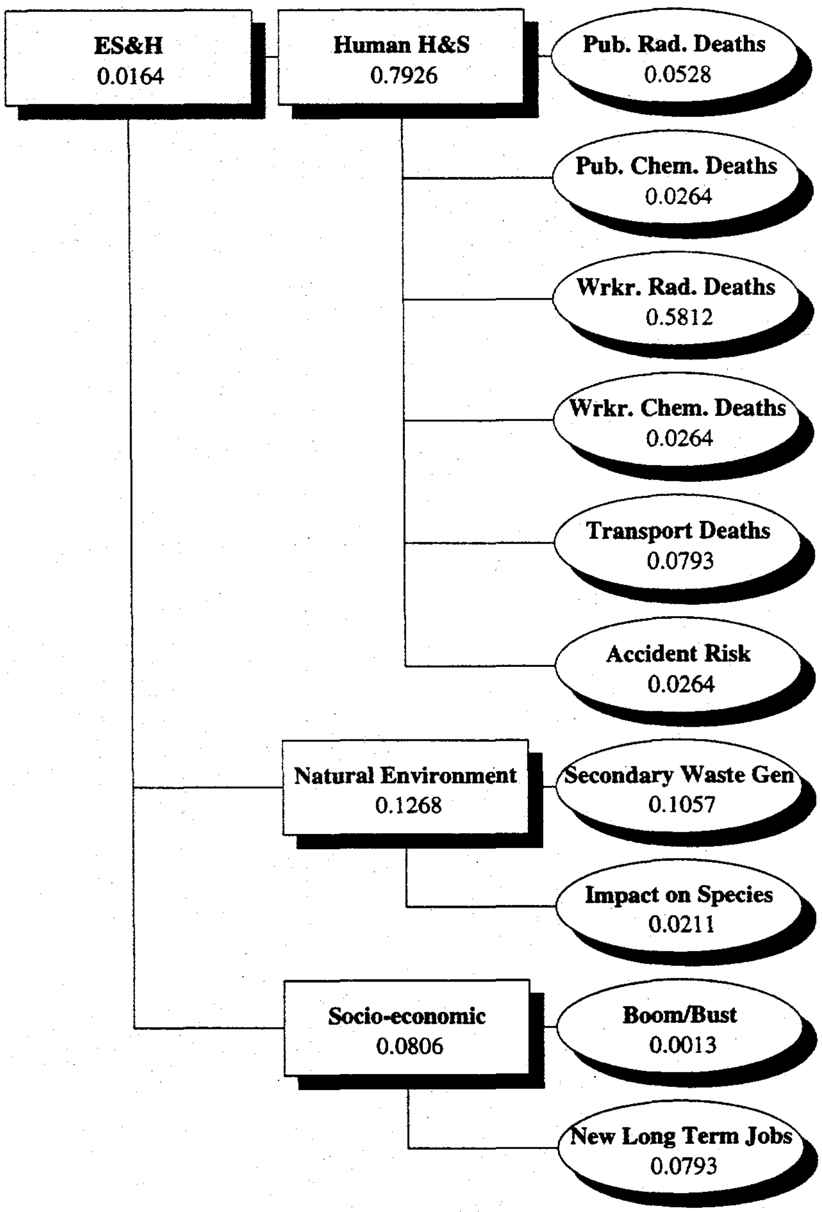


Figure 20c - Environment, Safety and Health Weights



7. Evaluation of the Alternatives

7.1 Evaluation and Ranking

Once the single measure value functions have been completely defined, the data from the alternatives-by-objectives matrix are converted to component utilities, as shown in Table 7. 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.

The component value function scores have been aggregated, using the additive multi-attribute utility function (1), within each of the three major objectives, and within each of the categories of objectives identified 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, since it provides scores for each alternative for the three major objectives of the plutonium disposition problem, and for the categories of objectives identified in Figure 2. At this stage it is possible to examine the relative strengths and weaknesses of the alternatives in more detail.

The discussion of the evaluation of the alternatives will be organized according to the three major objectives highlighted in Figure 2, and defined in more detail in Figures 3a, 3b, and 3c. These results are presented in the form of *stacked bar graphs,* which provide a visual representation of the aggregated performance of each alternative on each major objective. In addition, these stacked bar graphs can be segmented to show the relative contributions of the individual sub-objectives and measures to the overall score for each alternative. Each segment represents the value of the performance of each alternative on each sub-objective or measure (Section 4) weighted by its relative importance captured through the tradeoff responses (Section 6) using the additive multiattribute utility model. This "base case" analysis is followed by an extensive "sensitivity analysis" presented in Section 8 which explores how changes in: 1) estimates of the performance levels of the alternatives, 2) in tradeoffs between measures and objectives, and 3) in the form of the multi-attribute utility model would affect the results.

7.2 Non-proliferation Objective

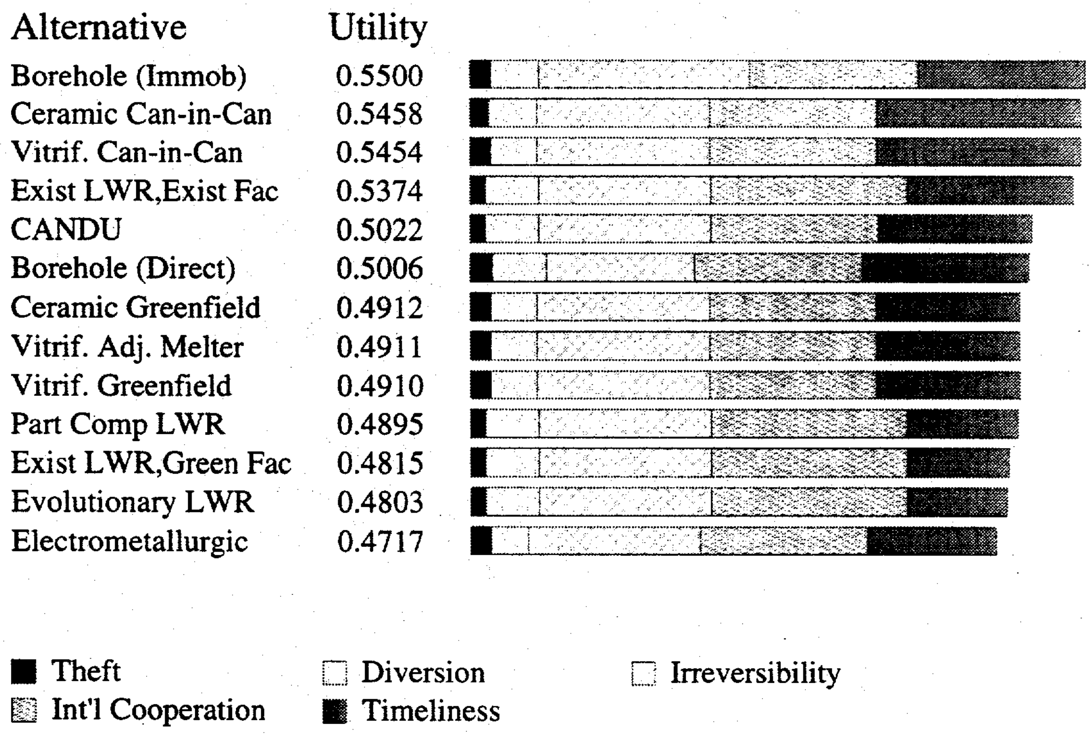
The Non-proliferation objective highlighted in Figure 3a is the most complex of the three major high-level objectives of the plutonium disposition effort shown in Figure 2. The Non-proliferation objective consists of five sub-objectives: Theft, Diversion, Irreversibility, International Cooperation, and Timeliness. The rankings of the thirteen alternatives on the Non-proliferation objective are shown in Figure 21, along with a stacked bar graph that shows the relative contributions of performances on these five sub-objectives to the overall rankings.

Several observations can be made immediately based on the summary provided by Figure 21. The Borehole (Immobilized) alternative is ranked first, and, based on inspection of the length of the component bars, this ranking is the result of superior performance on the sub-objective Irreversibility. The relatively poor performances of the Partially Completed LWR, the Existing LWR, Greenfield Facilities, and the Evolutionary

LWR are due primarily to the Timeliness sub-objective, with the measures Time to Start and Time to Complete the mission. The Electrometallurgical alternative suffers from relatively poor estimates of performance on the Diversion and International Cooperation sub-objectives.

The Ceramic and Vitrification Can-in-Canister immobilization alternatives can be started and completed quickly, so they score well on the Timeliness measures. However, the light water reactor alternatives are superior regarding the measures related to International Cooperation. These observations can be confirmed, of course, by reference to the data displayed in Table 7, but Figure 21 may aid in identifying specific areas of performance that are "discriminators" among the alternatives.

Figure 21 - Non-proliferation Ranking



Additional insights may be derived from a review of rankings of the alternatives using stacked bar graphs for each of the five sub-objectives within Non-proliferation. These bar graphs are shown in Figures 22a through 22e.

The rankings on the Theft sub-objective are shown in Figure 22a. There is no cross-hatched bar corresponding to Material Characteristics in this graph since all of the alternatives received identical value function scores of 0.0 on the underlying measures (see Table 7). Otherwise, the immobilization and borehole alternatives rank higher than the reactor alternatives because of better performance on the Environment sub-objective, primarily because they require fewer processing steps.

In contrast, the reactor options perform relatively well on the Diversion sub-objective as shown in Figure 22b, due to higher scores on the Safeguards & Security* sub-objective. This result is due to the Measurement Uncertainty* associated with the immobilization alternatives, which complicates the problem of allowing verification of the disposition process by IAEA or other third-party observers. The Borehole (Direct) alternative is the top ranked alternative on this sub-objective, primarily because it has even fewer processing steps than the other immobilization alternatives, and it does not present the same verification difficulties since the material is not immobilized.

Stacked bar graphs for the Material Characteristics, Environment and Safeguards & Security sub-objectives for both Theft and Diversion are presented in Appendix D. An inspection of these graphs will provide additional insights regarding the results shown in Figures 22a and 22b.

Figure 22a - Theft Sub-objective Ranking

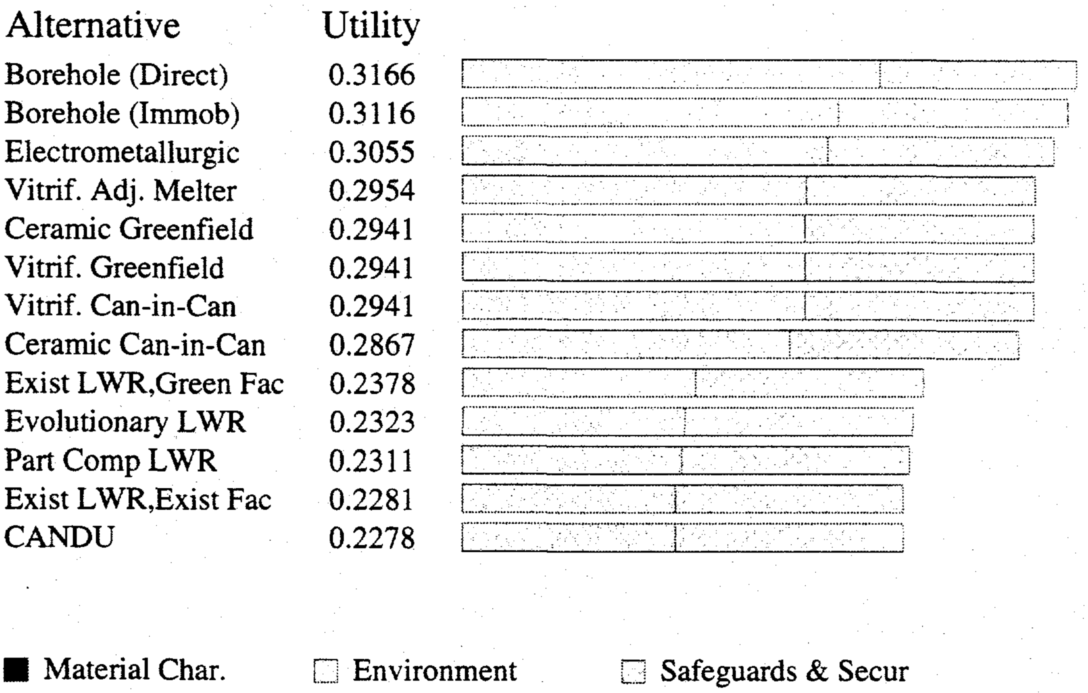


Figure 22b - Diversion Sub-objective Ranking

Alternative	Utility
Borehole (Direct)	0.3017
Part Comp LWR	0.2879
CANDU	0.2879
Exist LWR,Green Fac	0.2879
Exist LWR,Exist Fac	0.2879
Evolutionary LWR	0.2877
Borehole (Immob)	0.2664
Ceramic Can-in-Can	0.2635
Ceramic Greenfield	0.2599
Vitrif. Greenfield	0.2584
Vitrif. Can-in-Can	0.2584
Vitrif. Adj. Melter	0.2584
Electrometallurgic	0.2093

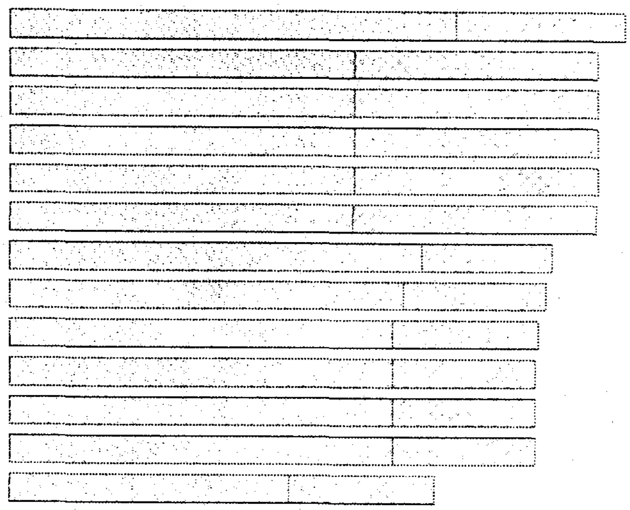


Figure 22c - Irreversibility Sub-objective Ranking

Alternative	Utility
Borehole (Immob)	0.8500
Ceramic Greenfield	0.7000
Vitrif. Greenfield	0.7000
Ceramic Can-in-Can	0.7000
Vitrif. Can-in-Can	0.7000
Electrometallurgic	0.7000
Vitrif. Adj. Melter	0.7000
Part Comp LWR	0.7000
Evolutionary LWR	0.7000
CANDU	0.7000
Exist LWR,Green Fac	0.7000
Exist LWR,Exist Fac	0.7000
Borehole (Direct)	0.6000

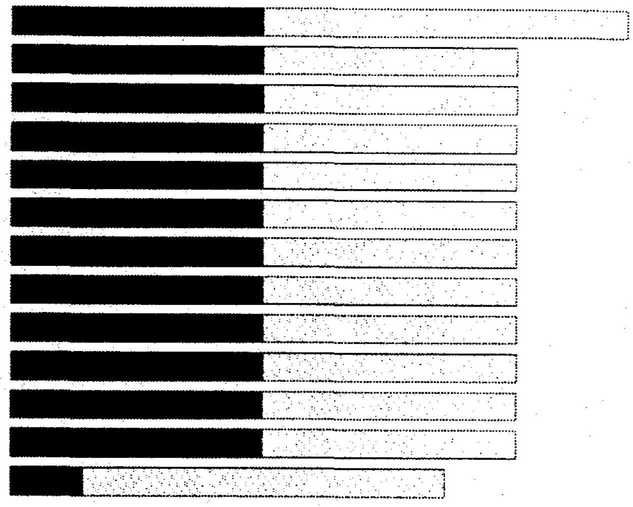
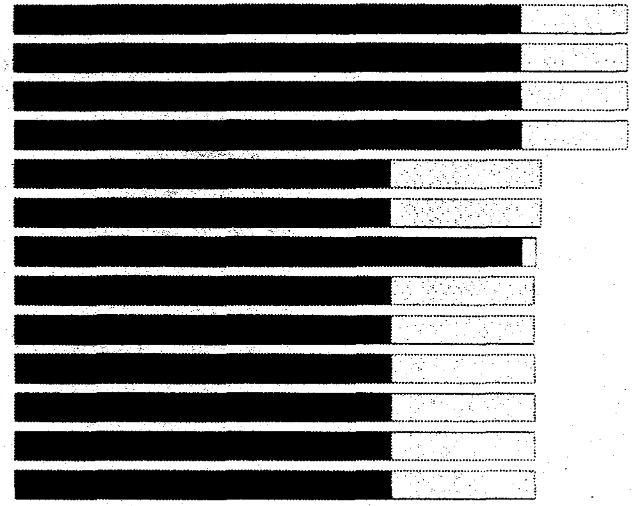


Figure 22d - International Cooperation Sub-objective Ranking

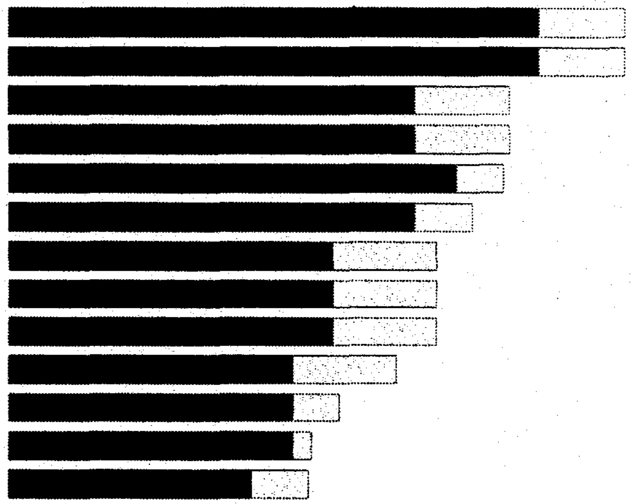
Alternative	Utility
Part Comp LWR	0.5278
Evolutionary LWR	0.5278
Exist LWR,Green Fac	0.5278
Exist LWR,Exist Fac	0.5278
Borehole (Direct)	0.4548
Borehole (Immob)	0.4548
CANDU	0.4496
Ceramic Greenfield	0.4483
Vitrif. Greenfield	0.4483
Ceramic Can-in-Can	0.4483
Vitrif. Can-in-Can	0.4483
Electrometallurgic	0.4483
Vitrif. Adj. Melter	0.4483



■ Russian Cooperation ☐ Civil Use of Pu

Figure 22e - Timeliness Sub-objective Ranking

Alternative	Utility
Ceramic Can-in-Can	0.8162
Vitrif. Can-in-Can	0.8162
Borehole (Direct)	0.6667
Borehole (Immob)	0.6667
Exist LWR,Exist Fac	0.6577
CANDU	0.6162
Ceramic Greenfield	0.5712
Vitrif. Greenfield	0.5712
Vitrif. Adj. Melter	0.5712
Electrometallurgic	0.5171
Part Comp LWR	0.4414
Exist LWR,Green Fac	0.4036
Evolutionary LWR	0.4000



■ Time to Start ☐ Time to Complete

Figure 22c presents the results for the Irreversibility sub-objective. All of the alternatives are judged to have identical performance, except for the Borehole (Immobilized) which benefits from both a desirable final material form, and the final location in the borehole, and the Borehole (Direct) alternative which has a final material form that would be relatively easy for the host nation to reuse in weapons.

The rankings for the alternatives on the International Cooperation sub-objective are presented in Figure 22d, and show the relative impacts of differential performances on the measures Russian Cooperation and Civil Use of Plutonium. The reactor options are ranked high on the International Cooperation sub-objective, but receive somewhat lower scores than the other alternatives on the Civil Use of Plutonium measure. The CANDU reactor alternative represents an extreme example with regard to both of these measures (tied for the highest score on Russian Cooperation but the lowest score on Civil Use of Plutonium). Of course, the analysis is predicated on the assumption that the Russians would be willing to send their plutonium to Canada if the U.S. sent its surplus weapons plutonium there.

Finally, the Timeliness sub-objective goal rankings are presented in Figure 22e. The Vitrification Can-in-Can and Ceramic Can-in-Can alternatives rank at the top of the graph due to the estimates that both would allow for the start of the disposition process at the earliest time, and they require a relatively short Time to Complete the disposition effort. The Evolutionary LWR is ranked last on this sub-objective because of the estimate that it would require the longest time to start the disposition process, and would also require the third longest time duration to complete the mission. The Existing LWR, Existing Facilities ranks the highest among the reactor alternatives.

7.3 Operational Effectiveness Objective

Figure 23 presents the rankings of the alternatives on the Operational Effectiveness objective. The Vitrification Can-in-Can and Ceramic Can-in-Can alternatives perform very well on this objective, and are the highest ranked alternatives. The relatively high Investment Cost associated with the Evolutionary LWR alternative explains its low ranking on this objective.

7.4 Environment, Safety & Health Objective

The rankings of the alternatives on the ES&H objective are shown in Figure 24. The use of either of the Existing LWR alternatives is expected to avoid incremental human fatalities due to the reduction in the need for mining and processing the uranium that would be displaced by the MOX fuel. In contrast, the Evolutionary LWR and Partially Completed LWR alternatives would require the operation of new reactors, and would result in forecasts of additional risks to human health and safety [DOE-PEIS 96]. The alternatives do not vary significantly with regard to the measures of impacts on the natural environment and socio-economic conditions. Additional details regarding the performances of the alternatives on the individual measures associated with ES&H are shown in Figure 25.

Figure 23 - Operational Effectiveness Ranking

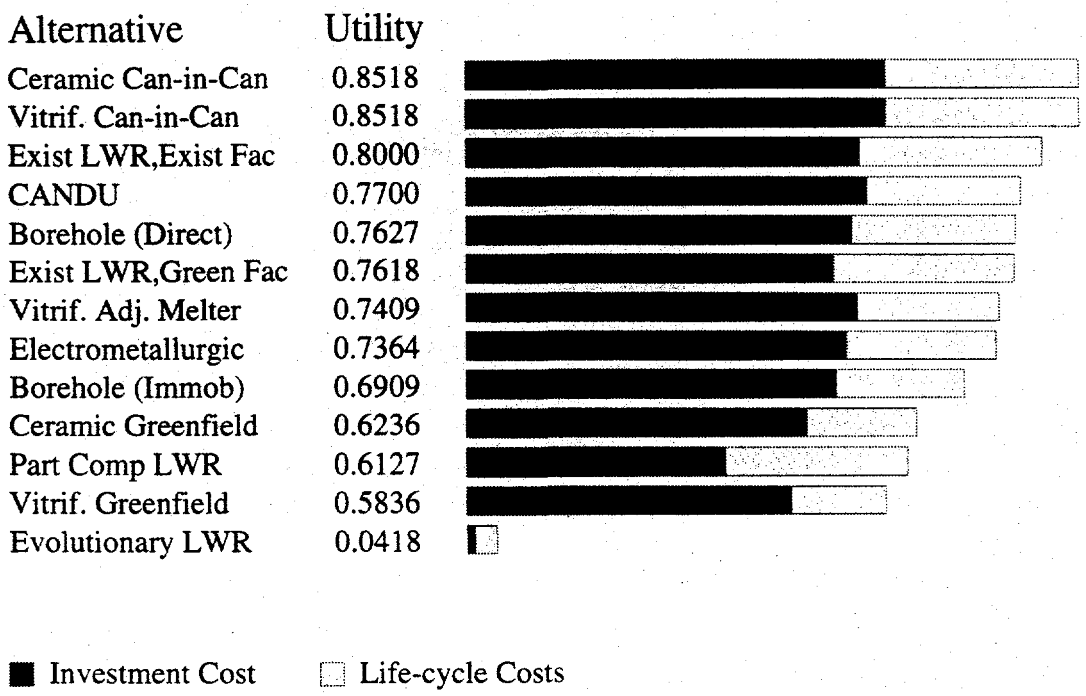


Figure 24 - ES&H Ranking Highlighting Sub-objectives

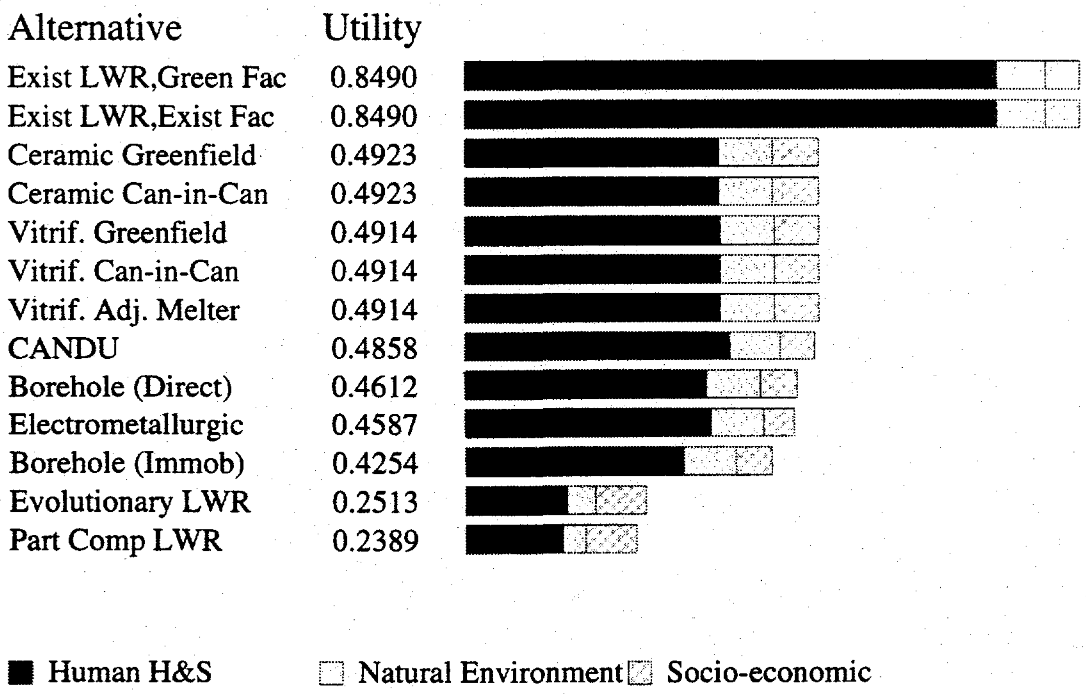
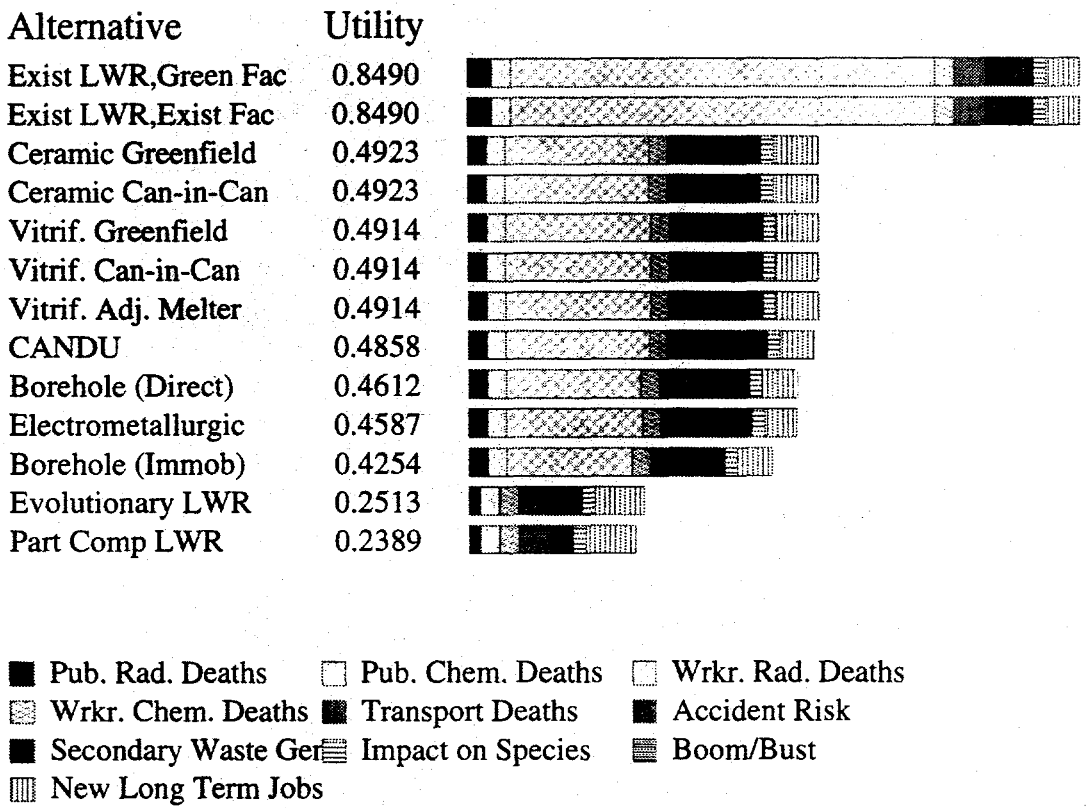


Figure 25 - ES&H Ranking Highlighting Measures



7.5 Technology Families

In the previous discussion illustrated with stacked bar graphs, the reactor, immobilization and borehole options were compared against one another on the major objectives. Comparisons within technology families may be useful in highlighting the relative strengths and weaknesses of relatively similar alternatives and variants. For the purposes of this discussion, the alternatives are divided into the reactor family and the immobilization and borehole family.

7.5.1 The Reactor Alternatives

The reactor alternatives are compared with respect to performance on the Non-proliferation objective in Figure 26. The stacked bar graph highlights the fact that there is very little difference, if any, among the pure reactor alternatives with respect to the Theft, Diversification, and Irreversibility sub-objectives.

Figures 27a and 27b provide details for the reactor alternatives with respect to the International Cooperation and Timeliness sub-objectives. The CANDU alternative scores the lowest of all the reactor alternatives on the Civil Use of Plutonium measure. The Existing LWR, Existing Facilities and the CANDU alternatives have significant advantages on the Timeliness sub-objective as a result of the estimates of shorter times for starting the processes.

Figure 26 - Reactor Alternatives Non-proliferation Ranking

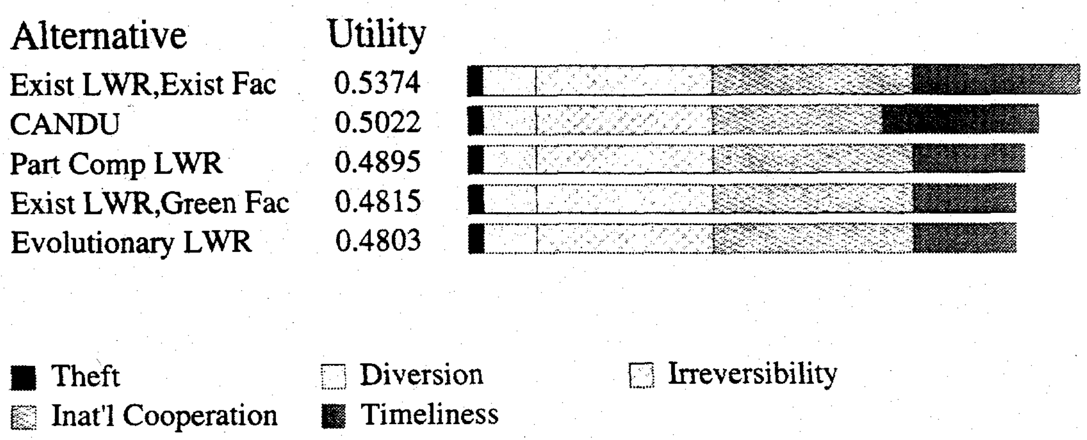


Figure 27a - Reactor Alternatives International Cooperation Ranking

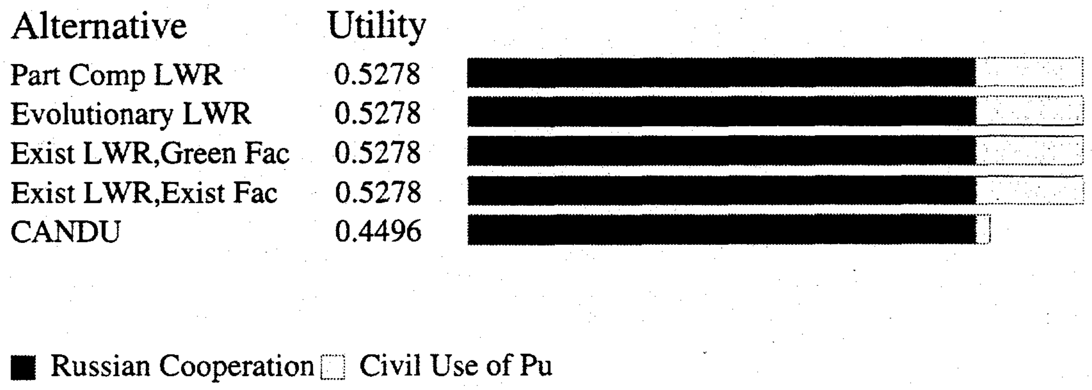
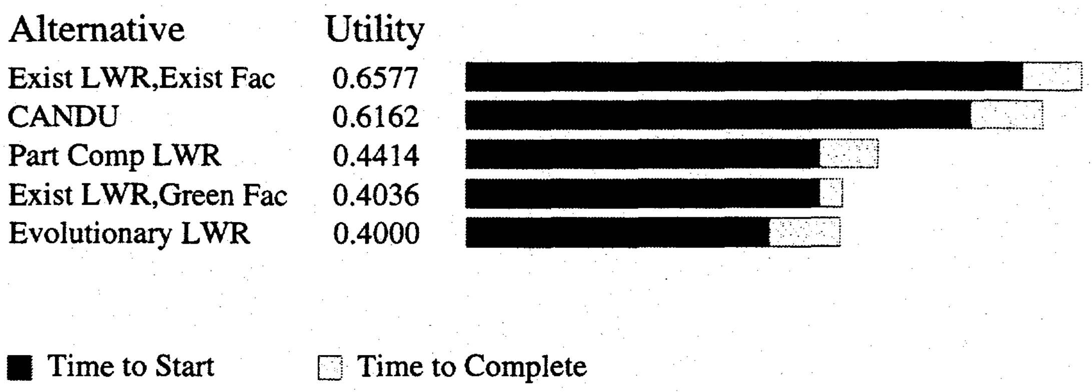


Figure 27b - Reactor Alternatives Timeliness Sub-objective Ranking



Again for ease of comparison, stacked bar graphs for the reactor alternatives are shown in Figures 28 and 29 for the Operational Effectiveness and ES&H objectives. Investment Cost is the significant discriminator among the alternatives on the Operational Effectiveness objective; the Partially Completed and Evolutionary LWRs are particularly expensive, which accounts for their lower rankings in Figure 28. The existing reactors perform well on the ES&H objectives due to the estimated impacts of the displacement of uranium fuel by MOX fuel on human health and safety [DOE-PEIS 96]. The Partially Complete and Evolutionary LWRs score poorly because they add incremental risks to public and worker safety.

Figure 28 - Reactor Alternatives Operational Effectiveness Ranking

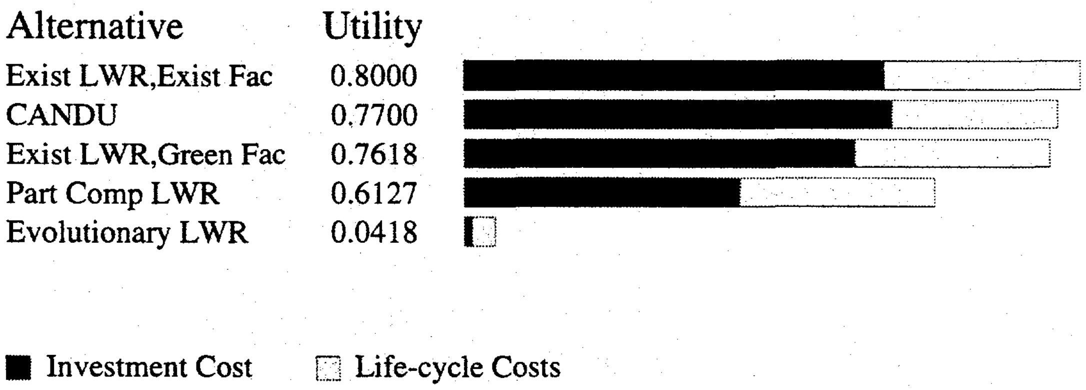
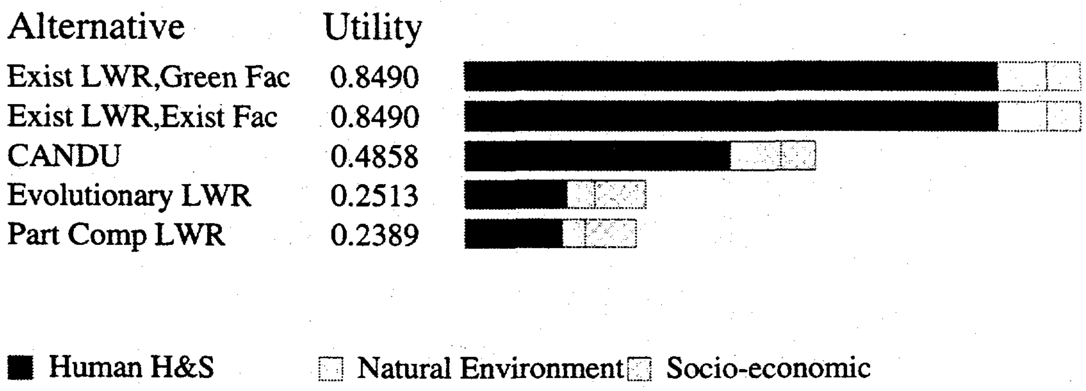


Figure 29 - Reactor Alternatives ES&H Ranking



7.5.2 The Immobilization and Borehole Alternatives

Similar stacked bar graphs are shown for the immobilization and borehole alternatives in Figure 30 for the Non-proliferation objective. The primary differences among these alternatives appear to be in the Diversion and Timeliness sub-objectives, which are shown in additional detail in Figures 31a and 31b. The Borehole (Direct) alternative is ranked highest among the alternatives in this technology family on the Diversion sub-objective primarily because of the simplicity of its processing environment, while the Vitrification Can-in-Can and Ceramic Can-in-Can alternatives have the advantage of the earliest start time relative to the other immobilization and borehole alternatives.

Figure 30 - Non-reactor Alternatives Non-proliferation Ranking

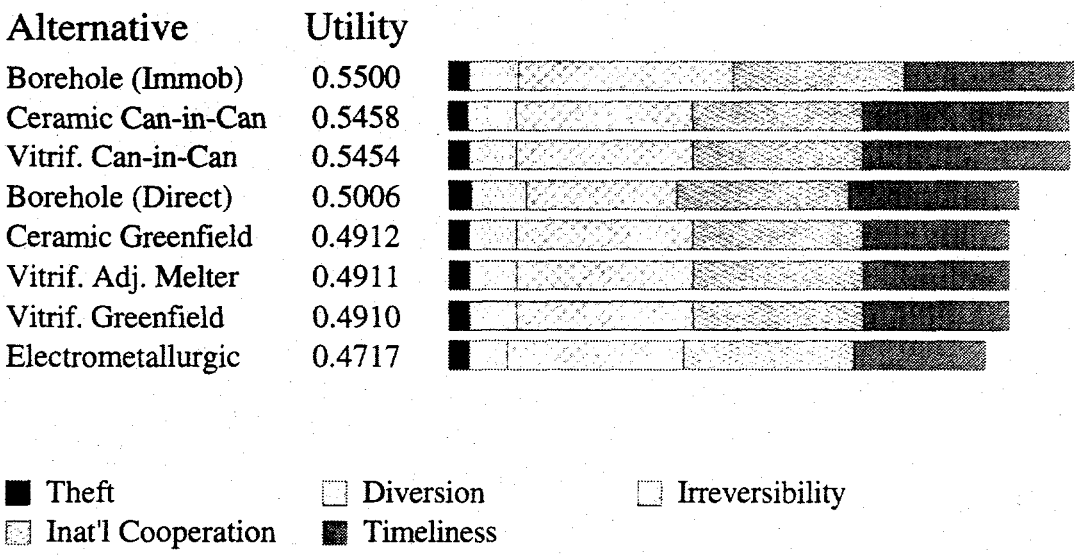


Figure 31a - Non-reactor Alternatives Diversion Sub-objective Ranking

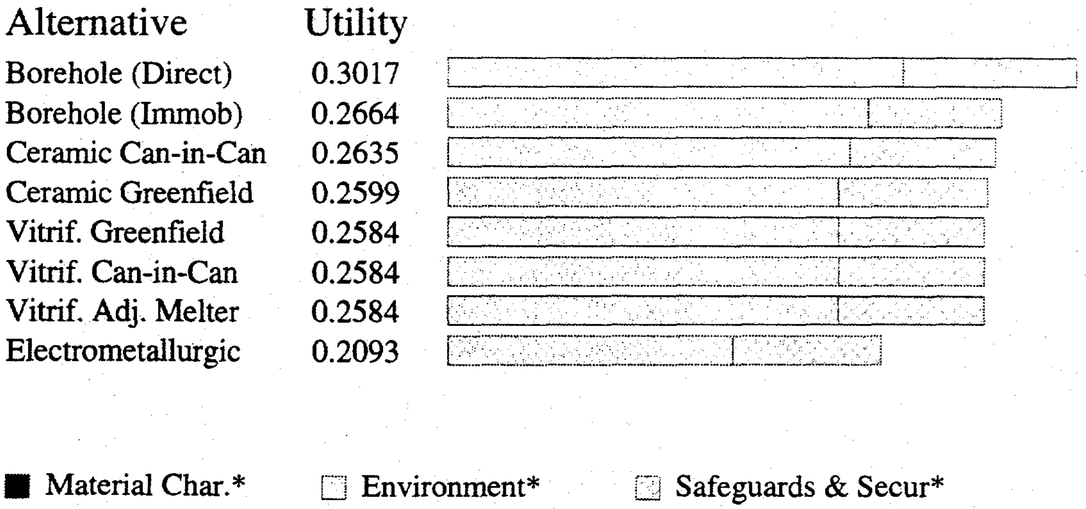
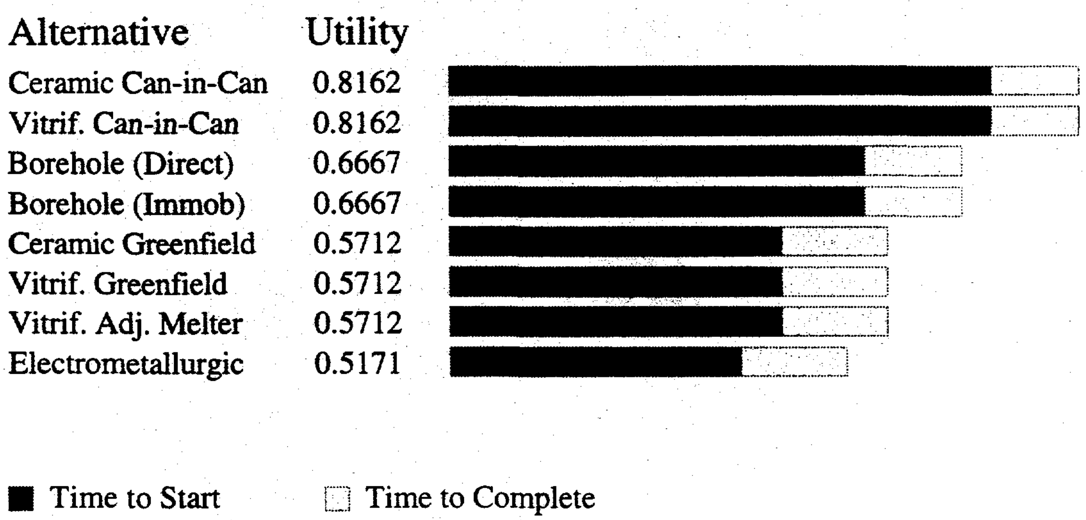
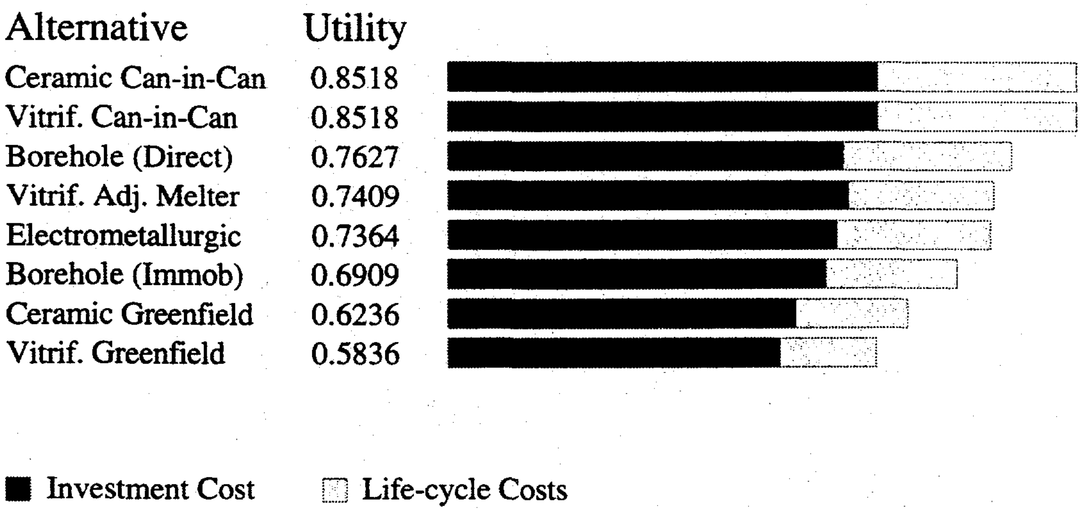


Figure 31b -Non-reactor Alternatives Timeliness Sub-objective Ranking



The stacked bar graphs for the Operational Effectiveness and ES&H comparisons are shown in Figures 32 and 33. The Vitrification Can-in-Can and Ceramic Can-in-Can alternatives are again ranked first among this subset of alternatives on the Operational Effectiveness objective, primarily because of their low Investment Costs. The differences among these alternatives relative to the E,S&H objective are primarily due to forecasts of some additional risks to human health and safety associated with the two Borehole and the Electrometallurgical alternatives.

Figure 32 - Non-reactor Alternatives Operational Effectiveness Ranking



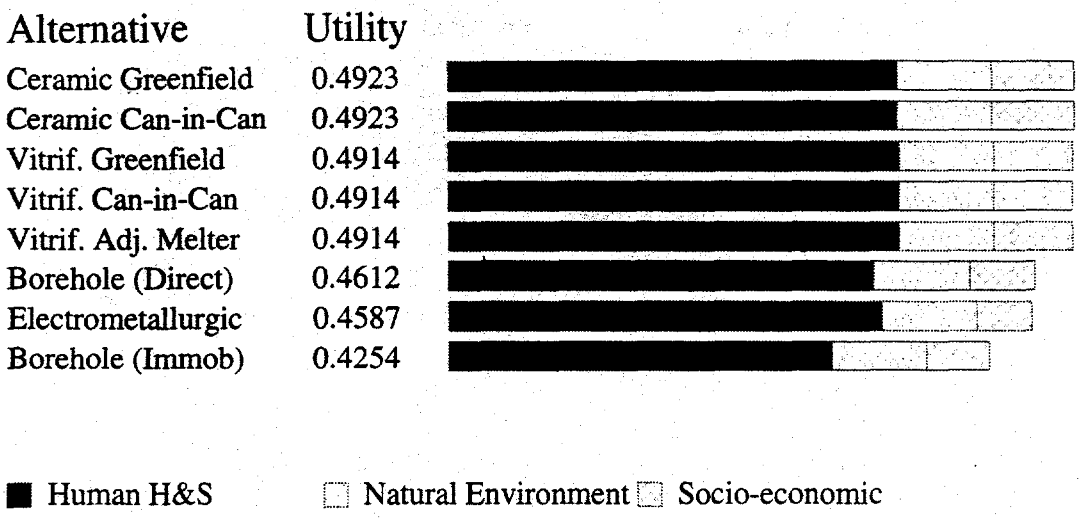


Figure 33 - Non-reactor Alternatives ES&H Ranking

7.6 Overall Ranking

The discussion of the results of the MAU analysis has focused on the performance of the alternatives within the three major objectives of the plutonium disposition program in order to provide insights regarding their relative strengths and weaknesses. Using the final set of tradeoffs presented in Section 6, an overall ranking of the alternatives can also be established. As we noted in the discussion of the tradeoffs among the various measures, some of the judgments that are required may be considered expert opinion, as provided by the S&S team to assist in aggregating measures related to the sub-objectives of Theft and Diversion. However, at the higher levels of the objective hierarchy shown in Figure 2, the tradeoffs and their implied weights on the value function scores become more a matter of policy decisions, and different individuals and stakeholder groups may have differing opinions about these expressions of policy.

The tradeoffs used to aggregate the measures of performance across the three major objectives were provided by OFMD personnel, and are presented here as a "base case" for the analysis. In the following section, an extensive sensitivity analysis will be provided to determine how robust this base case ranking is, and to develop further insights regarding the alternatives.

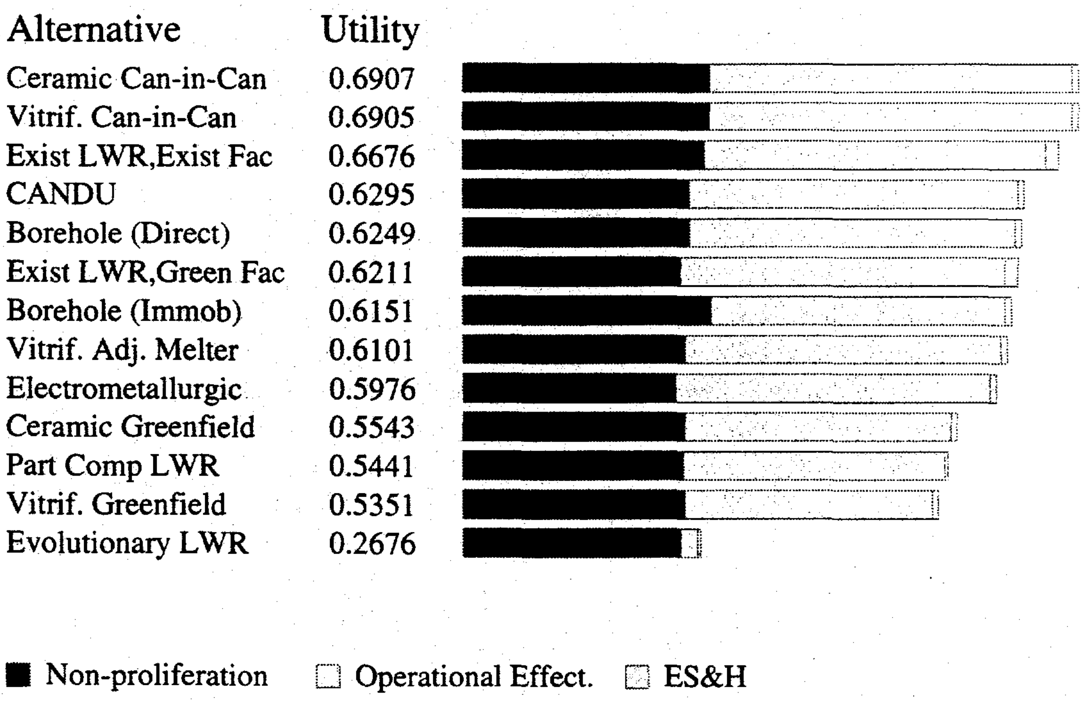
The base case overall ranking of the alternatives is shown by the stacked bar graph presented in Figure 34. The segments of the bars represent the contributions of the performances of the alternatives on the three major objectives discussed above.

The Ceramic Can-in-Can and Vitrification Can-in-Can alternatives achieve the highest rankings, with almost identical total scores. The Existing LWR, Existing Facilities alternative is ranked third, primarily because it receives a lower score on the Operational Effectiveness objective than the Can-in-Can alternatives. The fourth and fifth ranked alternatives are the CANDU reactors and the Borehole (Direct).

The intuition behind this overall ranking should follow immediately from the discussion presented above. The Can-in-Can alternatives were ranked first on the

Operational Effectiveness objective and second and third in Non-proliferation, due in large part to their low Investment Costs and early forecasted start times, respectively. These two alternatives were also near the top of the ES&H rankings. The Existing LWR, Existing Facilities alternative ranked number four on the Non-proliferation objective, third on Operational Effectiveness objectives, and tied for number one on the ES&H objective rankings. The CANDU alternative was ranked fifth on the Non-proliferation objective, fourth on the Operational Effectiveness objective, and eighth on the ES&H objective. Finally, the Borehole (Direct) alternative was ranked sixth, fifth and ninth on the three major objectives, respectively.

Figure 34 - Overall Ranking



7.6.1 Reactor Alternatives

For ease of reference, the overall ranking of the reactor alternatives using the base case data is shown in Figure 35. The Evolutionary LWR ranks below the four alternatives that utilize existing or partially completed reactors. Therefore, we will eliminate it from further discussion in this section.

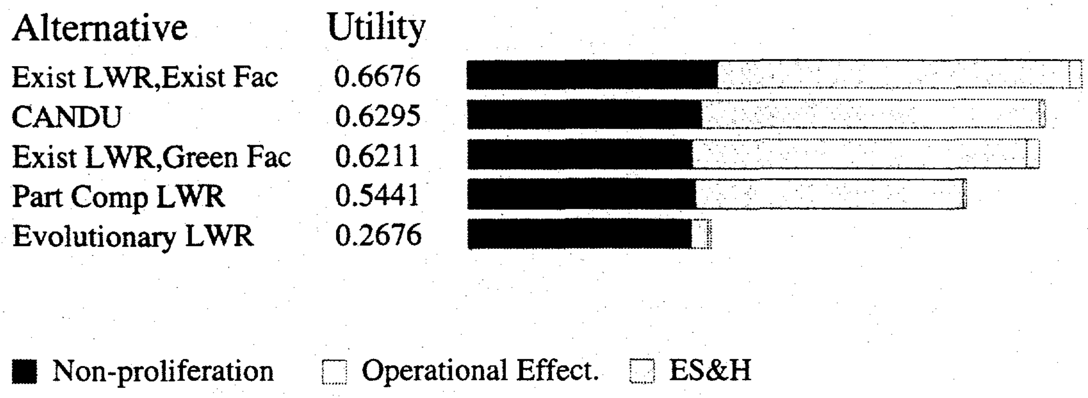


Figure 35 - Reactor Alternatives Overall Ranking

The two top ranked reactor alternatives are the Existing LWR, Existing Facilities and the CANDU reactors. Therefore, it is worthwhile to explore the differences among them. Table 9 shows a comparison of these two alternatives. At the top of this table are the aggregated MAU scores for these alternatives, and the difference between these scores. The rows in the table are the measures on which the two options differ, and the levels of performance of each alternative on each of these measures. Italics are used to highlight measures on which the lower ranked alternative actually performs better than the higher ranked alternative. The column labeled Difference presents the difference in the aggregated MAU scores that is attributed to this measure, and the percentage difference is shown in the next column. This same format will be used for all subsequent comparisons of pairs of alternatives in this section.

Another natural comparison is between the Existing LWR, Existing Facilities and the Existing LWR, Greenfield Facilities alternatives. This comparison is shown in Table 10. This table highlights the differences between these alternatives, with the use of an Existing LWR, Existing Facilities having a shorter start time and a shorter duration, and costing less in terms of both Investment Costs and Life-cycle Costs. The Existing LWR, Greenfield Facilities would offer an advantage only in terms of reducing the number of SST Trips and miles traveled because the greenfield facilities would be co-located.

Table 9 - Existing LWR, Existing Facilities vs. CANDU

Exist LWR, Exist Fac	0.6676
CANDU	*0.6295*
Difference	0.0381

Measure	Exist LWR, Exist Fac Level	*CANDU* Level	Difference	% of Total Difference
Life-cycle Costs	$1,220	$1,660	0.0191	50.04
Civil Use of Pu	70	10	0.0132	34.55
Wrkr. Rad. Deaths	-13.0	1.5	0.0063	16.47
Start Year	9	10	0.0061	16.00
Investment Cost	*$980*	*$870*	*-0.0048*	*-12.51*
Time to Complete	*15*	*14*	*-0.0014*	*-3.73*
Transport Deaths	*1.3270*	*0.6770*	*-0.0003*	*-0.74*
Pub. Rad. Deaths	-0.3500	0.0004	0.0002	0.40
Accident Risk	*0.2803*	*0.0003*	*-0.0001*	*-0.32*
Secondary Waste Gen	*2,151*	*1,998*	*-0.0001*	*-0.17*
SST Trans Miles	5300	5350	0.0000	0.02

Table 10 - Existing LWR, Existing Facilities vs. Existing LWR, Greenfield Facilities

Exist LWR, Exist Fac	0.6676
Exist LWR, Green Fac	*0.6211*
Difference	0.0465

Measure	Exist LWR, Exist Fac Level	*Exist LWR, Green Fac* Level	Difference	% of Total Difference
Start Year	9	13	0.0244	52.38
Investment Cost	$980	$1,380	0.0173	37.24
Time to Complete	15	18	0.0043	9.17
Life-cycle Costs	$1,220	$1,240	0.0009	1.86
SST Trans Miles	*5300*	*3900*	*-0.0002*	*-0.47*
No. of Trips	*4*	*3*	*-0.0001*	*-0.18*

Finally, Table 11 presents a comparison of the Existing LWR, Existing Facilities and the Partially Completed LWR alternatives. According to the forecasts of performance, the use of a partially completed reactor would require significantly higher Investment Costs and would take an extra four years to start processing material. As a new operating power plant, this option would also have some negative ES&H implications relative to the use of existing facilities, particularly in the areas of Worker Radiation Fatalities and Secondary Waste Generated.

Table 11 - Existing LWR, Existing Facility vs. Partially Complete LWR

Exist LWR, Exist Fac	0.6676
Part Comp LWR	*0.5441*
Difference	0.1235

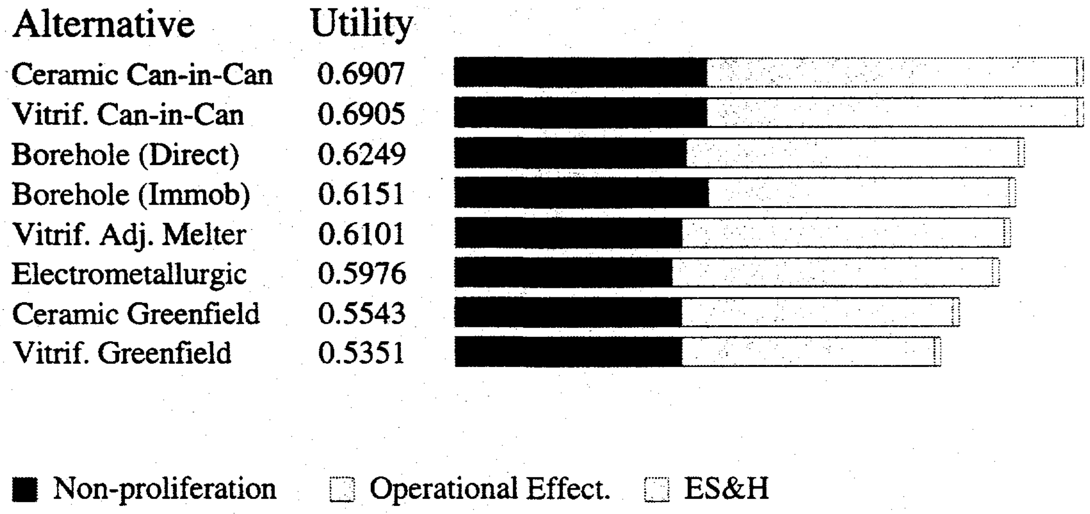
Measure	Exist LWR, Exist Fac Level	*Part Comp LWR* Level	Difference	% of Total Difference
Investment Cost	$980	$3,050	0.0897	72.60
Start Year	9	13	0.0244	19.73
Wrkr. Rad. Deaths	-13.0	8.9	0.0095	7.68
Secondary Waste Gen	2,151	3,425	0.0006	0.45
Life-cycle Costs	*$1,220*	*$1,210*	*-0.0004*	*-0.35*
New Long Term Jobs	*1,792*	*2,622*	*-0.0004*	*-0.29*
Pub. Rad. Deaths	-0.3500	0.3900	0.0003	0.26
SST Trans Miles	*5300*	*4700*	*-0.0001*	*-0.08*
Boom/Bust	0%	1%	0.0000	0.00

In summary, the CANDU reactor alternative offers some advantages, but would require the cooperation of the Canadian government to implement. This alternative is also judged to offer some possible advantages in encouraging Russian cooperation, but may be perceived as in conflict with U.S. policies regarding the Civil Use of Plutonium. In addition, as mentioned previously in the discussion about other objectives and Table 2, this alternative would require the shipment of plutonium across international borders. The Existing LWR, Existing Facilities involves only domestic facilities and regulatory institutions, and appears to be the most desirable of the reactor alternatives based on the performance estimates currently available.

7.6.2 Non-reactor Alternatives

A comparison of the overall scores of the immobilization alternatives and the two borehole variants is shown in Figure 36. The Ceramic Can-in-Can and the Vitrification Can-in-Can alternatives receive virtually identical scores in the overall ranking. Therefore, the comparison between these two alternatives is a natural one to consider.

Figure 36 - Non-reactor Overall Ranking



The Vitrification Can-in-Can alternative is compared with the Ceramic Can-in-Can alternative in Table 12. The differences between these two alternatives are apparently minor ones, as might be anticipated by the small difference between their overall scores. The Ceramic Can-in-Can alternative is scored higher on the Diversion measure of Maximum Inventory*, but this difference is approximately offset by the estimates that it will require additional processing steps, which affect its evaluation on the Theft and Diversion measures. The other estimated differences in the two alternatives are very small in terms of absolute numbers and in terms of impact on the overall score. Given these extremely close forecasts of performance levels, it seems reasonable to assume that the choice between these two alternatives could be based on other considerations not formally considered in this analysis, as suggested in the discussion regarding Table 2.

Table 12 - Vitrification Can-in-Can vs. Ceramic Can-in-Can

Ceramic Can-in-Can	0.6907
Vitrif. Can-in-Can	*0.6905*
Difference	0.0002

Measure	Ceramic Can-in-Can Level	*Vitrif. Can-in-Can* Level	Difference	% of Total Difference
MAX Inventory*	0.0400	5.0000	0.0010	463.30
*No. Processing Steps**	*15*	*13*	*-0.0006*	*-261.50*
No. Processing Steps	*15*	*13*	*-0.0003*	*-127.54*
New Long-term Jobs	2,402	2,300	4.42E-05	20.90
MAX Pu Inventory	2.00	5.00	4.06E-05	19.18
Wrkr. Rad. Deaths	*1.5*	*1.4*	*-2.17E-05*	*-10.24*
Transport Deaths	*1.1910*	*1.1710*	*-8.66E-06*	*-4.10*
Pub. Rad. Deaths	2.45E-06	2.52E-06	3.00E-11	1.42E-05
Accident Risk	1.91E-06	1.98E-06	2.97E-11	1.41E-05

Finally, Table 13 shows a comparison between the Vitrification Can-in-Can alternative and the Borehole (Direct) alternative. The major difference between these alternatives is that the vitrification alternative is cheaper, both Investment and Life-cycle Costs, and starts sooner than Borehole (Direct). The Borehole does benefit from the increased irreversibility of the location of the material and a slight advantage in Time to Complete and Civil use of Plutonium. These measures receive lower weight in the evaluation and are overshadowed by the vitrification alternative's advantages.

Table 13 - Vitrification Can-in-Can vs. Borehole (Direct)

Vitrif. Can-in-Can	0.6905
Borehole (Direct)	*0.6249*
Difference	0.0657

Measure	Vitrif. Can-in-Can Level	*Borehole (Direct)* Level	Difference	% of Total Difference
Material Form	E	C	0.0281	42.82
Investment Cost	$580	$1,110	0.0230	34.96
Life-cycle Costs	$1,050	$1,500	0.0195	29.68
Time to Start	7	10	0.0183	27.84
Material Location	*R*	*B*	*-0.0169*	*-25.69*
*Measure Uncert.**	*20.0%*	*3.0%*	*-0.0044*	*-6.65*
Intn'l Class	N	Y	0.0026	3.91
*No. Processing Steps**	*13*	*6*	*-0.0019*	*-2.95*
Time to Complete	*11*	*10*	*-0.0014*	*-2.17*
Civil Use of Pu	*95*	*100*	*-0.0011*	*-1.67*
No. Processing Steps	*13*	*6*	*-0.0009*	*-1.44*
Type of NAS*	50%	30%	0.0007	1.13
*MAX Inventory**	*5.0000*	*2.0000*	*-0.0006*	*-0.90*
Measure Uncertainty	0.80%	1.60%	0.0005	0.79
Wrkr. Rad. Deaths	1.4	2.0	0.0002	0.36
SST Trans Miles	*5000*	*3500*	*-0.0002*	*-0.35*
New Long-term Jobs	2,300	1,884	0.0002	0.27
Transport Deaths	1.1710	1.3575	0.0001	0.12
MAX Pu Inventory	*5.00*	*2.00*	*-4.06E-05*	*-0.06*
Secondary Waste Gen	*1,859*	*1,850*	*-3.90E-06*	*-0.01*
Accident Risk	1.98E-06	2.05E-06	3.03E-11	4.62E-08
Pub. Rad. Deaths	*2.52E-06*	*2.46E-06*	*-2.64E-11*	*-4.02E-08*

Table 14 compares the Vitrification Can-in-Can and Existing LWR, Existing Facilities alternatives. As shown in Figure 23, Vitrification Can-in-Can benefits from the lowest Investment Cost of all alternatives (this distinction is shared with Ceramic Can-in-Can). In addition, all of the vitrification alternatives start earlier than the reactor alternatives due to delays in establishing the MOX operations. The Existing Reactor is better in terms of Russian Cooperation and Worker Fatalities Radiation, but these advantages only partially offset the estimated benefits of the Vitrification Can-in-Can alternative.

Table 14 - Vitrification Can-in-Can vs. Existing LWR, Existing Facilities

Vitrif. Can-in-Can	0.6905
Exist LWR, Exist Fac	*0.6676*
Difference	0.0229

Measure	Vitrif. Can-in-Can Level	*Exist LWR, Exist Fac* Level	Difference	% of Total Difference
Russian Cooperation	*37.3*	*50.2*	*-0.0189*	*-82.27*
Investment Cost	$580	$980	0.0173	75.56
Start Year	7	9	0.0122	53.15
Life-cycle Costs	$1,050	$1,220	0.0074	32.12
*Measure Uncert.**	*20.0%*	*1.5%*	*-0.0073*	*-32.05*
Wrkr. Rad. Deaths	*1.4*	*-13.0*	*-0.0062*	*-27.24*
Time to Complete	11	15	0.0057	24.80
Civil Use of Pu	95	70	0.0055	23.92
Intn'l Class	N	Y	0.0026	11.19
No. Processing Steps*	13	22	0.0025	10.85
No. Processing Steps	13	22	0.0012	5.29
*MAX Inventory**	*5.0000*	*0.5000*	*-0.0009*	*-3.88*
No. of Trips	2	4	0.0009	3.72
Type of NAS*	50%	30%	0.0007	3.23
New Long Term Jobs	2,300	1,792	0.0002	0.96
Pub. Rad. Deaths	*0.0000*	*-0.3500*	*-0.0002*	*-0.66*
Secondary Waste Gen	1,859	2,151	0.0001	0.55
Accident Risk	0.0000	0.2803	0.0001	0.53
Transport Deaths	1.1710	1.3270	0.0001	0.29
MAX Pu Inventory	*5.00*	*0.50*	*-0.0001*	*-0.27*
SST Trans Miles	5000	5300	0.0000	0.20

8. Sensitivity Analysis

The base case analysis must be tested to see if the evaluation of alternatives is robust. This sensitivity analysis basically amounts to making changes in the weights on sub-objectives and measures, in assumptions underlying the base case analysis, or in the performance of alternatives on the measures, and observing changes in the resulting evaluations and rankings.

8.1 Changes in the Weights

8.1.1 Graphical Analysis

The most common form of sensitivity analysis in a MAU evaluation is to 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. In an evaluation of alternatives for a government agency, this approach to sensitivity analysis is particularly important, since different stakeholders may have very different values that would be expressed through different tradeoffs than the ones shown for the base case in Section 6, and these different tradeoffs would lead to different weights on the sub-objectives and measures. This sensitivity analysis has been separated into the two technology families because the graphs are otherwise too "busy" to interpret easily.

Figure 37a provides an example of the this type of sensitivity analysis based on the base case data for the reactor alternatives. The weight placed on the Non-proliferation objective is varied from 0 to 1 holding the ratios among all other weights unchanged. As shown in Figure 19, the current weight on the Non-proliferation sub-objective is .5072, which is indicated by the vertical line crossing the lower axis at .5072. The list of the reactor alternatives at the bottom of the figure is in rank order on this objective at the base case weight of .5072.

As the weight on the Non-proliferation objective approaches 1.00, the rankings of the reactor alternatives would be the same as the rankings shown in Figure 21 for the Non-proliferation sub-objective only. An inspection of Figure 37a suggests that relatively small changes in this weight would not lead to shifts in the rankings of the reactor alternatives. The score for the Evolutionary LWR alternative does increase with the weight on Non-proliferation because it is severely penalized by its relatively high Investment and Life-cycle Costs.

Figure 37b shows a similar analysis for the non-reactor options. This graph clearly demonstrates the superiority of the Vitrification Can-in-Can and Ceramic Can-in-Can alternatives relative to the other non-reactor alternatives. They consistently score well above all other alternatives as the weight on Non-proliferation varies from 0.0 to .95. Only when the Non-proliferation weight exceeds .95 does the Borehole (Immobilized) alternative approach and eventually surpass the score of the Can-in-Can alternatives.

Figure 37a - Sensitivity to Weight on Non-proliferation for Reactors

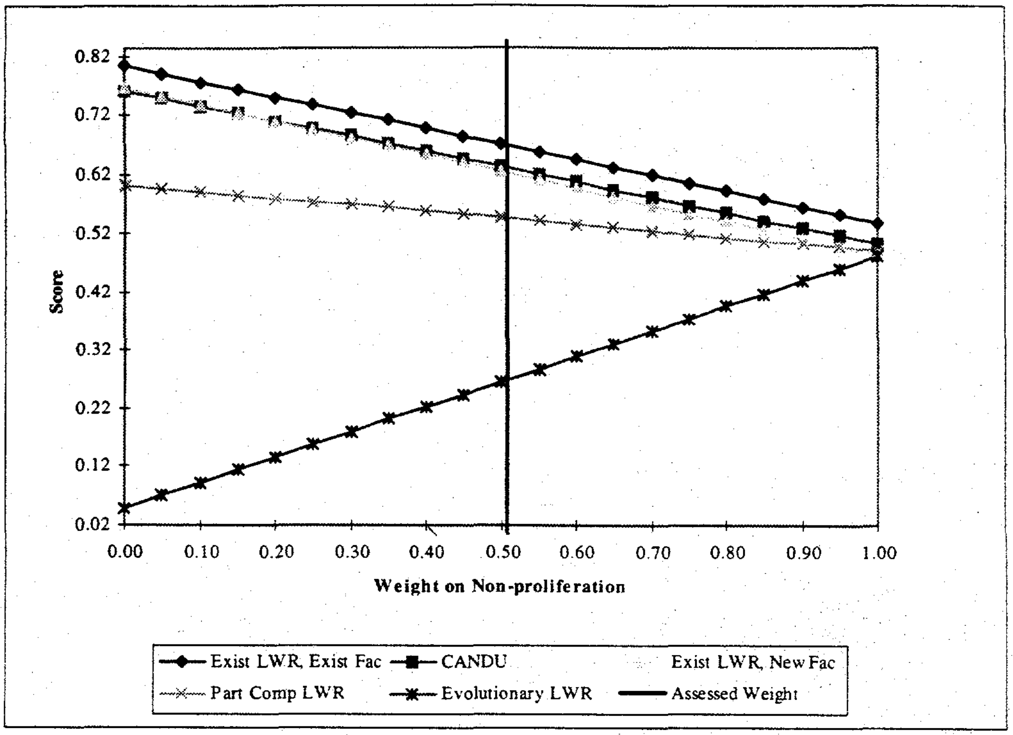
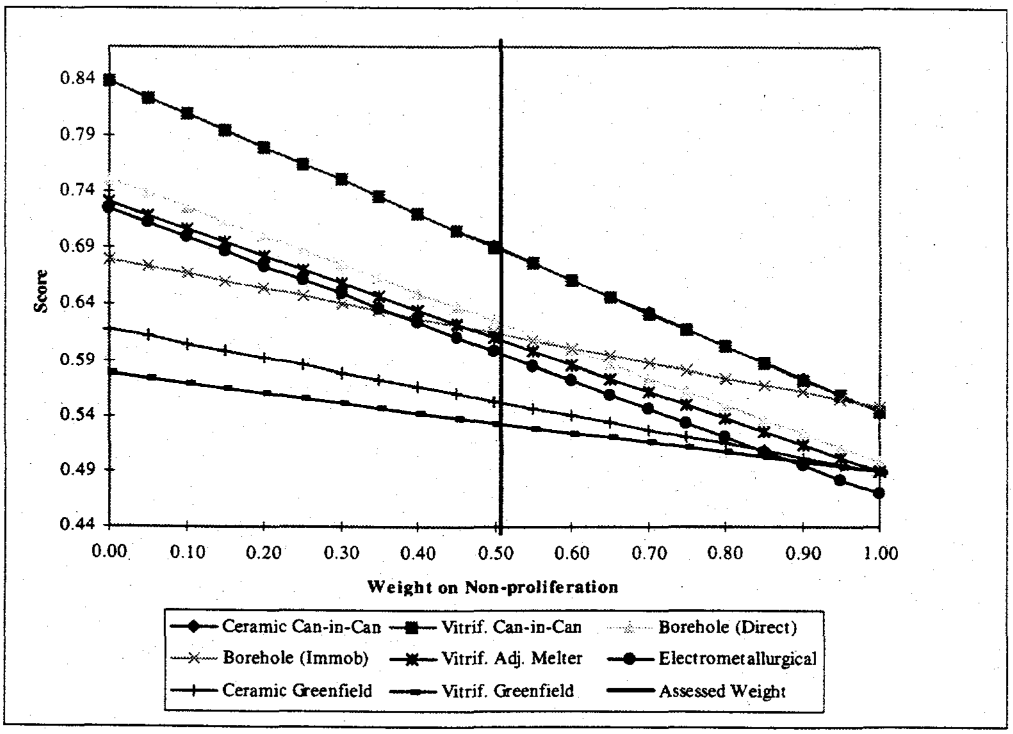


Figure 37b - Sensitivity to Weight on Non-proliferation for Non-reactors



Similar sensitivity graphs are shown for the reactor and non-reactor alternatives for changes in the weight on Operational Effectiveness in Figures 38a and 38b, and for changes in the weight on ES&H in Figures 39a and 39b. Among the reactor options, the Evolutionary LWR alternative suffers most from an increase in the weight on Operational Effectiveness, and among the non-reactor options the Ceramic and Vitrification Greenfield alternatives and the Borehole (Immobilized) alternative are also affected in a negative manner. Otherwise, the rankings of these alternatives within their technology families would shift somewhat, but do not show high sensitivity to relatively small changes in the Operational Effectiveness weight. Similar comments apply to the sensitivity of these rankings to changes in the ES&H weight.

Figure 38a - Sensitivity to Weight on Operational Effectiveness for Reactors

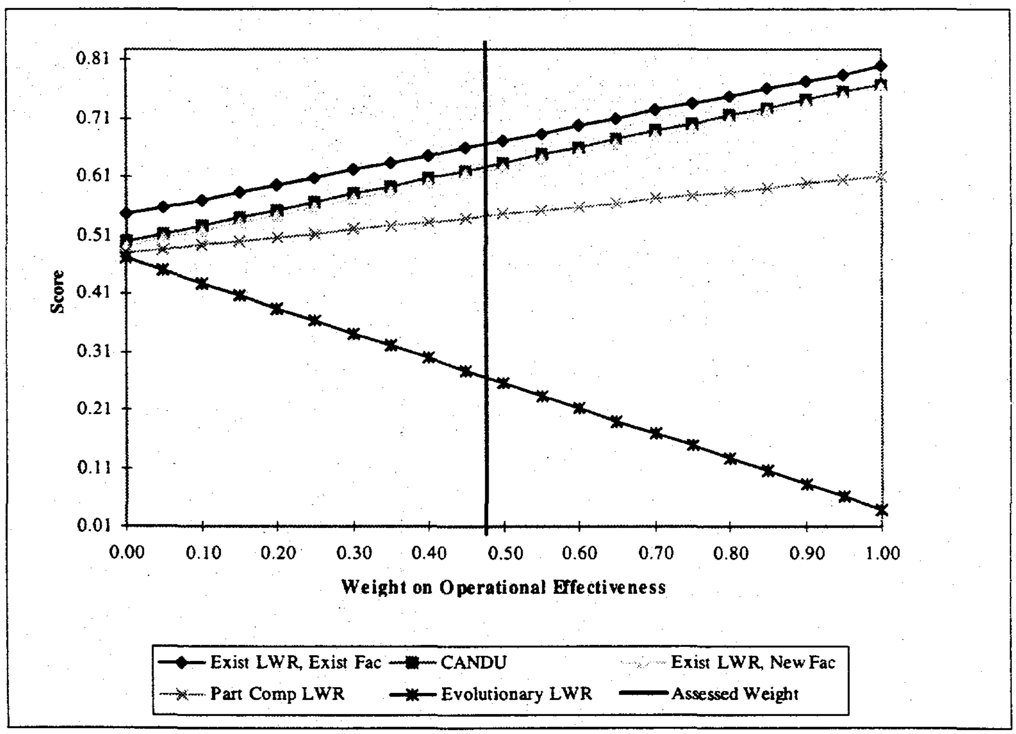


Figure 38b - Sensitivity to Weight on Operational Effectiveness for Non-reactors

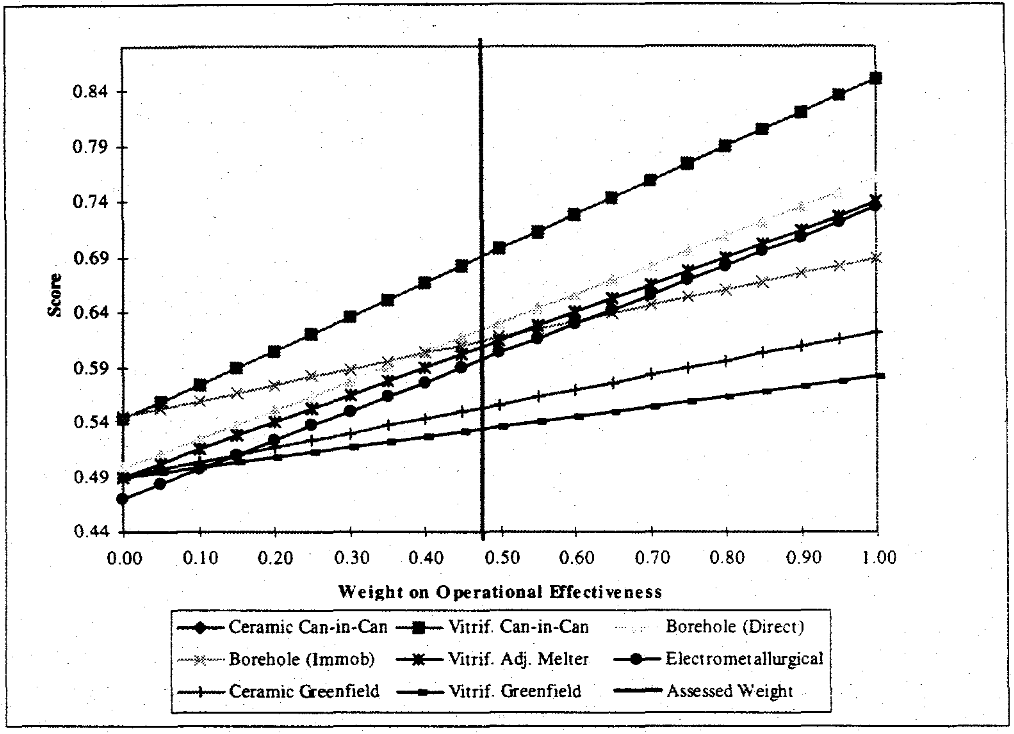


Figure 39a - Sensitivity to Weight on ES&H for Reactors

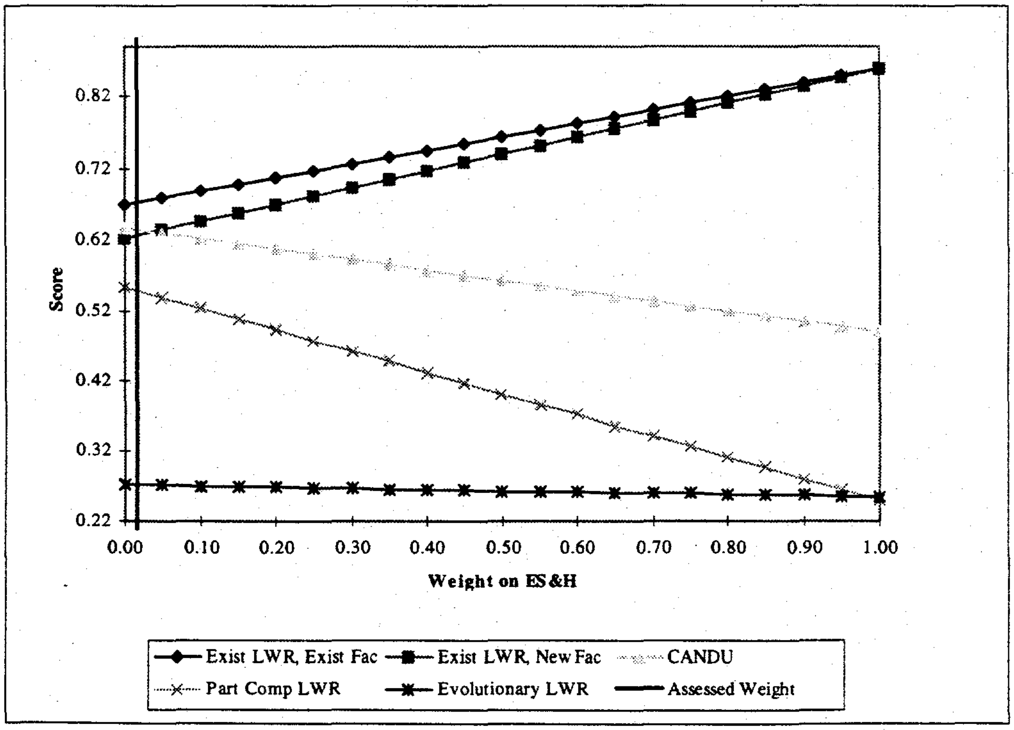
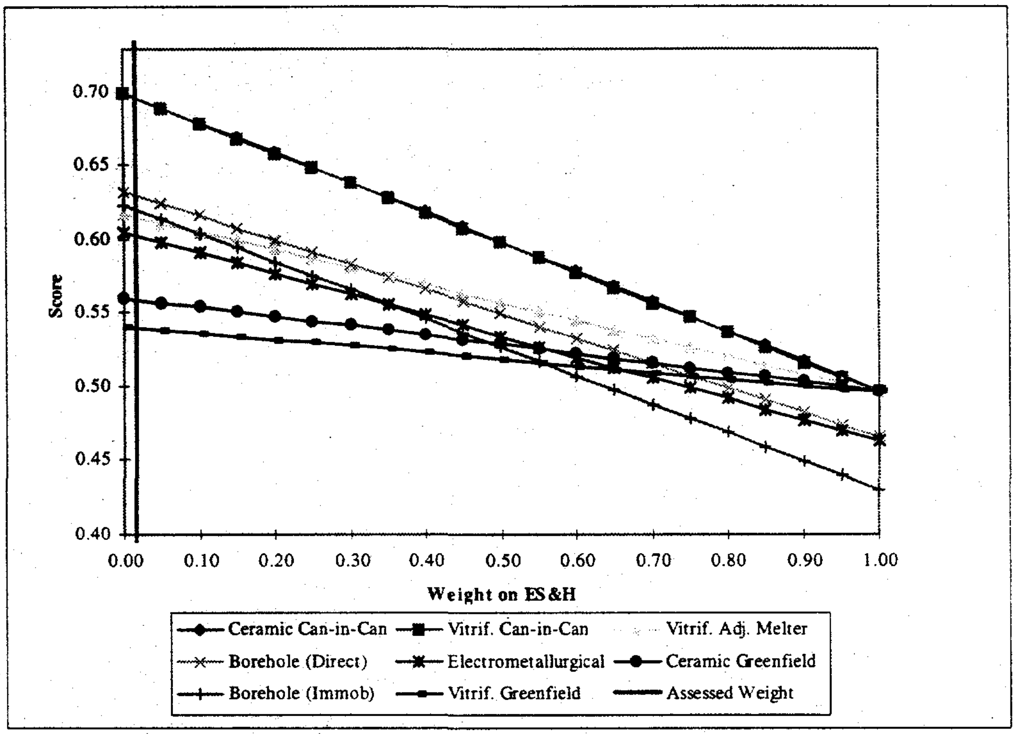


Figure 39b - Sensitivity to Weight on ES&H for Non-reactor Alternatives



Figures 40a and 40b show sensitivity graphs for the two measures associated with the International Cooperation sub-objective for all of the alternatives. These graphs suggest that the rankings of the alternatives are relatively sensitive to changes in the corresponding weights. As Figure 40a illustrates, a reduction in the weight on the measure Russian Cooperation would not lead to a significant change in the rankings of the alternatives, but an increase would favor the reactor alternatives relative to the immobilization and borehole alternatives. In contrast, an increase in the weight on the measure Civil Use of Plutonium would favor the immobilization and borehole alternatives.

Figure 40a - Sensitivity to Weight on Russian Cooperation

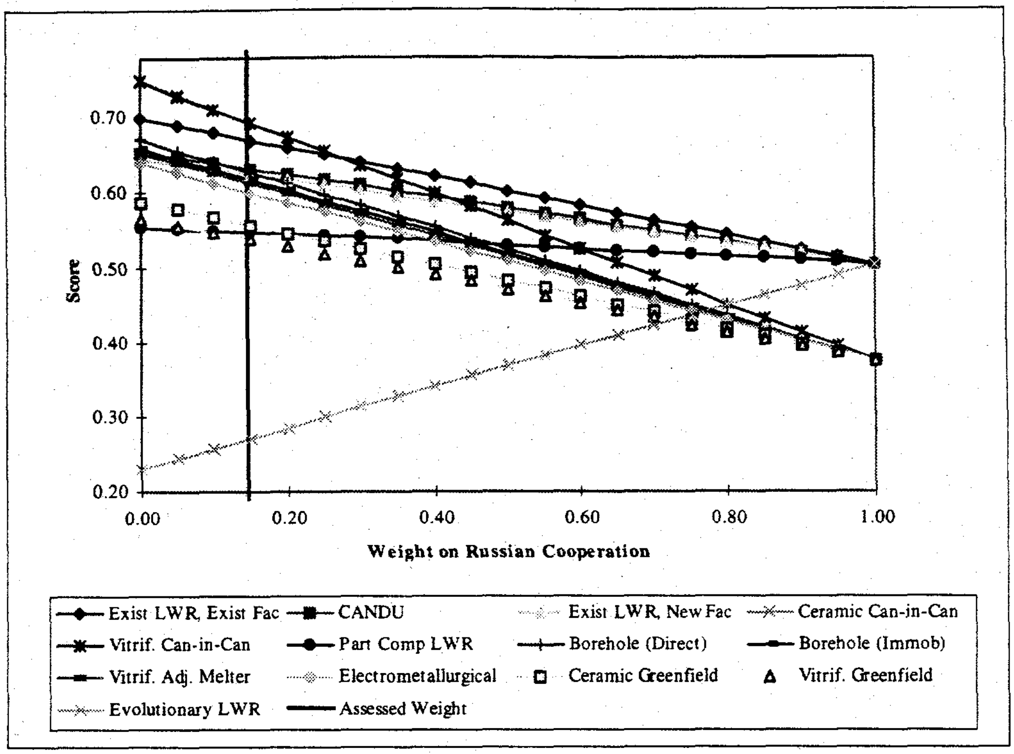
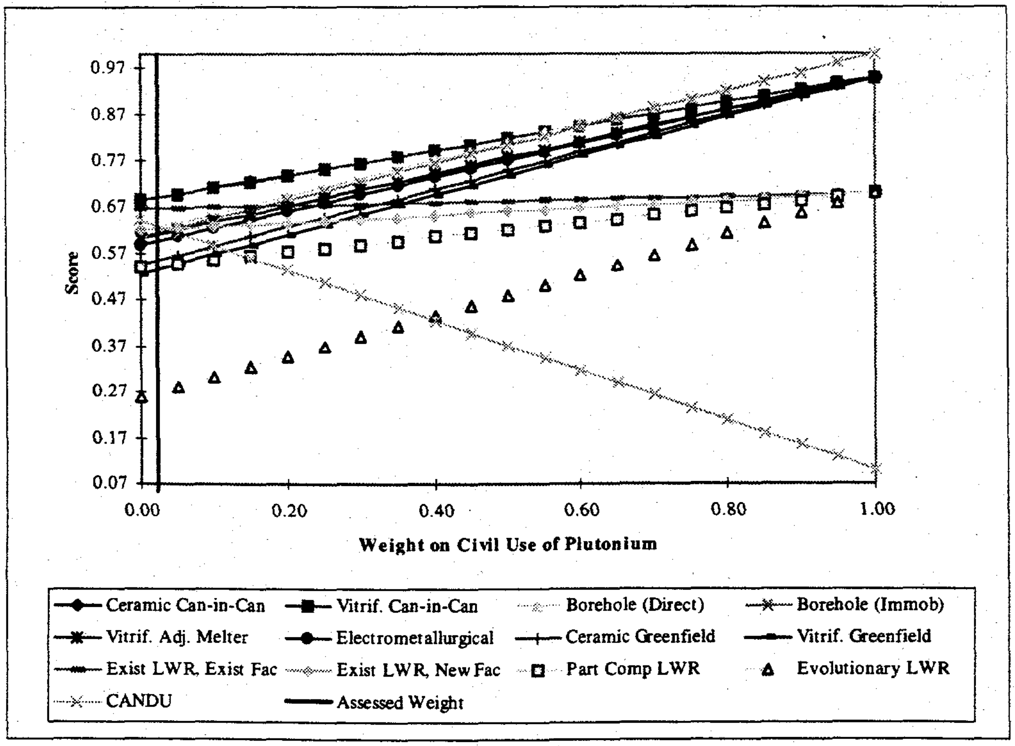


Figure 40b - Sensitivity to Weight on Civil Use of Plutonium



Similar sensitivity graphs are shown for selected sub-objectives and measures in Appendix E. An inspection of these graphs suggests that the rankings of the reactor alternatives are relatively more sensitive to changes in the weights on Investment Costs and International Cooperation, while the non-reactor alternatives are relatively more sensitive to changes in the weights on Time to Start and Cost.

8.1.2 Simulation Analysis

The sensitivity analysis presented in the previous sections provides insights regarding changes in one sub-objective or measure weight at a time. It is also useful to explore the results of changing all of the weights, perhaps simultaneously, in order to explore the robustness of the rankings of the alternatives in more detail. However, it would be extremely tedious to try to explore all reasonable combinations of values for the weights one at a time.

As an alternative to changing weights one at a time, weights have been selected at random using a simple computer simulation program so that the results of many combinations of weights can be explored in an efficient manner. In addition, this simulation study provides a convenient means of testing the robustness of the MAU results to the use of the additive MAU model (1) rather than the multiplicative model (2).

The base case analysis is based on the use of an additive MAU model (1). Although the assessment meetings with S&S and OFMD personnel indicated that this was a reasonable assumption, this simulation study allows for the possibility that some substructures of the MAU model are multiplicative, which implies some interaction effects between measures on the objectives. For example, though Safeguards and Security measures are always important, they may be considered relatively less important when the material in process is spent fuel rather than pits. In other words, a good score on Material characteristics might substitute or compensate for a lower score in Safeguards and Security. To incorporate this relationship, a multiplicative utility model must be used. The multiplicative model (2) includes the additive relationship (1) as a special case (Keeney and Raiffa, 1976).

Simulation models

Three types of simulation models were used to explore the robustness of the rankings relative to changes in the weights, and to the use of a multiplicative rather than an additive MAU model. For a complete description of the simulation methodology, see Butler, Jia, Dyer (1997)

Random weights

As an extreme case, weights for the measures can be generated completely at random. This approach implies no knowledge whatsoever of the relative importance of the sub-objectives and measures. The procedure of generating *n* weights for an additive model amounts to generating *n*-1 first differences.[3] This process guarantees that the

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[3] To generate the additive weights for n-attribute case, we first select n - 1 random numbers from a uniform distribution on (0, 1) independently, then rank these numbers. Suppose the ranked numbers are: $1 \geq r_{(n-1)} \geq \ldots \geq r_{(2)} \geq r_{(1)} \geq 0$. The first differences of these ranked numbers (including the

weights are each between 0 and 1, the sum of the weights is one, and that the weight combinations are uniformly distributed on the hyperplane. Generation of multiplicative weights is slightly more complicated because while each measure weight is between 0 and 1, the weights generally do not sum to one. Butler, Jia, and Dyer (1997)outlines the procedure for randomly generating these weights.

Rank order weights

The idea of random weights ignores all judgments regarding the tradeoffs among the sub-objectives and measures, which may be considered unreasonable given general agreement that some objectives are "more important" than others. On the other hand, the exact weights used in the base case analysis may legitimately be questioned. For example, the assessed base case weights for the Non-proliferation, Operational Effectiveness, and ES&H objectives are 0.5072, 0.4764 and 0.0164 respectively. These numbers may imply an accuracy that is not appropriate for this analysis.

However, there may be general agreement with the order of weights for these three objectives; that is, most thoughtful reviewers of these results might agree, given the ranges of impacts associated with the alternatives, that the weight on the Non-proliferation objective should be larger than the weight on the Operational Effectiveness objective, which in turn should be larger than the weight on the ES&H objective. Given rank order information for weights, the random weights (of either the additive model or multiplicative model) generated above can be placed in a corresponding rank order and assigned to the corresponding measures. In this analysis, the rank order weights on the measures determined for the base case is maintained, but the weights are otherwise generated at random.

Response-error weights

The third type of sensitivity analysis using simulation recognizes that the weight assessment procedure is subject to response error. The idea is to consider the weights determined in the base case as responses obtained from possible distributions of responses. In order to use simulation to explore the implications of response error, the base case weights are treated as means of probability distributions, and weights are then chosen randomly from these distributions. Although this approach will result in choices of weights that are relatively close (depending on the assumption regarding the underlying distribution) to the actual weights, it may allow for the selection of weights that violate the rank order of the base case weights.[4]

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bounds 0 and 1) can be obtained as $w_n = 1 - r_{(n-1)}$, $w_{n-1} = r_{(n-1)} - r_{(n-2)}$, . . ., and $w_1 = r_{(1)} - 0$. Then, the set of numbers ($w_1, w_2, \ldots, w_n$) will be uniformly distributed on the possible domain of weights for an additive model.

[4] In this study, we use a Dirichlet distribution of weights is used for an additive model. Since the marginal distributions of Dirichlet are Beta distributions, the Dirichlet weights are well behaved (i.e., all weights range from 0 to 1, and the sum of the weights is equal to 1). The means of Beta distributions are required to be equal to the assessed weights in the base case model. The amounts of uncertainty (or response errors) in weights can be controlled by adjusting the sum of Dirichlet parameters. For a

Simulation results

The results of the sensitivity analyses using the three simulation approaches described above are presented in Tables 15, 16, 17a, and 17b. Each simulation study is based on 5000 iterations. For each iteration, a complete set of weights for the measures is selected using one of the three approaches, the scores are aggregated for the alternatives using these weights, and the ranking of each alternative is recorded. In each table, the Best Rank is the highest ranking achieved by the alternative across all 5000 sets of weights, and the Worst Rank is its lowest rank. The third and forth columns in the tables present the mean and mode ranks for all 5000 iterations. In all cases, it was assumed that the additive model applied to all objectives and sub-objectives except for Theft and Diversion. In these two Non-proliferation sub-objectives, a multiplicative model was used. As mentioned earlier, this assumption was used because discussions with the S&S team indicated that some of the measures were "substitutes" in economic terminology. In other words, excellent performance on Material Characteristics could offset poor performance on the sub-objective Environment, because it is less important to accurately account for spent fuel compared to pits.

The last five columns in the tables provide percentile results. For example, the 25% column for an alternative is a ranking such that in 25 percent of the 5000 iterations (or in 1250 of the 5000 iterations) the alternative achieved this rank or a better one.

When the selection of the weights is completely random, the results in Table 15 indicate that every alternative is ranked third or higher for at least one set of the 5000 sets of weights generated, and that every alternative is ranked ninth or lower. This result is not surprising, since none of the alternatives are completely dominated by another alternative. With 5000 randomly generated sets of weights, a relatively large weight is likely to be generated on one or more measures in which each alternative performs relatively well; likewise, a large weight will be generated for the measure or measures on which an alternative does not score well, leading to low rankings.

For the random weights, the mean and mode ranks are perhaps more meaningful. Alternatives that rank high on these measures would tend to be those that perform well on a majority of the performance measures. The Ceramic Can-in-Can alternative has the best mean and mode. The Vitrification Can-in-Can and Existing Reactor, Existing Facilities also score well with random weights, while the Evolutionary Reactor, Partially Complete Reactor, and Vitrification Greenfield alternatives appear to be inferior. In fact, there was no combination of weights generated which lead to the Evolutionary LWR, CANDU or Vitrification Greenfield alternative being the most preferred.

Table 16 presents similar results for the simulation model that maintains the same rank order of weights for the measures as those provided in the base case, but otherwise selects values for the weights at random. With this additional restriction, the best and worst ranks for many of the alternatives are closer together, although there is still considerable variability. The Ceramic Can-in-Can alternative is still superior according to the mean and mode averages. Alternatives requiring new facilities, including the Partially

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multiplicative model, independent Beta distributions for weights are used, and the normalized weights (sum to 1) are required to have means equal to the assessed weights.

Complete and Evolutionary reactors, appear to have dropped in the rankings. This lowering in rank order suggests that these alternatives scored relatively low on the measures that were assessed as having the higher weights.

Finally, Tables 17a and 17b show results for two simulation studies that use the base case weights as means of probability distributions, and sample from these distributions to obtain results for each iteration. The variances associated with these distributions in Table 17a are relatively large, while the variances associated with these distributions in Table 17b are relatively small. A graphical depiction of these differences is provided in Appendix F.

Although comparisons of these Tables with each other and with Tables 15 and 16 reveal some differences, the basic conclusions are still the same. The 95% column is particularly interesting in Table 17b, since it indicates that the base case results are very robust given relatively small variations around the base case weights.

Table 15 - Ranking Based on Random Weights

Alternative	*Best rank*	*Worst rank*	*Mean rank*	*Ranking Mode*	*5% Perc*	*25% Perc*	*50% Perc*	*75% Perc*	*95% Perc*
Exist LWR, Exist Fac	1	11	3.57	3	1	1	3	5	9
Part Comp LWR	1	13	10.57	12	5	10	12	12	12
Exist LWR, Green Fac	1	13	5.74	2	2	4	5	8	11
Evolutionary LWR	3	13	12.79	13	12	13	13	13	13
CANDU	2	13	8.64	11	5	7	9	11	12
Vitrif. Greenfield	3	12	9.61	11	5	8	10	11	12
Vitrif. Can-in-Can	1	10	2.65	2	1	2	2	4	4
Vitrif. Adj. Melter	1	10	5.28	5	3	4	5	6	8
Ceramic Greenfield	1	11	7.98	10	4	6	8	10	11
Ceramic Can-in-Can	1	9	1.85	1	1	1	1	3	4
Electrometallurgical	1	13	8.61	8	6	7	8	10	12
Borehole (Direct)	1	13	5.98	5	3	5	6	7	10
Borehole (Immob)	1	12	7.74	9	2	6	9	10	11

Table 16 - Ranking Based on Order Weights

Alternative	*Best rank*	*Worst rank*	*Mean rank*	*Ranking Mode*	*5% Perc*	*25% Perc*	*50% Perc*	*75% Perc*	*95% Perc*
Exist LWR, Exist Fac	1	9	2.41	1	1	1	3	3	5
Part Comp LWR	3	12	11.71	12	10	12	12	12	12
Exist LWR, Green Fac	2	13	6.10	4	2	4	6	8	10
Evolutionary LWR	8	13	12.98	13	13	13	13	13	13
CANDU	2	13	8.19	11	4	6	8	11	12
Vitrif. Greenfield	6	12	10.50	11	8	10	11	11	12
Vitrif. Can-in-Can	1	5	2.36	2	1	2	2	3	4
Vitrif. Adj. Melter	4	10	6.24	6	5	6	6	7	8
Ceramic Greenfield	5	11	9.26	10	7	9	10	10	10
Ceramic Can-in-Can	1	6	1.78	1	1	1	2	2	3
Electrometallurgical	5	13	8.38	9	7	8	8	9	10
Borehole (Direct)	1	13	5.78	5	3	4	5	7	9
Borehole (Immob)	1	10	5.30	4	3	4	5	7	8

Table 17a - Ranking Based on Partial Weights (Sum of Dirichlet Parameters = 30)

Alternative	*Best rank*	*Worst rank*	*Mean rank*	*Ranking Mode*	*5% Perc*	*25% Perc*	*50% Perc*	*75% Perc*	*95% Perc*
Exist LWR, Exist Fac	1	4	2.90	3	1	3	3	3	3
Part Comp LWR	7	12	11.03	12	10	10	11	12	12
Exist LWR, Green Fac	2	10	6.00	6	4	5	6	7	8
Evolutionary LWR	13	13	13.00	13	13	13	13	13	13
CANDU	4	10	4.90	4	4	4	5	5	7
Vitrif. Greenfield	11	12	11.64	12	11	11	12	12	12
Vitrif. Can-in-Can	1	4	1.86	2	1	2	2	2	2
Vitrif. Adj. Melter	5	9	7.28	7	6	7	7	8	8
Ceramic Greenfield	9	11	10.31	10	10	10	10	11	11
Ceramic Can-in-Can	1	4	1.25	1	1	1	1	1	2
Electrometallurgical	7	10	8.84	9	8	9	9	9	9
Borehole (Direct)	3	9	5.39	5	4	5	5	6	8
Borehole (Immob)	3	10	6.60	7	4	6	7	8	9

Table 17b - Ranking Based on Partial Weights (Sum of Dirichlet Parameters = 100)

Alternative	*Best rank*	*Worst rank*	*Mean rank*	*Ranking Mode*	*5% Perc*	*25% Perc*	*50% Perc*	*75% Perc*	*95% Perc*
Exist LWR, Exist Fac	1	3	2.99	3	3	3	3	3	3
Part Comp LWR	10	12	11.04	11	10	11	11	11	12
Exist LWR, Green Fac	4	9	5.89	6	4	5	6	7	8
Evolutionary LWR	13	13	13.00	13	13	13	13	13	13
CANDU	4	8	4.52	4	4	4	4	5	6
Vitrif. Greenfield	11	12	11.76	12	11	12	12	12	12
Vitrif. Can-in-Can	1	3	1.92	2	1	2	2	2	2
Vitrif. Adj. Melter	6	8	7.67	8	7	7	8	8	8
Ceramic Greenfield	10	11	10.20	10	10	10	10	10	11
Ceramic Can-in-Can	1	3	1.09	1	1	1	1	1	2
Electrometallurgical	8	9	8.99	9	9	9	9	9	9
Borehole (Direct)	4	8	5.22	5	4	5	5	6	7
Borehole (Immob)	4	9	6.70	7	5	6	7	7	8

8.2 Sensitivity to Assumptions

In addition to changes in the weights, it is also worthwhile to explore the sensitivity of the analysis to changes in some of the assumptions in the base case data and evaluation model. The first change to be explored is related to the notion of the "spent fuel" standard as the appropriate criterion for the end result of the plutonium disposition process. The impacts of other approaches to the aggregation of S&S measures for Theft and Diversion will also be investigated. In addition, the implications of ignoring Investment Costs in favor of exclusively focusing on Life-cycle Costs will be shown, along with alternative approaches for valuing worker and public fatalities avoided.

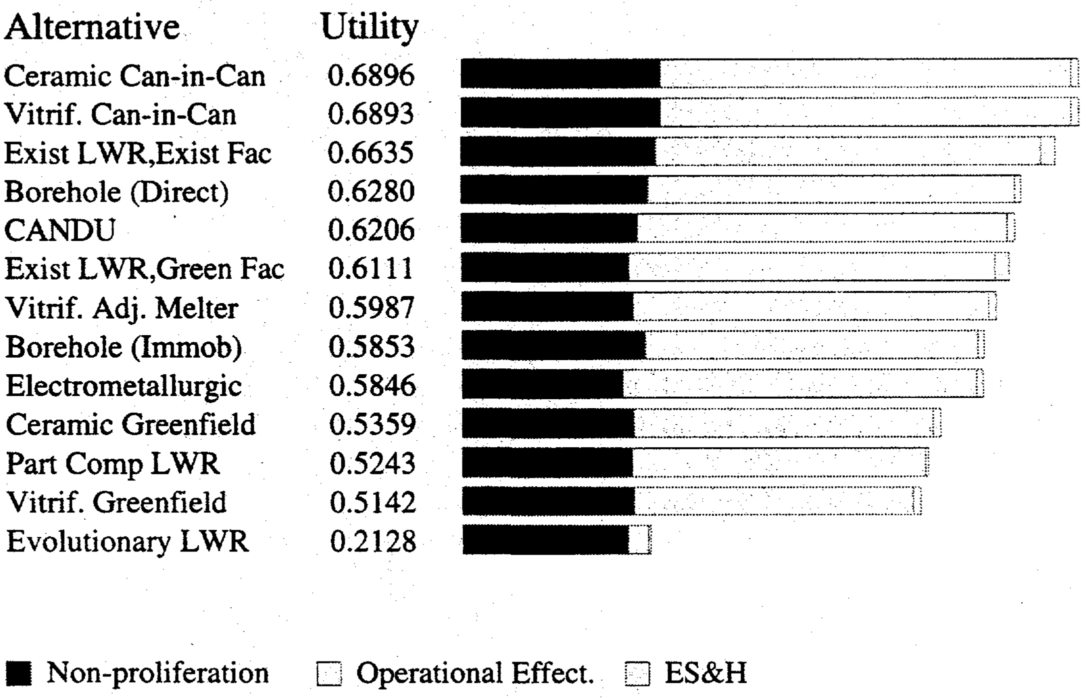
8.2.1 Irreversibility

The sub-objective Irreversibility is decomposed into the two measures, Material Form and Location. This sub-objective and the two measures focus on the final result of the plutonium disposition effort, and consider the degree to which the material would be attractive to the host nation for potential retrieval and reuse. In fact, the performances of the alternatives on these two measures were judged equal for all of the alternatives, except for the borehole variants. They received a higher valued performance measure score due to the inaccessibility of the material in the borehole, although the Borehole (Direct) alternative received a lower valued performance measure score due to its material form.

In contrast, the argument has been made that the objective of a plutonium disposition effort should be to meet the "spent fuel standard", which means that the material would be more difficult to retrieve and reuse for the purpose of creating weapons-usable plutonium than the alternative of retrieving and reusing material from spent fuel from existing nuclear reactors (e.g., see the discussion of the spent fuel standard in [NAS 94]). According to this point of view, no "bonus" value should be assigned to disposition alternatives that go beyond the spent fuel standard.

In order to test the sensitivity of the results to adopting this point of view, the analysis was repeated after removing the Irreversibility sub-objective (effectively setting its weight to 0.0 and maintaining the ratios between all other weights). The new overall ranking of the alternatives is shown in Figure 41. As expected, a comparison with the overall ranking for the alternatives for the base case shown in Figure 34 reveals that the Borehole (Immobilization) alternative has moved down, while the Borehole (Direct) alternative has moved up. Nevertheless, both borehole alternatives are ranked behind two immobilization alternatives and one reactor alternative.

Figure 41 - Overall Ranking if Irreversibility Sub-objective Removed



8.2.2 Aggregation of S&S Measures

The base case analysis is based on an aggregation of scores for the Non-proliferation sub-objectives Theft and Diversion using the "weak link" concept. As discussed in Section 4.5, the alternatives for disposal require that materials be processed in two or more facilities. The "weak link" approach uses the performance measures for the facility for each alternative that is identified as the lowest ranked of the facilities on the Theft and Diversion measures, respectively.

As an alternative, the Theft and Diversion measures can be based on the "weighted average" of the scores of the facilities associated with an alternative, where the "weight" is the proportion of processing steps required at the facility (see Section 4.5 for additional details). The evaluation of the alternatives was repeated for this "weighted average" approach, as shown in Figure 42. A comparison of the overall results with the "weak link" rankings in Figure 34 shows only minor variations; the Ceramic Can-in-Can and the

Vitrification Can-in-Can alternatives switch ranks, as do the Borehole (Direct) and the CANDU.

This change only affects the Theft and Diversion sub-objectives, so Figures 43a, 43b, and 43c show the rankings for the Non-proliferation objective, as well as for Theft and Diversion. Comparisons with the corresponding base case bar graphs again show only minor changes in the relative rankings of the alternatives.

Figure 42 - Overall Ranking Using Weighted Average S&S Scores

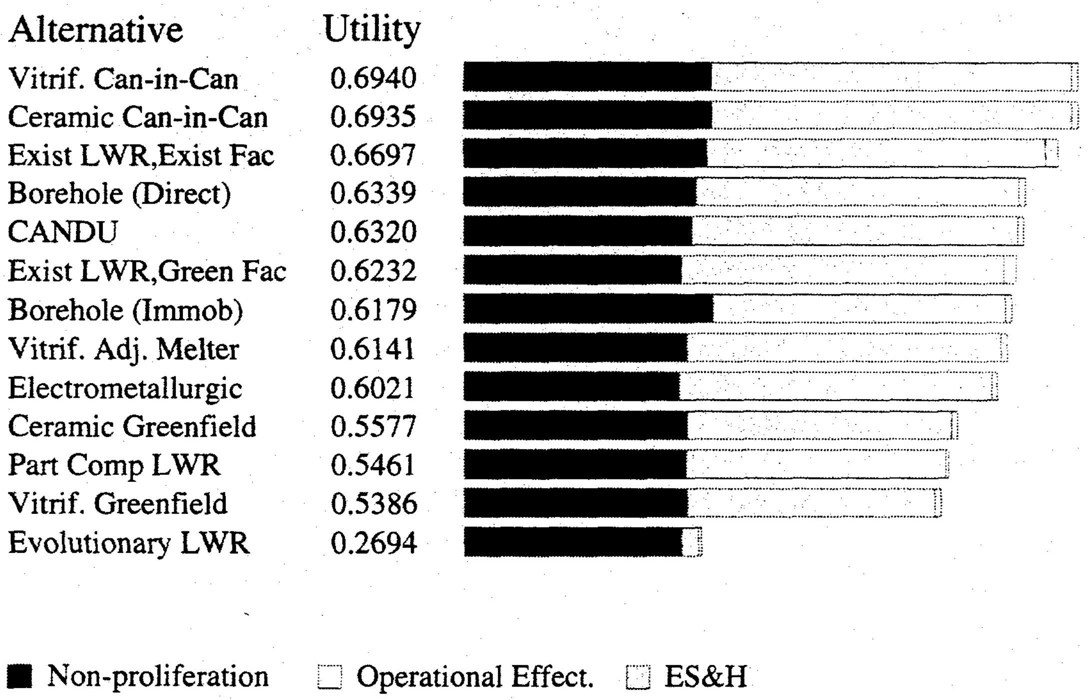


Figure 43a - Non-proliferation Ranking using Weighted Average S&S Scores

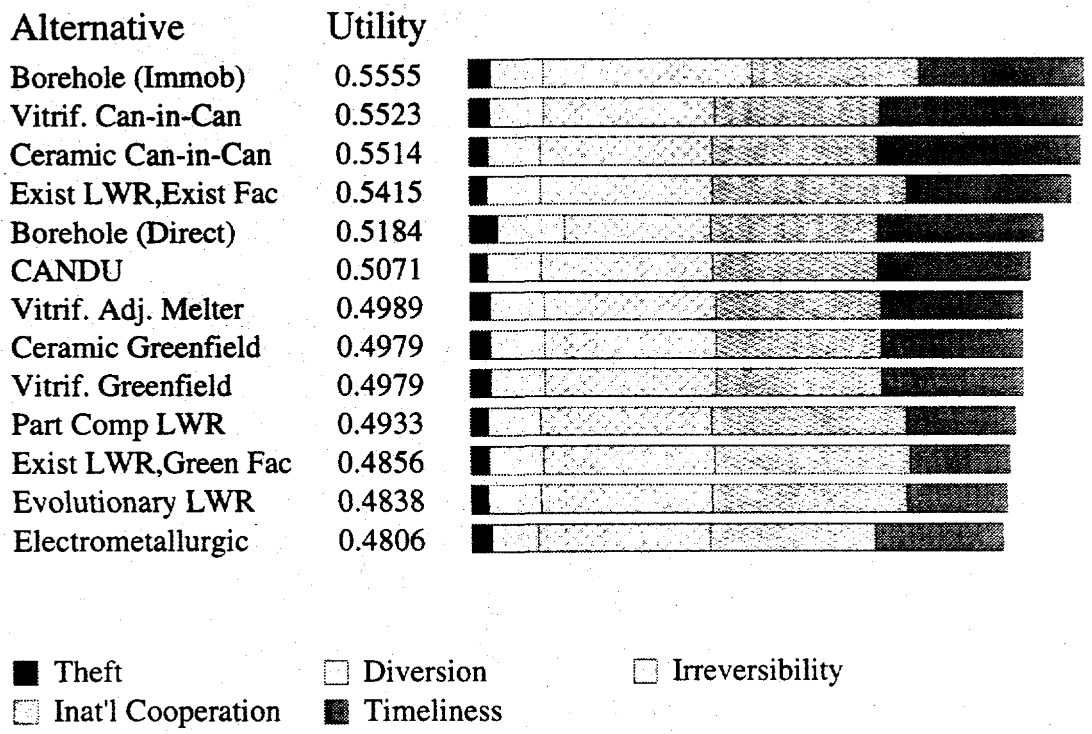


Figure 43b - Theft Ranking using Weighted Average S&S

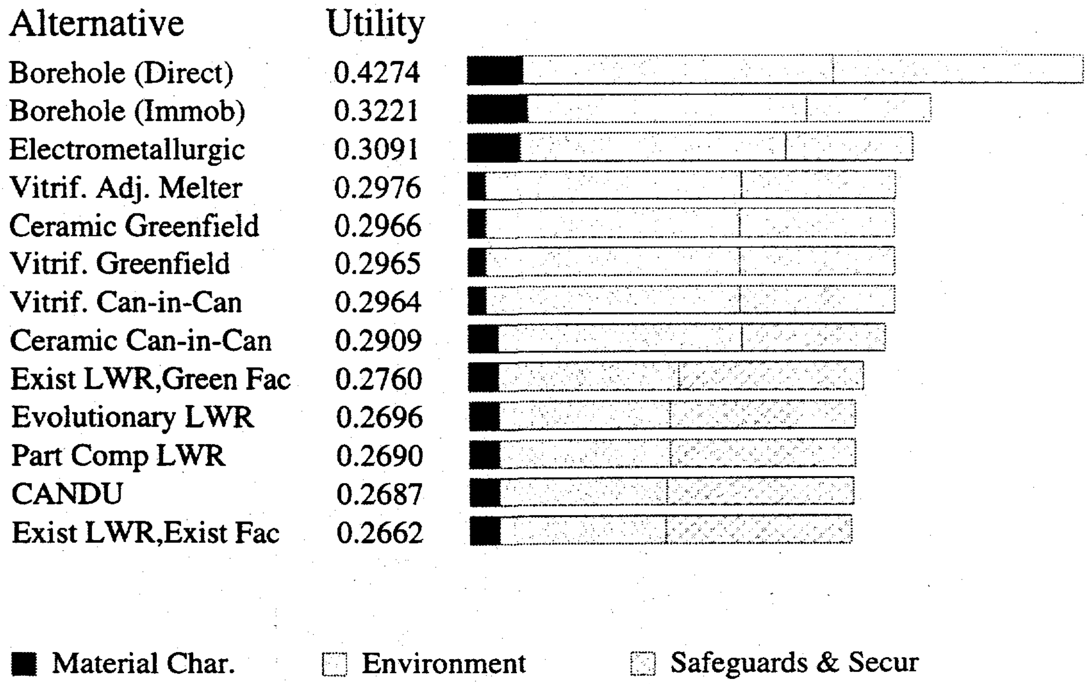
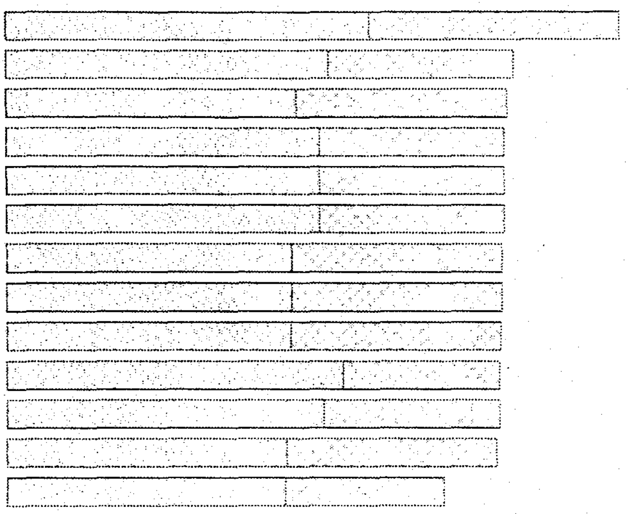


Figure 43c - Diversion Ranking using Weighted Average for S&S

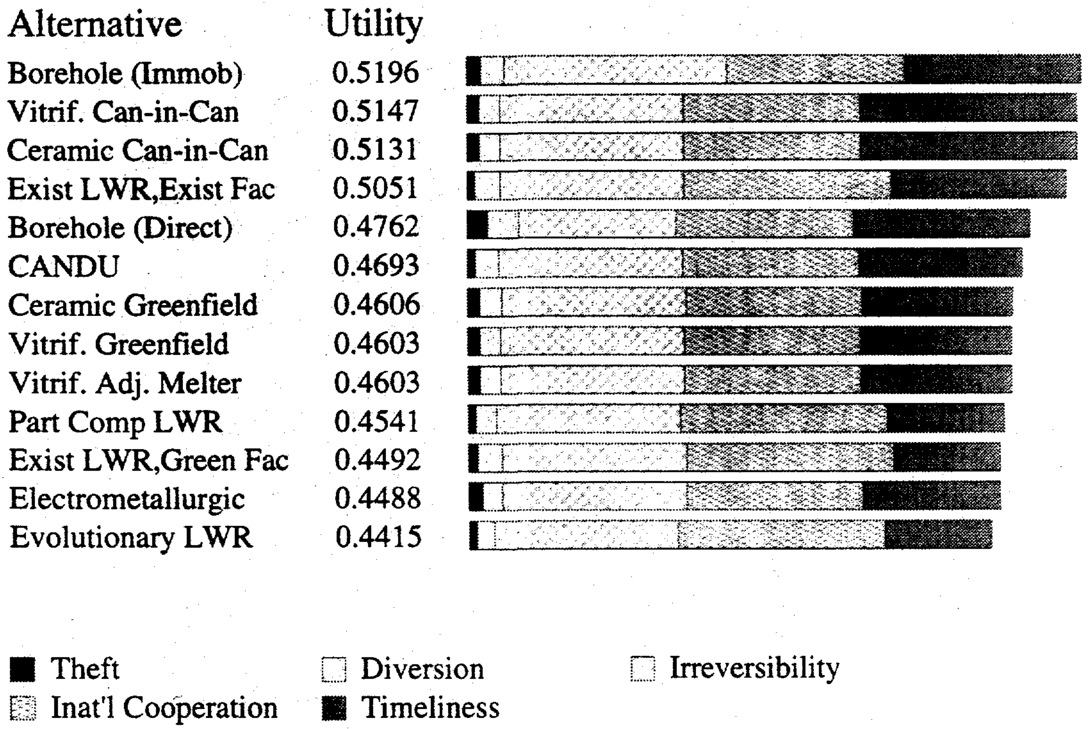
Alternative	Utility
Borehole (Direct)	0.3692
Vitrif. Adj. Melter	0.3058
CANDU	0.3025
Ceramic Greenfield	0.3000
Vitrif. Greenfield	0.2997
Vitrif. Can-in-Can	0.2997
Exist LWR,Green Fac	0.2987
Exist LWR,Exist Fac	0.2987
Part Comp LWR	0.2973
Borehole (Immob)	0.2962
Ceramic Can-in-Can	0.2959
Evolutionary LWR	0.2952
Electrometallurgic	0.2626



Finally, another evaluation was carried out for the "worst case" approach to aggregating the Theft and Diversion sub-objectives (see Section 4.5 for a discussion). The overall rankings using this approach are not shown, as they are also identical to the base case, except that Existing LWR, Greenfield Facilities and Borehole (Direct) are virtually tied at sixth, rather than fifth and sixth in the base case.

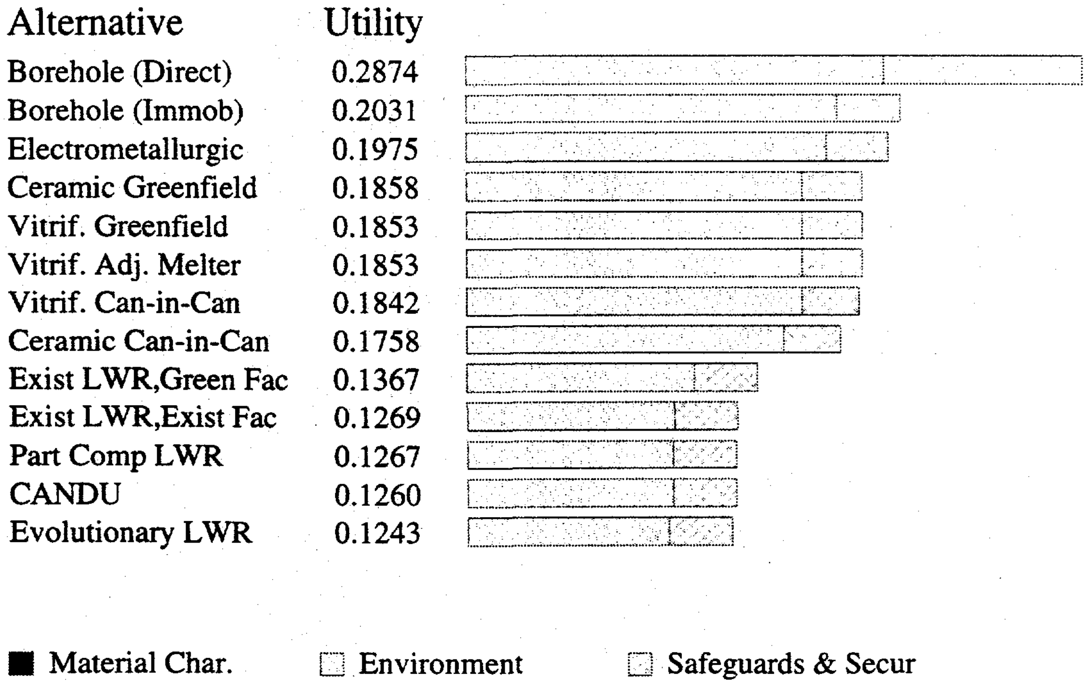
Again, the Theft and Diversion sub-objectives are the only ones affected by this change, so Figures 44, 45a, and 45b present the rankings for Non-proliferation and for these two affected sub-objectives. There are only minor changes in the rankings among the alternatives on the Non-proliferation objective, and for the Theft sub-objective. As shown in Figure 45b, the rankings for the Diversion sub-objective do vary somewhat, with the vitrification alternatives moving up as a group, and the Partially Completed LWR moving down in the rankings.

Figure 44 - Non-proliferation Ranking using Worst Case for S&S



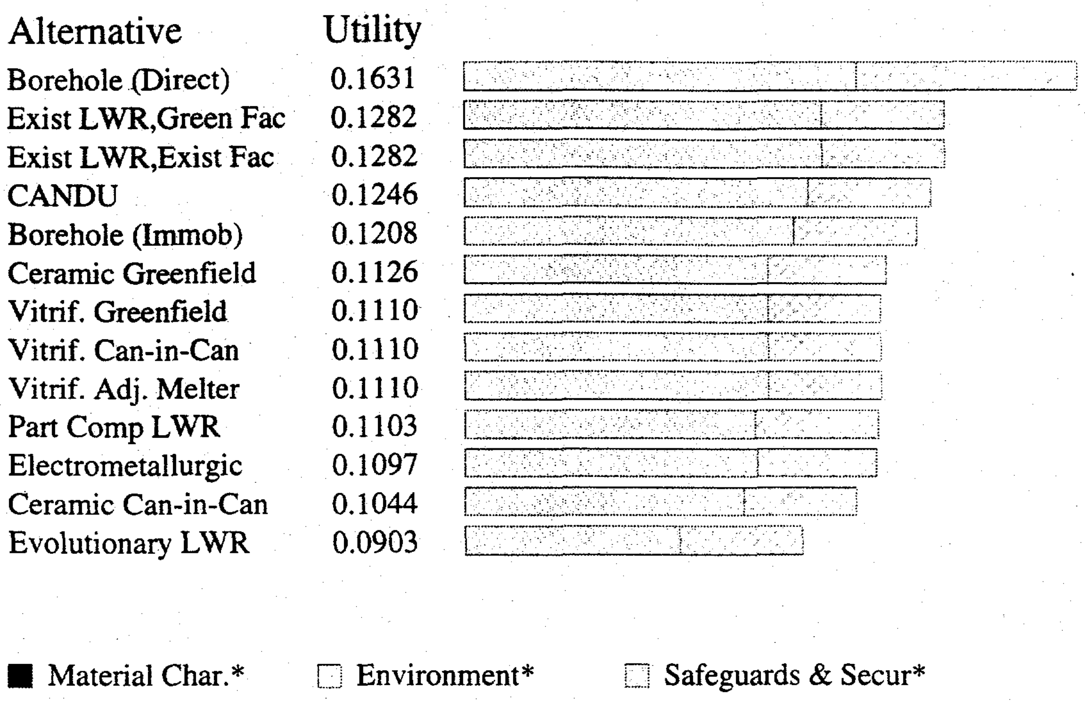
Alternative	Utility
Borehole (Immob)	0.5196
Vitrif. Can-in-Can	0.5147
Ceramic Can-in-Can	0.5131
Exist LWR,Exist Fac	0.5051
Borehole (Direct)	0.4762
CANDU	0.4693
Ceramic Greenfield	0.4606
Vitrif. Greenfield	0.4603
Vitrif. Adj. Melter	0.4603
Part Comp LWR	0.4541
Exist LWR,Green Fac	0.4492
Electrometallurgic	0.4488
Evolutionary LWR	0.4415

Figure 45a - Theft Ranking using Worst Case for S&S



Alternative	Utility
Borehole (Direct)	0.2874
Borehole (Immob)	0.2031
Electrometallurgic	0.1975
Ceramic Greenfield	0.1858
Vitrif. Greenfield	0.1853
Vitrif. Adj. Melter	0.1853
Vitrif. Can-in-Can	0.1842
Ceramic Can-in-Can	0.1758
Exist LWR,Green Fac	0.1367
Exist LWR,Exist Fac	0.1269
Part Comp LWR	0.1267
CANDU	0.1260
Evolutionary LWR	0.1243

Figure 45b - Diversion Ranking using Worst Case for S&S



8.2.3 Life-cycle Cost Model

The current debate in Congress indicates a general agreement in both political parties that progress should be made toward a balanced budget within a relatively short time period. This focus suggests that initial Investment Costs may influence the choice among alternatives for plutonium disposition, with those alternatives that require smaller initial government funding commitments being favored. An alternative view is that initial Investment Costs should not matter if they are offset by lower costs or positive revenue streams in the future, so the only relevant measure of cost is properly discounted Life-cycle Costs which includes the Investment Cost. Figures 46 and 47 show the impact of eliminating the measure Initial Investment Costs from the analysis, but adding its "weight" to the weight on Life-cycle Cost so that the same total weight is allocated to the Cost sub-objective.

Figure 46 - Overall Ranking After Removing Investment Cost

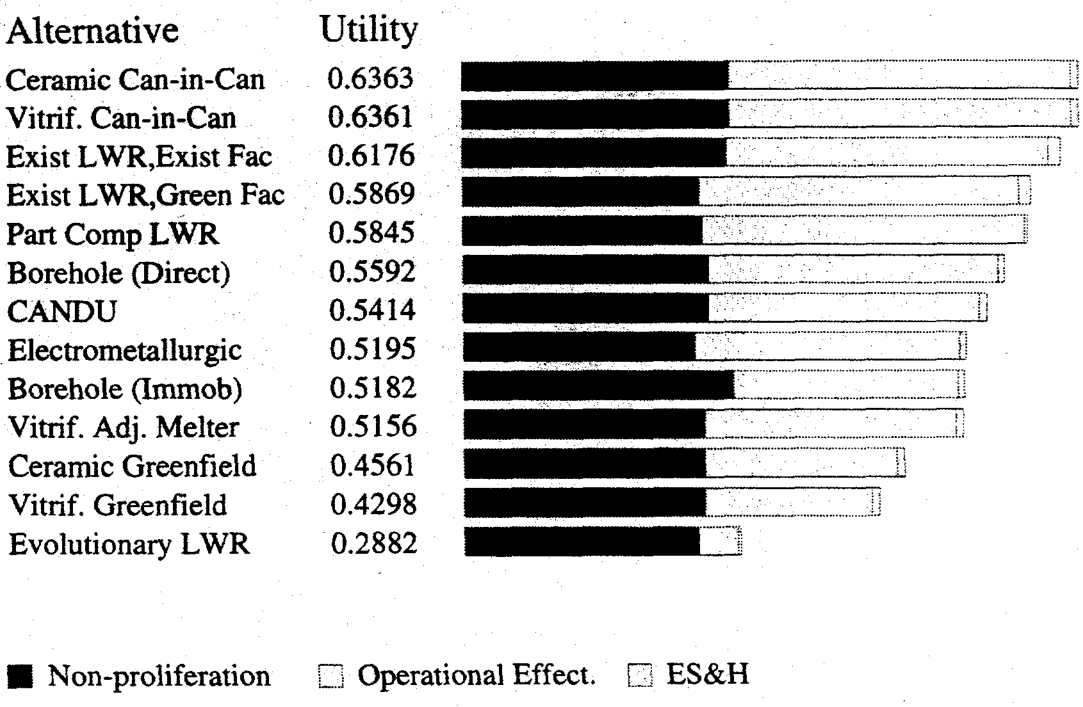
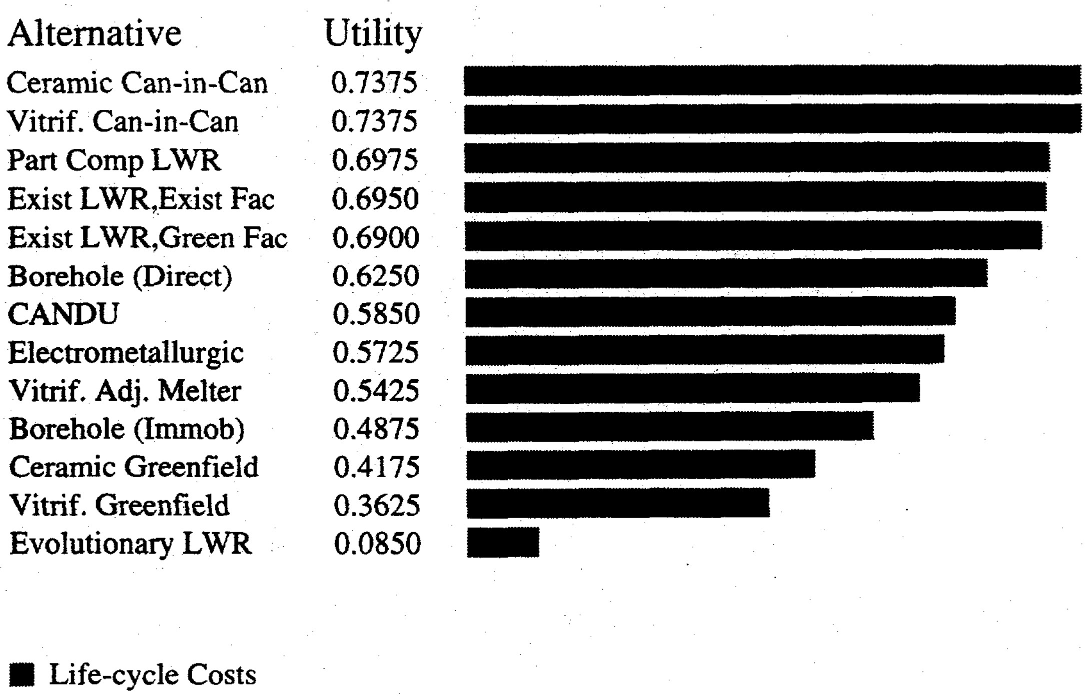


Figure 47 - Operational Effectiveness Ranking After Removing Investment Cost



The alternatives most affected by the removal of Investment Cost as a separate measure are the Existing LWR, Greenfield and the Partially Completed LWR. In particular, the Partially Completed LWR moves from an overall ranking of twelve to a ranking of five when the Investment Costs are removed as a separate measure, although it is still ranked behind the two Existing LWR alternatives. Also, the CANDU alternative drops from fourth to seventh when its relatively low initial Investment Cost is no longer considered an advantage.

8.2.4 Relative Value of Human Life

The tradeoffs presented in Section 6 imply that a public fatality and a worker fatality are equally undesirable. However, workers accept the risks associated with employment voluntarily and are compensated for their exposure to risks by their salaries. This point of view suggests that society should be willing to spend more to save the statistical life of a member of the public than a worker, and this policy has been implemented in other DOE applications of MAU (e.g., [DOE-LIPS 95]).

Figures 48 and 49 display the rankings that result when the unit weight on a public fatality avoided is increased to twice the unit weight on a worker fatality avoided. The use of a 2:1 ratio of the weights on public and worker fatalities has little affect on the rankings of the alternatives.

Figure 48 - Ranking Associated with 2:1 Ratio of Public:Worker Fatalities

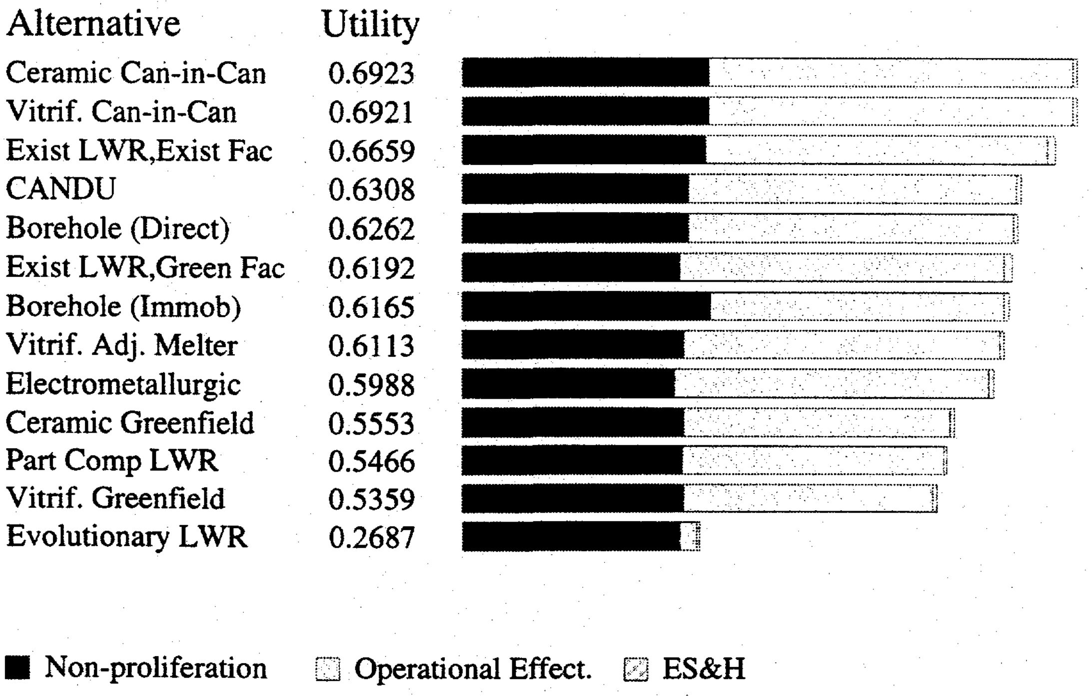
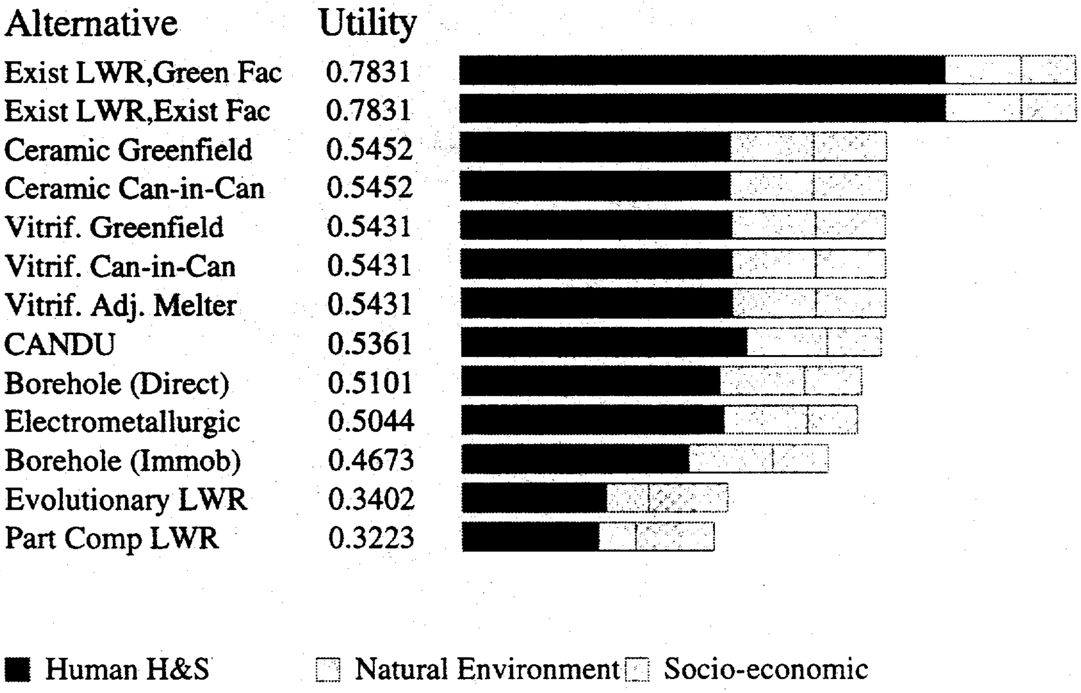


Figure 49 - ES&H Ranking Associated with 2:1 Ratio of Public:Worker Fatalities



8.3 Summary and Conclusions

This series of sensitivity analyses indicates that the ranking of the alternatives that was determined using the base case tradeoffs and assumptions is relatively insensitive to changes in these assumptions over reasonable ranges. Among the reactor alternatives, the Existing LWR, Existing Facilities and the CANDU alternatives are typically rated among the top two or three, and among the immobilization alternatives, the Vitrification and Ceramic Can-in-Can alternatives dominate the other alternatives.

However, the sensitivity analysis does provide some additional insights regarding a choice between a reactor and an immobilization alternative. According to the sensitivity analysis of the weights on the two measures associated with the International Cooperation sub-objective, the reactor alternatives become relatively more attractive if the weight on the measure Russian Cooperation is increased (Figure 40a). Since one of the primary goals of the OFMD plutonium disposition effort is to prevent the proliferation of nuclear weapons, Russian Cooperation could become a key issue, and become an extremely important consideration in the final choice of a U.S. disposition strategy.

Therefore, it is logical that the ROD recommends proceeding with the parallel development of two of the highest ranked alternatives from this analysis, the Vitrification Can-in-Can immobilization alternative and the Existing LWR, Existing Facilities reactor alternative. In the next section, we consider the implementation of this strategy, and the eventual basis for a choice between them.

9. DEPLOYMENT STRATEGIES

The base case analysis indicates that the four most desirable alternatives are, in order, Ceramic Can-in-Can, Vitrification Can-in-Can, Existing Reactor in Existing Facility, and CANDU. In the previous section, the results of the sensitivity analyses showed that these four alternatives are ranked at the top of the list for a wide range of possible weights that could be assigned to the measures. However, two important considerations were not fully captured by the analysis: the ability to influence the Russians to pursue a reciprocal disposition path and the risk of failure should a single technology be pursued. In this chapter we will discuss how parallel development of several technologies can better address these two concerns.

9.1 Influence on Russian and Other Nations

A key difference between the reactor and immobilization disposition alternatives is that irradiation of MOX fuel in reactors converts the material from a weapons grade to a reactor grade form of plutonium. It is more difficult, although not impossible, to fabricate weapons from reactor grade plutonium. The importance that Russia and other countries will place on this isotopic degradation is not known. Several studies have addressed this issue (see [NAS 95] and [DOE-NN 97]).

If Russian policy is to insist on isotopic degradation, Russia may not consider a U.S. disposition effort featuring immobilization as sufficient to meet the spent fuel standard for weapons grade plutonium. Further, under such a national policy, the Russians may be more likely to join a reactor-based disposition program. However, if the Russian policy did not require degradation of fissile material, the U.S.'s most cost effective and timely course of action would be to pursue immobilization of surplus plutonium in ceramic or glass material due to the overall performance measures of those alternatives as highlighted in the previous section.

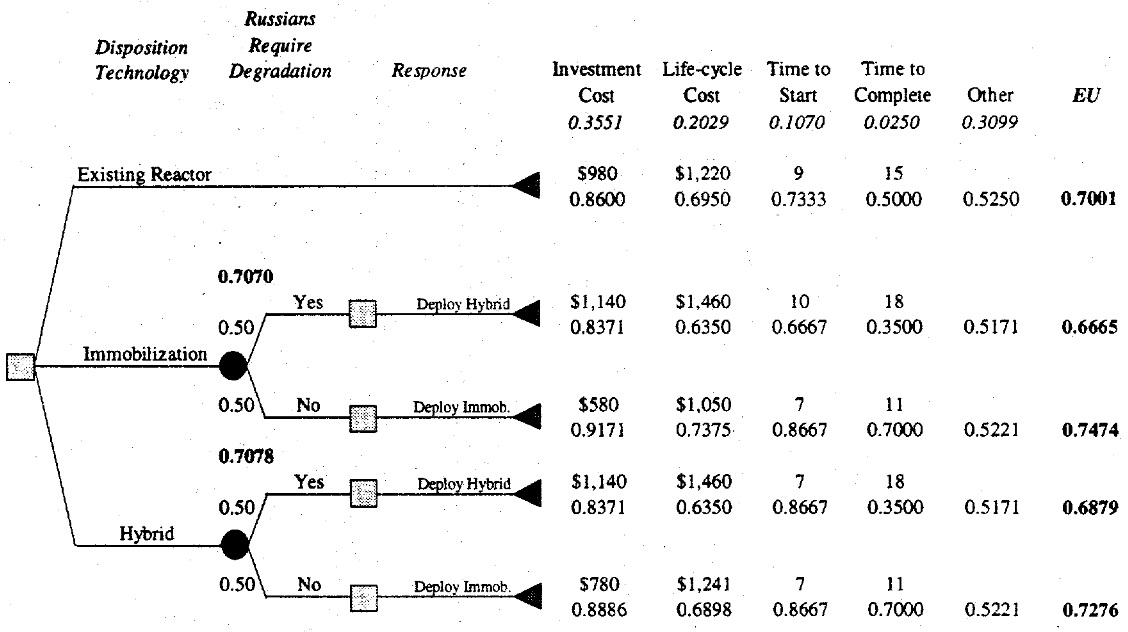
Of course, DOE could pursue a joint development approach featuring one reactor technology and one immobilization technology. This would lead to higher initial Investment Costs, but intuitively, such a "hybrid" should provide additional flexibility in light of the uncertainty about Russian policies, as well as other uncertainties cited in DOE-TSR 96. A "hybrid" alternative is defined here as a simultaneous deployment of two or more technologies; i.e. the investment in R&D, licensing and construction for two or more technologies.

In order to evaluate this strategy, the measure Russian Cooperation will be replaced with a probability distribution over the likelihood that that Russians will require degradation of fissile material. The weights on the other measures will be re-scaled so that the original ratios among the weights are maintained and the sum of the re-scaled weights is one.

This analysis may be illustrated by the decision tree shown in Figure 50. In this diagram, decisions nodes are represented by squares with alternatives shown as paths through the tree, uncertainty is represented by circles, and endpoints or values received by proceeding down a path are represented by triangles. The logic represented by this tree is as follows: first, the U.S. must select a disposition strategy without knowing the future Russian stand on isotopic degradation; second, after the U.S. announces its decision, the Russians official policy will become known; finally, the U.S. will have to react to the

Russian announcement. In Figure 50, the probability that Russia requires isotopic degradation is shown as 0.50 for illustrative purposes only. No attempt has been made to elicit an estimate of this probability from relevant experts. Instead, the objective of this analysis will be to identify the best development strategy for different values of the probability.

Figure 50 - Decision Tree for Existing Reactor in Existing Facility, Immobilization and Hybrid Disposition Alternatives



In this tree we have simplified the selection of a technology to a choice of three alternatives. From top to bottom in Figure 50 they consist of, Existing Reactor in Existing Facility, Immobilization, and the Hybrid. The Existing Reactor in Existing Facility was selected because it was the highest ranked reactor alternative. If the U.S. opted to follow this disposition technology, the Russian policy on degradation would be irrelevant; in either case, the reactor would not conflict with Russian policy. Therefore, there is no uncertainty associated with this alternative. With this technology, the U.S. program would expect the Investment Cost, Life-cycle Cost, Time to Start, and Time to Complete stated previously in this report. These measures were separated from the others in the objectives hierarchy because they are the most likely to be impacted by a hybrid deployment strategy. In addition, the thirty-two other measures (excluding Russian Cooperation) would contribute to the existing reactor's ability to achieve the disposition objectives. In Figure 50, these measures are all combined into a single expected utility score, 0.7001, using the methodology demonstrated in the previous sections.

The Vitrification Can-in-Can was arbitrarily selected as the immobilization technology because it was basically tied with its ceramic counterpart as the most preferred immobilization alternative. If the U.S. were to deploy an immobilization (only) alternative, the announcement of Russian policy would be an important factor in valuing this choice. If the Russians require degradation, we have assumed that the Russians would not begin to dispose of their stockpiles due to their dissatisfaction with U.S. proliferation assurance. In response to this requirement, we have assumed that the U.S. would then begin to deploy the existing reactor alternative and use the immobilization plant to dispose of material that is not suitable for MOX fuel. The costs associated with the hybrid alternative would ultimately be incurred, but the reactor portion of the hybrid schedule is assumed to be delayed by 1 year. Accordingly, reactor operations with isotopic degradation of weapons grade plutonium would begin in 10 years, and the Russians would regard plutonium disposition to have begun at this point. If the Russians do not require degradation, the immobilization program would proceed with no additional cost overruns or schedule delays.

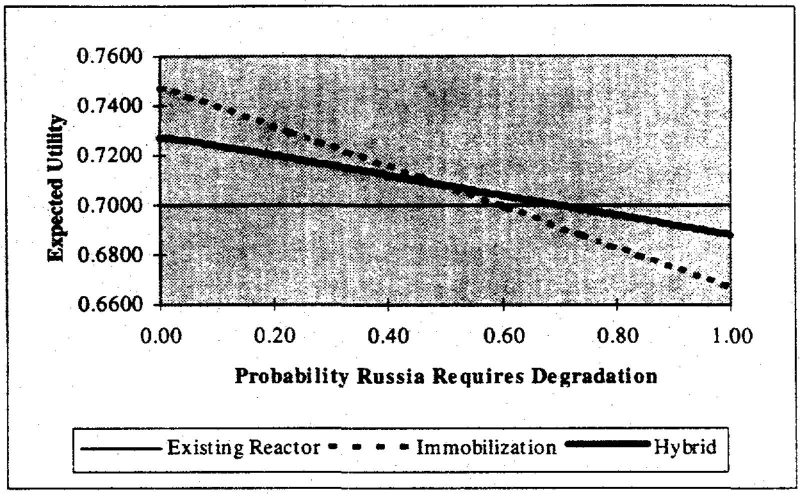
If the Russians require degradation, the utility of the immobilization alternative is 0.6665, while if it is not required, the utility is 0.7474. Using the assumed 50-50 probability, the expected utility of the immobilization alternative is $0.50*0.6665 + 0.50*0.7474 = 0.7070$ as shown in Figure 50.

The final alternative is the hybrid deployment strategy. This alternative would simultaneously invest in R&D and licensing activities for both the immobilization and reactor technologies. This dual commitment leads to higher front-end Investment Costs, but there are no schedule delays in the future because the U.S. could deploy the reactor component of the hybrid without delay should isotopic degradation be required. Calculating the expected utility of the hybrid alternative would give 0.7078 per Figure 50.

If the U.S. were confident that the probability that the Russians would require degradation of fissile materials were 50%, our analysis would be complete and we would recommend the hybrid deployment because $0.7078 > 0.7070 > 0.7001$. However, this probability was arbitrarily selected for illustrative purposes so there is no basis for believing that it is correct. Therefore, a sensitivity analysis was performed over the complete range of possible probability estimates

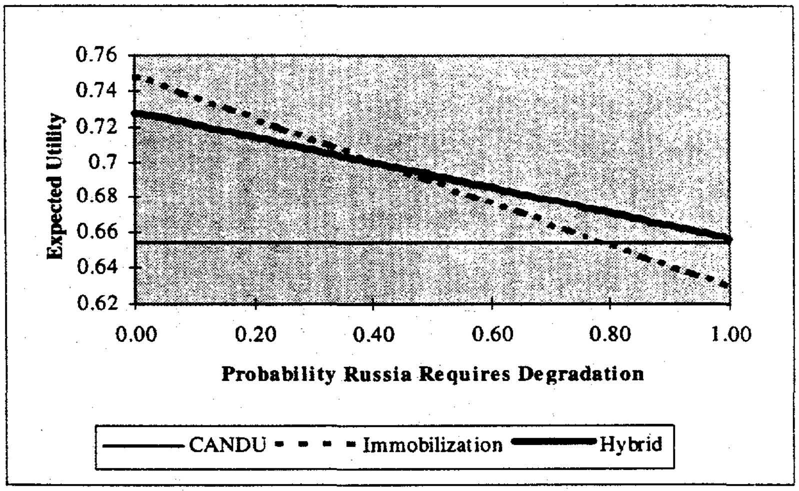
Figure 51 indicates that given these three alternatives, each is preferred over a given range of the probability that degradation is required. If a decision maker believes this probability is less than 0.48, immobilization (only) should be the technology utilized (the immobilization line in the figure is above the hybrid and reactor lines for this range of probability values). But, if this probability is between 0.48 and 0.69, the dual deployment hybrid is superior. Only if the probability is greater than 0.69 will the Existing Reactor, Existing Facility prove to be superior.

Figure 51 - Existing LWR Hybrid Evaluation as a Function of Probability



The other hybrid combination that was considered is similar except that the second highest reactor alternative, CANDU, was used. A tree similar to Figure 50 was developed and the probability profile in Figure 52 was generated. Based on Figure 52, when the CANDU reactor is considered, it is never optimal to implement the CANDU alternative alone. If the probability that degradation is required is between 0.0 and 0.41, the immobilization (only) alternative should be pursued. If this probability is greater than 0.41, the hybrid is superior.

Figure 52 - CANDU Hybrid Evaluation as a Function of Probability



Based on this analysis, if the probability that Russian policy requires degradation is estimated to be between 0.41 and 0.69, a hybrid development plan is superior, if either reactor alternative is considered. The reason for this is that the incremental cost associated with a hybrid is offset by the ability of the hybrid to scale each technology component after the policy becomes known with no time delay.

9.2 Other Advantages of the Hybrid

Other factors besides Russian insistence on isotopic degradation suggest the need for a hybrid strategy for plutonium disposition. For example, international concerns about the civil use of weapons plutonium in commercial reactors may delay the deployment schedule. Similarly, R&D necessary to qualify the immobilized plutonium for disposal in a geologic repository may identify problems that require more time and budget to resolve than initially anticipated. Thus, the institutional and technical uncertainties associated with each alternative suggest the need for a "hybrid" approach in order to avoid delays in deployment.

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Appendix A – ANRCP Meetings and Contacts

Dates	Contacts	MAU Team Representatives*	Purpose
5/3/95 - 5/4/95	Los Angeles	Dyer	Discussion and outline of program objectives with other DOE contractors
5/24/95 - 5/25/95	Dallas	Olson	Attended meeting with reactor team
5/25/95	DOE Headquarters	Dyer, Edmunds	Initial Contact with Program Director and Staff
5/31/95 - 6/2/95	San Francisco	Dyer	Meeting with LLNL staff to discuss screening objectives
6/6/95 - 6/7/95	DOE Headquarters	Dyer, Edmunds	OFMD staff briefing
6/14/95 - 6/15/95	TetraTech Offices	Dyer, Edmunds, Butler	Data gathering for ES&H objectives
6/27/95 - 6/28/95	DOE Headquarters	Dyer	Meeting with TetraTech and alternative teams
7/6/95 - 7/7/95	Sandia Labs, Albuquerque	Chandler, Rand	Initial contact with Sandia Safeguards and Security team
7/1/95	ORNL	Olson	Meeting with personnel responsible for providing cost estimates
7/12/95 - 7/13/95	DOE Headquarters	Dyer, Edmunds	Discussion of International Cooperation measures with Department of State, National Security Office, White House Office of Science and Technology, and OFMD staff
7/17/95 - 7/19/95	DOE Headquarters	Dyer, Edmunds	Presentation to Senior Technical Review Group
7/31/95 - 8/1/95	Sandia Labs, Albuquerque	Dyer, Butler, Rand	Definition of measures and scales for Safeguards and Security Measures
8/8/95 - 8/9/95	DOE Headquarters	Dyer, Edmunds	Discussion of data requirements for ES&H data and meeting with OFMD staff
8/16/95 - 8/17/95	Sandia Labs, Albuquerque	Dyer, Edmunds, Butler	Tradeoff and weight assessment for Safeguards and Security measures
9/6/95 - 9/8/95	TetraTech Offices	Dyer, Butler	ES&H data collection and preliminary weight assessment
9/11/95 - 9/12/95	DOE Headquarters	Dyer, Butler	Meetings with DOE Office of Environmental Management and DOE Office of Civilian Radioactive Waste
9/18/95 - 9/19/95	DOE Headquarters	Dyer	Discussion of assessment of public opinion
9/18/95 - 9/19/95	DOE Headquarters	Olson	Attended reactor team meeting
9/26/95 - 9/27/95	DOE Headquarters	Dyer, Edmunds, Butler, Jia	OFMD assessment of high level weights and presentation of preliminary results
10/10/95 - 10/11/95	DOE Headquarters	Dyer, Butler	Attended meeting with lab managers
10/19/95	Oak Ridge National Labs	Edmunds	Discussion of cost and schedule uncertainty

10/27/95 - 10/31/95	San Francisco	Dyer	Presentation and discussion at American Nuclear Society meeting
11/13/95 - 11/15/95	Sandia Labs, DC	Dyer, Butler	Presentation of preliminary results at Monthly Lab Manager's Meeting
11/27/95	Sandia Labs, Albuquerque	Edmunds	Discussion and review of Safeguards and Security data and weights
12/13/95 - 12/15/95	Sandia Labs, D.C.	Butler, Dyer	Presentation of preliminary results at Monthly Lab Manager's Meeting
1/22/96 - 1/25/96	DOE Headquarters	Dyer, Butler	Review of preliminary findings with OFMD
4/10/96	ORNL	Dyer, Edmunds, Butler	Discussion of data requirements and personnel required for assessment of cost and schedule uncertainty
6/18/96 - 6/19/96	Reno, NV	Dyer, Butler	Presentation of results at semi-annual meeting of American Nuclear Society
8/26/96 - 8/28/96	DOE Headquarters	Dyer, Butler	Project status review and planning with OFMD
1/10/97 - 1/12/97	DOE Headquarters	Dyer, Butler	Project status review and planning with OFMD

MAU Team Members:

Dyer	James S. Dyer, Chairman Management Science and Information Systems, University of Texas at Austin
Butler	John C. Butler, Analyst/Program Coordinator, University of Texas at Austin
Chandler	Michael Chandler, Program Coordinator 5/95 - 7/96
Edmunds	Thomas E. Edmunds, Decision Analysis Liaison to OFMD, Lawrence Livermore National Laboratories
Jia	Jianmin Jia, Analyst, University of Texas at Austin (currently professor of marketing/engineering Chinese University of Hong Kong
Olson	David S. Olson, Professor of Business Analysis, Texas A&M University
Rand	Jamie S. Rand, Assistant Program Coordinator, 5/95 - 8/96

Appendix B – Fundamental Data

Existing LWR, Existing Facility

THEFT	Pu Processing	Mox Fuel Fab	Reactor	Repository
Material Characteristics				
DOE Attractiveness	I-B	I-C	I-C	II-D
Other Separated Fissile Materials	Y	N	N	N
Environment				
Maximum Pu Inventory (MT)	0.5	3.2	22	31.5
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.2	0	0
SST Trans. Miles	2200	2200	900	0
No. of Trips	1	1	1	1
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	0.80%	0.60%	6.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
DIVERSION				
Material Characteristics				
IAEA Attractiveness	DUU	DUU	DUU	DUI
Environment				
Maximum Pu Inventory (MT)	0.5	3.2	22	31.5
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.2	0	0
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	1.50%	2.50%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
IRREVERSIBILITY OF END MATERIAL				
Material Form	E			
Location	R			
INTERNATIONAL COOPERATION				
Civil Use of Pu	70			
Russian Cooperation	50.2			
TIMELINESS				
Time to Start	9			
Time to Complete	24			

Partially Complete LWR

THEFT	Pu Processing	Mox Fuel Fab	Reactor	Repository
Material Characteristics				
DOE Attractiveness	I-B	I-C	I-C	II-D
Other Separated Fissile Materials	Y	N	N	N
Environment				
Maximum Pu Inventory (MT)	0.5	3.1	36.4	39
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.1	0	0
SST Trans. Miles	2200	2200	300	0
No. of Trips	1	1	1	1
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	0.80%	0.60%	6.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
DIVERSION				
Material Characteristics				
IAEA Attractiveness	DUU	DUU	DUU	DUI
Environment				
Maximum Pu Inventory (MT)	0.5	3.1	36.4	39
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.1	0	0
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	1.50%	2.50%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
IRREVERSIBILITY OF END MATERIAL				
Material Form	E			
Location	R			
INTERNATIONAL COOPERATION				
Civil Use of Pu	70			
Russian Cooperation	50.2			
TIMELINESS				
Time to Start	13			
Time to Complete	28			

Existing LWR, Greenfield Facility

THEFT	Pu Processing	Mox Fuel Fab	Reactor	Repository
Material Characteristics				
DOE Attractiveness	I-B	I-C	I-C	II-D
Other Separated Fissile Materials	Y	N	N	N
Environment				
Maximum Pu Inventory (MT)	0.5	3.2	22	31.5
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.2	0	0
SST Trans. Miles	2200	0	1700	0
No. of Trips	1	0	1	1
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	0.80%	0.60%	6.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
DIVERSION				
Material Characteristics				
IAEA Attractiveness	DUU	DUU	DUU	DUI
Environment				
Maximum Pu Inventory (MT)	0.5	3.2	22	31.5
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.2	0	0
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	1.50%	2.50%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
IRREVERSIBILITY OF END MATERIAL				
Material Form	E			
Location	R			
INTERNATIONAL COOPERATION				
Civil Use of Pu	70			
Russian Cooperation	50.2			
TIMELINESS				
Time to Start	13			
Time to Complete	31			

Evolutionary LWR

THEFT	Pu Processing	Mox Fuel Fab	Reactor	Repository
Material Characteristics				
DOE Attractiveness	I-B	I-C	I-C	II-D
Other Separated Fissile Materials	Y	N	N	N
Environment				
Maximum Pu Inventory (MT)	0.6	3.6	47.4	36.5
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.6	0	0
SST Trans. Miles	2200	2200	50	0
No. of Trips	1	1	1	1
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	0.80%	0.60%	6.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
DIVERSION				
Material Characteristics				
IAEA Attractiveness	DUU	DUU	DUU	DUI
Environment				
Maximum Pu Inventory (MT)	0.6	3.6	47.4	36.6
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	3.6	0	0
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	1.50%	2.50%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	CHY	CRY
IRREVERSIBILITY OF END MATERIAL				
Material Form	E			
Location	R			
INTERNATIONAL COOPERATION				
Civil Use of Pu	70			
Russian Cooperation	50.2			
TIMELINESS				
Time to Start	14			
Time to Complete	28			

CANDU

THEFT	Pu Processing	Mox Fuel Fab	Reactor	Repository
Material Characteristics				
DOE Attractiveness	I-B	I-C	I-C	II-D
Other Separated Fissile Materials	Y	N	N	N
Environment				
Maximum Pu Inventory (MT)	0.5	0.525	16.15	33
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	2.1	0	0
SST Trans. Miles	2200	2200	950	0
No. of Trips	1	1	2	0
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	0.80%	0.60%	6.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY	CRY
DIVERSION				
Material Characteristics				
IAEA Attractiveness	DUU	DUU	DUU	DUI
Environment				
Maximum Pu Inventory (MT)	0.5	0.525	16.15	33
No. Processing Steps	16	5	1	0
Bulk Throughput (MT/yr.)	5	2.1	0	0
Safeguards and Security				
Type of NAS (% Item)	30	50	100	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	1.50%	2.50%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY	CRY
IRREVERSIBILITY OF END MATERIAL				
Material Form	E			
Location	R			
INTERNATIONAL COOPERATION				
Civil Use of Pu	10			
Russian Cooperation	50.2			
TIMELINESS				
Time to Start	10			
Time to Complete	24			

Vitrification Greenfield

THEFT	Pu Processing	Immobilization	
		Facility	Repository
Material Characteristics			
DOE Attractiveness	I-B	I-C	IV-E
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	5	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
SST Trans. Miles	2800	2200	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	0.80%	12.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUI
Environment			
Maximum Pu Inventory (MT)	5	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.50%	20.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	E		
Location	R		
INTERNATIONAL COOPERATION			
Civil Use of Pu	95		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	12		
Time to Complete	21		

Vitrification Can-In-Can

THEFT	Pu Processing	Immobilization Facility	Repository
Material Characteristics			
DOE Attractiveness	I-B	I-C	IV-E
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	5	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
SST Trans. Miles	2800	2200	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	0.80%	16.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUI
Environment			
Maximum Pu Inventory (MT)	5	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.50%	20.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	E		
Location	R		
INTERNATIONAL COOPERATION			
Civil Use of Pu	95		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	7		
Time to Complete	18		

Vitrification Adjunct Melter

THEFT	Pu Processing	Immobilization	
		Facility	Repository
Material Characteristics			
DOE Attractiveness	I-B	I-C	IV-E
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	2	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
SST Trans. Miles	2800	2200	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	0.80%	12.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUI
Environment			
Maximum Pu Inventory (MT)	2	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.50%	20.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	E		
Location	R		
INTERNATIONAL COOPERATION			
Civil Use of Pu	95		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	12		
Time to Complete	21		

Ceramic Greenfield

THEFT	Pu Processing	Immobilization Facility	Repository
Material Characteristics			
DOE Attractiveness	I-B	I-C	IV-E
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	5	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
SST Trans. Miles	2800	2200	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	0.80%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUI
Environment			
Maximum Pu Inventory (MT)	5	5	50
No. Processing Steps	11	2	0
Bulk Throughput (MT/yr.)	5	5	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.50%	15.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	E		
Location	R		
INTERNATIONAL COOPERATION			
Civil Use of Pu	95		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	12		
Time to Complete	21		

Ceramic Can-In-Can

THEFT	Pu Processing	Immobilization	
		Facility	Repository
Material Characteristics			
DOE Attractiveness	I-B	I-C	IV-E
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	2	0.04	50
No. Processing Steps	11	4	0
Bulk Throughput (MT/yr.)	5	5	0
SST Trans. Miles	2800	2200	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	0.80%	15.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUI
Environment			
Maximum Pu Inventory (MT)	2	0.04	50
No. Processing Steps	11	4	0
Bulk Throughput (MT/yr.)	5	5	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.50%	20.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	E		
Location	R		
INTERNATIONAL COOPERATION			
Civil Use of Pu	95		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	7		
Time to Complete	18		

Electrometallurgical

THEFT	Pu Processing	Immobilization	
		Facility	Repository
Material Characteristics			
DOE Attractiveness	I-B	I-C	IV-E
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	2	25	50
No. Processing Steps	8	7	0
Bulk Throughput (MT/yr.)	4	4	0
SST Trans. Miles	1100	600	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	0.85%	8.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUI
Environment			
Maximum Pu Inventory (MT)	2	25	50
No. Processing Steps	8	7	0
Bulk Throughput (MT/yr.)	4	4	0
Safeguards and Security			
Type of NAS (% Item)	30	50	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.60%	15.00%	0.00%
Accessibility of Plutonium	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	E		
Location	R		
INTERNATIONAL COOPERATION			
Civil Use of Pu	95		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	13		
Time to Complete	22		

Deep Borehole (Direct)

THEFT	Disassembly/ Conversion	Borehole Facility	Borehole Disposal
Material Characteristics			
DOE Attractiveness	I-B	I-C	II-C
Other Separated Fissile Materials	Y	N	N
Environment			
Maximum Pu Inventory (MT)	2	2	50
No. Processing Steps	3	3	0
Bulk Throughput (MT/yr.)	5	5	0
SST Trans. Miles	2800	700	0
No. of Trips	1	1	0
Safeguards and Security			
Type of NAS (% Item)	30	100	100
Classification	Y	N	N
Measurement Uncertainty (%)	1.60%	2.00%	0.00%
Accessibility of Plutonium	THN	CHN	CRY
DIVERSION			
Material Characteristics			
IAEA Attractiveness	DUU	DUU	DUU
Environment			
Maximum Pu Inventory (MT)	2	2	50
No. Processing Steps	3	3	0
Bulk Throughput (MT/yr.)	5	5	0
Safeguards and Security			
Type of NAS (% Item)	30	100	100
Classification	Y	N	N
Measurement Uncertainty (%)	3.00%	4.00%	0.00%
Accessibility of Plutonium	THN	CHN	CRY
IRREVERSIBILITY OF END MATERIAL			
Material Form	C		
Location	B		
INTERNATIONAL COOPERATION			
Civil Use of Pu	100		
Russian Cooperation	37.3		
TIMELINESS			
Time to Start	10		
Time to Complete	20		

Deep Borehole (Immobilized)

THEFT	Disassembly/ Conversion	Immobilization Process	Surface Facility	Borehole Disposal
Material Characteristics				
DOE Attractiveness	I-B	I-C	II-D	IV-E
Other Separated Fissile Materials	Y	N	N	N
Environment				
Maximum Pu Inventory (MT)	2	2	2	50
No. Processing Steps	6	4	1	0
Bulk Throughput (MT/yr.)	5	5	5	0
SST Trans. Miles	2800	0	700	0
No. of Trips	1	0	1	0
Safeguards and Security				
Type of NAS (% Item)	30	30	30	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	0.80%	6.00%	6.00%	0.00%
Accessibility of Plutonium	THN	THN	THN	CRY
DIVERSION				
Material Characteristics				
IAEA Attractiveness	DUU	DUU	DUU	DUU
Environment				
Maximum Pu Inventory (MT)	2	2	2	50
No. Processing Steps	6	4	1	0
Bulk Throughput (MT/yr.)	5	5	5	0
Safeguards and Security				
Type of NAS (% Item)	30	30	30	100
Classification	Y	N	N	N
Measurement Uncertainty (%)	1.50%	10.00%	10.00%	0.00%
Accessibility of Plutonium	THN	THN	THN	CRY
IRREVERSIBILITY OF END MATERIAL				
Material Form	E			
Location	B			
INTERNATIONAL COOPERATION				
Civil Use of Pu	100			
Russian Cooperation	37.3			
TIMELINESS				
Time to Start	10			
Time to Complete	20			

Operational Effectiveness Measures		
	Investment Cost($M)	Life-cycle Costs ($M)
Existing LWR, Existing Facility	980	1,220
Partially Complete LWR	3,050	1,210
Existing LWR, Greenfield Facility	1,380	1,240
Evolutionary LWR	6,880	3,660
CANDU	870	1,660
Vitrification Greenfield	2,030	2,550
Vitrification Can-in-Can	580	1,050
Vitrification Adjunct Melter	1,020	1,830
Ceramic Greenfield	1,810	2,330
Ceramic Can-in-Can	580	1,050
Electrometallurgical	1,190	1,710
Borehole (Direct)	1,110	1,500
Borehole (Immobilization)	1,350	2,050

Location	Protect Human Health and Safety					
	Public Fatalities Radiation	**Public Fatalities Chemical**	**Worker Fatalities Radiation**	**Worker Fatalities Chemical**	**Transportation Fatalities**	**Accident Risk**
Pit Disassembly/Conversion Facility						
Hanford	8.0E-05	0.0E+00	1.70	0.0E+00	0.203	4.7E-05
NTS	1.5E-06	0.0E+00	0.43	0.0E+00	0.107	1.1E-06
INEL	1.5E-05	0.0E+00	1.50	0.0E+00	0.155	1.4E-05
Pantex	3.3E-05	0.0E+00	0.49	0.0E+00	0.033	1.6E-05
ORR	6.0E-04	0.0E+00	0.64	0.0E+00	0.155	1.8E-04
SRS	5.6E-04	0.0E+00	1.50	0.0E+00	0.190	5.1E-05
Pu Conversion Facility						
Hanford	4.2E-05	3.20E-08	1.5	1.40E-05	0.455	3.6E-05
NTS	9.5E-07	4.70E-09	0.5	7.40E-06	0.211	8.1E-07
INEL	6.0E-06	6.80E-08	1.4	1.40E-05	0.340	1.1E-05
Pantex	1.9E-05	1.80E-07	0.6	7.20E-06	0.293	1.2E-05
ORR	3.7E-04	1.90E-07	0.7	1.5E-05	0.557	1.3E-04
SRS	3.3E-04	8.70E-09	1.4	1.30E-05	0.635	3.8E-05
MOX Fuel Fabrication Facility						
Hanford	5.3E-05	0.0E+00	1.90	0.0E+00	0.359	8.1E-05
NTS	1.2E-06	0.0E+00	0.23	0.0E+00	0.359	1.8E-06
INEL	8.3E-06	0.0E+00	1.70	0.0E+00	0.359	2.4E-05
Pantex	2.4E-05	0.0E+00	0.31	0.0E+00	0.359	2.7E-05
ORR	4.1E-04	0.0E+00	0.51	0.0E+00	0.359	3.2E-04
SRS	3.7E-04	0.0E+00	1.70	0.0E+00	0.359	8.9E-05
Deep Borehole - Direct Emplacement						
Generic	9.00E-09	0.0E+00	1.00	0.0E+00	1.04	1.40E-07
Deep Borehole - Immobilized Disposal						
Generic	1.10E-08	0.0E+00	1.0E+00	0.0E+00	0.00	1.30E-08
Deep Borehole - Immobilized without Radionuclides						
Hanford	7.5E-09	0.0E+00	1.4E+00	0.0E+00	1.75	1.8E-08
NTS	1.7E-10	0.0E+00	4.5E-01	0.0E+00	1.84	3.6E-10
INEL	1.2E-09	0.0E+00	1.3E+00	0.0E+00	1.80	4.8E-09
Pantex	3.2E-09	0.0E+00	5.0E-01	0.0E+00	1.92	1.1E-08
ORR	5.5E-08	0.0E+00	6.2E-01	0.0E+00	1.80	7.0E-08
SRS	6.0E-08	0.0E+00	1.3E+00	0.0E+00	1.76	2.3E-08

Location	Protect Human Health and Safety					
	Public Fatalities Radiation	**Public Fatalities Chemical**	**Worker Fatalities Radiation**	**Worker Fatalities Chemical**	**Transportation Fatalities**	**Accident Risk**
Immobilization with Radionuclides - New Glass Vitrification Facility						
Hanford	4.0E-06	0.0E+00	1.40	0.0E+00	0.76	3.0E-06
NTS	7.0E-08	0.0E+00	0.45	0.0E+00	0.85	7.0E-08
INEL	8.0E-07	0.0E+00	1.30	0.0E+00	0.81	9.4E-07
Pantex	1.7E-06	0.0E+00	0.50	0.0E+00	0.93	9.1E-07
ORR	2.2E-05	0.0E+00	0.62	0.0E+00	0.81	6.3E-06
SRS	2.5E-05	0.0E+00	1.30	0.0E+00	0.77	3.0E-06
Immobilization with Radionuclides - New Ceramic Immobilization Facility						
Hanford	2.0E-07	0.0E+00	1.5E+00	0.0E+00	0.78	6.7E-08
NTS	8.5E-10	0.0E+00	5.0E-01	0.0E+00	0.87	1.4E-09
INEL	7.0E-08	0.0E+00	1.4E+00	0.0E+00	0.83	1.8E-09
Pantex	9.5E-08	0.0E+00	5.4E-01	0.0E+00	0.95	3.9E-08
ORR	1.6E-07	0.0E+00	6.6E-01	0.0E+00	0.83	2.6E-07
SRS	3.4E-07	0.0E+00	1.4E+00	0.0E+00	0.79	8.5E-08
Electrometallurgical Treatment with Radionuclides						
INEL	1.2E-02	0.0E+00	8.9E-01	0.0E+00	0.92	3.7E-07
Existing Light Water Reactors						
Generic	1.1E-04	0.0E+00	-0.35	0.0E+00	0.65	2.8E-01
Partially Completed Light Water Reactors						
Generic	5.2E-03	0.0E+00	-0.35	0.0E+00	0.65	2.8E-01
Evolutionary Light Water Reactors						
Hanford	2.7E-01	0.0E+00	-0.35	0.0E+00	0.65	5.1E-06
NTS	2.7E-04	0.0E+00	-0.35	0.0E+00	0.65	1.1E-07
INEL	8.2E-02	0.0E+00	-0.35	0.0E+00	0.65	1.4E-06
Pantex	7.6E-02	0.0E+00	-0.35	0.0E+00	0.65	2.4E-06
ORR	4.4E-02	0.0E+00	-0.35	0.0E+00	0.65	2.0E-05
SRS	2.7E-01	0.0E+00	-0.35	0.0E+00	0.65	5.7E-06

Location	Protect the Natural Environment	
	Impact on Species	**Secondary Waste Generated**
Pit Disassembly/Conversion Facility		
Hanford	0	102
NTS	1	102
INEL	0	102
Pantex	1	102
ORR	0	102
SRS	0	102
Pu Conversion Facility		
Hanford	0	1,743
NTS	1	1,743
INEL	0	1,743
Pantex	0	1,743
ORR	0	1,743
SRS	0	1,743
MOX Fuel Fabrication Facility		
Hanford	0	153
NTS	1	153
INEL	0	153
Pantex	1	153
ORR	0	153
SRS	0	153
Deep Borehole - Direct Emplacement		
Generic	0	5
Deep Borehole - Immobilized without Radionuclides		
Generic	0	29
Deep Borehole - Immobilized Facility		
Hanford	0	14
NTS	1	14
INEL	0	14
Pantex	1	14
ORR	1	14
SRS	0	14

Location	Protect the Natural Environment	
	Impact on Species	**Secondary Waste Generated**
Immobilization with Radionuclides - New Glass Vitrification Facility		
Hanford	0	14
NTS	1	14
INEL	0	14
Pantex	1	14
ORR	1	14
SRS	0	14
Immobilization with Radionuclides - New Ceramic Immobilization Facility		
Hanford	0	14
NTS	1	14
INEL	0	14
Pantex	1	14
ORR	1	14
SRS	0	14
Electrometallurgical Treatment with Radionuclides		
INEL	0	55
Existing Light Water Reactors		
Generic	0	153
Partially Completed Light Water Reactors		
Generic	0	1,427
Evolutionary Light Water Reactors		
Hanford	0	1,233
NTS	1	1,233
INEL	0	1,233
Pantex	3	1,233
ORR	0	1,233
SRS	2	1,233

Location	Protect Human Environment	
	Minimize Boom/Bust employment loss	Maximize sustained increase in employment
Pit Disassembly/Conversion Facility		
Hanford	0%	520
NTS	0%	520
INEL	0%	520
Pantex	0%	520
ORR	0%	520
SRS	0%	520
Pu Stabilization/Conversion Facility		
Hanford	0%	1022
NTS	0%	1022
INEL	0%	1022
Pantex	0%	1022
ORR	0%	1022
SRS	0%	1022
MOX Fuel Fabrication Facility		
Hanford	0%	250
NTS	0%	250
INEL	0%	250
Pantex	0%	250
ORR	0%	250
SRS	0%	250
Deep Borehole - Direct Emplacement		
Generic	0%	342
Deep Borehole - Immobilized Disposal		
Generic	0%	280
Deep Borehole - Immobilized Facility		
Hanford	0%	0
NTS	0%	0
INEL	0%	0
Pantex	0%	0
ORR	0%	0
SRS	0%	0

Location	Minimize Boom/Bust employment loss	Maximize sustained increase in employment
Immobilization with Radionuclides - New Glass Vitrification Facility		
Hanford	0%	758
NTS	0%	758
INEL	0%	758
Pantex	0%	758
ORR	0%	758
SRS	0%	758
Immobilization with Radionuclides - New Ceramic Immobilization Facility		
Hanford	0%	860
NTS	0%	860
INEL	0%	860
Pantex	0%	860
ORR	0%	860
SRS	0%	860
Electrometallurgical Treatment		
INEL	0%	83
Existing Light Water Reactors		
Generic	0%	0
Partially Completed Light Water Reactors		
Generic	0.60%	830
Evolutionary Light Water Reactors		
Hanford	1.45%	830
NTS	0.68%	830
INEL	3.06%	830
Pantex	2.11%	830
ORR	1.04%	830
SRS	1.93%	830

Appendix C - Alternative Theft and Diversion Aggregations Data

Table C.1 - Weighted Average S&S Aggregation Data

	Non-proliferation						
	Theft						
	Material Characteristics		Environment				
	DOE Attractiveness	*Other FM Separated?*	*Bulk Throughput*	*No. processing steps*	*MAX Pu Inventory*	*No. of Trips*	*SST Trans Miles*
Exist LWR, Exist Fac	0.0136	0.2727	0.1150	0.3824	0.9589	0.0500	0.4700
Part Comp LWR	0.0136	0.2727	0.1157	0.3824	0.9463	0.0500	0.5300
Exist LWR, Green Fac	0.0136	0.2727	0.1150	0.3824	0.9589	0.1000	0.6100
Evolutionary Reactor	0.0136	0.2727	0.1123	0.3824	0.9326	0.0500	0.5550
CANDU	0.0136	0.2727	0.1225	0.3824	0.9764	0.0500	0.4650
Vitrif. Greenfield	0.0077	0.1538	0.0600	0.6471	0.9007	0.5500	0.5000
Vitrif. Can-in-Can	0.0077	0.1538	0.0600	0.6471	0.9007	0.5500	0.5000
Vitrif. Adj. Melter	0.0077	0.1538	0.0600	0.6471	0.9515	0.5500	0.5000
Ceramic Greenfield	0.0077	0.1538	0.0600	0.6471	0.9007	0.5500	0.5000
Ceramic Can-in-Can	0.0133	0.2667	0.0600	0.5882	0.9712	0.5500	0.5000
Electrometallurgical	0.0233	0.4667	0.0900	0.5882	0.7459	0.5500	0.8300
Borehole (Direct)	0.0250	0.5000	0.0600	0.8529	0.9608	0.5500	0.6500
Borehole (Immob)	0.0545	0.4545	0.0600	0.7059	0.9608	0.5500	0.6500

Table C.1 - Weighted Average S&S Aggregation Data Continued

	Non-proliferation							
	Theft				Diversion			
	Safeguards & Security				Materi-al Char*	Environment*		
	Measure Uncertainty	*Type of NAS*	*Access-ibility*	*U.S. Classif-ication*	*IAEA Attract-iveness*	*Bulk Through-put**	*No. process-ing steps**	*MAX Inventory**
Exist LWR, Exist Fac	0.8619	0.1040	0.0303	0.2727	0.0000	0.1150	0.3824	0.9589
Part Comp LWR	0.8619	0.1040	0.0303	0.2727	0.0000	0.1157	0.3824	0.9463
Exist LWR, Green Fac	0.8619	0.1040	0.0303	0.2727	0.0000	0.1150	0.3824	0.9589
Evolutionary Reactor	0.8619	0.1040	0.0303	0.2727	0.0000	0.1123	0.3824	0.9326
CANDU	0.8619	0.1040	0.0455	0.2727	0.0000	0.1225	0.3824	0.9764
Vitrif. Greenfield	0.7780	0.0549	0.0000	0.1538	0.0000	0.0600	0.6471	0.9007
Vitrif. Can-in-Can	0.7767	0.0549	0.0000	0.1538	0.0000	0.0600	0.6471	0.9007
Vitrif. Adj. Melter	0.7780	0.0549	0.0000	0.1538	0.0000	0.0600	0.6471	0.9515
Ceramic Greenfield	0.7786	0.0549	0.0000	0.1538	0.0000	0.0600	0.6471	0.9007
Ceramic Can-in-Can	0.6972	0.0635	0.0000	0.2667	0.0000	0.0600	0.5882	0.9712
Electrometallurgical	0.5584	0.0787	0.0000	0.4667	0.0000	0.0900	0.5882	0.7459
Borehole (Direct)	0.7224	0.5217	0.1667	0.5000	0.0000	0.0600	0.8529	0.9608
Borehole (Immob)	0.5731	0.0433	0.0000	0.4545	0.0000	0.0600	0.7059	0.9608

Table C.1 - Weighted Average S&S Aggregation Data Continued

	Non-proliferation			
	Diversion			
	Safeguards & Security*			
	*Measure Uncert.**	*Type of NAS**	*Accessi-bility**	*Int'l Class*
Exist LWR, Exist Fac	0.7079	0.1040	0.0303	0.2727
Part Comp LWR	0.7079	0.1040	0.0303	0.2727
Exist LWR, Green Fac	0.7079	0.1040	0.0303	0.2727
Evolutionary Reactor	0.7079	0.1040	0.0303	0.2727
CANDU	0.7079	0.1040	0.0455	0.2727
Vitrif. Greenfield	0.6787	0.0549	0.0000	0.1538
Vitrif. Can-in-Can	0.6787	0.0549	0.0000	0.1538
Vitrif. Adj. Melter	0.6787	0.0549	0.0000	0.1538
Ceramic Greenfield	0.6803	0.0549	0.0000	0.1538
Ceramic Can-in-Can	0.6106	0.0635	0.0000	0.2667
Electrometallurgical	0.4862	0.0787	0.0000	0.4667
Borehole (Direct)	0.4449	0.5217	0.1667	0.5000
Borehole (Immob)	0.5069	0.0433	0.0000	0.4545

Table C.2 - Worst Case S&S Aggregation Data

	Non-proliferation						
	Theft						
	Material Characteristics		Environment				
	DOE Attractiveness	*Other FM Separated?*	*Bulk Throughput*	*No. processing steps*	*MAX Pu Inventory*	*No. of Trips*	*SST Trans Miles*
Exist LWR, Exist Fac	IB	Y	5	22	31.5	4	5300
	0.0000	0.0000	0.0600	0.3824	0.3703	0.0500	0.4700
Part Comp LWR	IB	Y	5	22	39	4	4700
	0.0000	0.0000	0.0600	0.3824	0.2202	0.0500	0.5300
Exist LWR, Green Fac	IB	Y	5	22	31.5	3	3900
	0.0000	0.0000	0.0600	0.3824	0.3703	0.1000	0.6100
Evolutionary Reactor	IB	Y	5	22	47.4	4	4450
	0.0000	0.0000	0.0600	0.3824	0.0520	0.0500	0.5550
CANDU	IB	Y	5	22	33	4	5350
	0.0000	0.0000	0.0600	0.3824	0.3403	0.0500	0.4650
Vitrif. Greenfield	IB	Y	5	13	50	2	5000
	0.0000	0.0000	0.0600	0.6471	0.0000	0.5500	0.5000
Vitrif. Can-in-Can	IB	Y	5	13	50	2	5000
	0.0000	0.0000	0.0600	0.6471	0.0000	0.5500	0.5000
Vitrif. Adj. Melter	IB	Y	5	13	50	2	5000
	0.0000	0.0000	0.0600	0.6471	0.0000	0.5500	0.5000
Ceramic Greenfield	IB	Y	5	13	50	2	5000
	0.0000	0.0000	0.0600	0.6471	0.0000	0.5500	0.5000
Ceramic Can-in-Can	IB	Y	5	15	50	2	5000
	0.0000	0.0000	0.0600	0.5882	0.0000	0.5500	0.5000
Electrometallurgical	IB	Y	4	15	50	2	1700
	0.0000	0.0000	0.0900	0.5882	0.0000	0.5500	0.8300
Borehole (Direct)	IB	Y	5	6	50	2	3500
	0.0000	0.0000	0.0600	0.8529	0.0000	0.5500	0.6500
Borehole (Immob)	IB	Y	5	11	50	2	3500
	0.0000	0.0000	0.0600	0.7059	0.0000	0.5500	0.6500

Table C.2 - Worst Case S&S Aggregation Data Continued

	Non-proliferation							
	Theft				Diversion			
	Safeguards & Security				Material Char*	Environment*		
	Measure Uncertainty	*Type of NAS*	*Accessibility*	*U.S. Classification*	*IAEA Attractiveness*	*Bulk Through-put**	*No. processing steps**	*MAX Inventory**
Exist LWR, Exist Fac	0.06	30	THN	Y	DUU	5	22	31.5
	0.1979	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.3703
Part Comp LWR	0.06	30	THN	Y	DUU	5	22	39
	0.1979	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.2202
Exist LWR, Green Fac	0.06	30	THN	Y	DUU	5	22	31.5
	0.1979	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.3703
Evolutionary Reactor	0.06	30	THN	Y	DUU	5	22	47.4
	0.1979	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.0520
CANDU	0.06	30	THN	Y	DUU	5	22	33
	0.1979	0.0433	0.0000	0.0000	0.0000	0.0600	0.3824	0.3403
Vitrif. Greenfield	0.12	30	THN	Y	DUU	5	13	50
	0.1853	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.0000
Vitrif. Can-in-Can	0.16	30	THN	Y	DUU	5	13	50
	0.1768	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.0000
Vitrif. Adj. Melter	0.12	30	THN	Y	DUU	5	13	50
	0.1853	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.0000
Ceramic Greenfield	0.1	30	THN	Y	DUU	5	13	50
	0.1895	0.0433	0.0000	0.0000	0.0000	0.0600	0.6471	0.0000
Ceramic Can-in-Can	0.15	30	THN	Y	DUU	5	15	50
	0.1789	0.0433	0.0000	0.0000	0.0000	0.0600	0.5882	0.0000
Electrometallurgical	0.08	30	THN	Y	DUU	4	15	50
	0.1937	0.0433	0.0000	0.0000	0.0000	0.0900	0.5882	0.0000
Borehole (Direct)	0.02	30	THN	Y	DUU	5	6	50
	0.6898	0.0433	0.0000	0.0000	0.0000	0.0600	0.8529	0.0000
Borehole (Immob)	0.06	30	THN	Y	DUU	5	11	50
	0.1979	0.0433	0.0000	0.0000	0.0000	0.0600	0.7059	0.0000

Table C.2 - Worst Case S&S Aggregation Data Continued

	Non-proliferation			
	Diversion			
	Safeguards & Security*			
	*Measure Uncert.**	*Type of NAS**	*Accessi-bility**	*Int'l Class*
Exist LWR, Exist Fac	0.1	30	THN	Y
	0.1895	0.0433	0.0000	0.0000
Part Comp LWR	0.1	30	THN	Y
	0.1895	0.0433	0.0000	0.0000
Exist LWR, Green Fac	0.1	30	THN	Y
	0.1895	0.0433	0.0000	0.0000
Evolutionary Reactor	0.1	30	THN	Y
	0.1895	0.0433	0.0000	0.0000
CANDU	0.1	30	THN	Y
	0.1895	0.0433	0.0000	0.0000
Vitrif. Greenfield	0.2	30	THN	Y
	0.1684	0.0433	0.0000	0.0000
Vitrif. Can-in-Can	0.2	30	THN	Y
	0.1684	0.0433	0.0000	0.0000
Vitrif. Adj. Melter	0.2	30	THN	Y
	0.1684	0.0433	0.0000	0.0000
Ceramic Greenfield	0.15	30	THN	Y
	0.1789	0.0433	0.0000	0.0000
Ceramic Can-in-Can	0.2	30	THN	Y
	0.1684	0.0433	0.0000	0.0000
Electrometallurgical	0.15	30	THN	Y
	0.1789	0.0433	0.0000	0.0000
Borehole (Direct)	0.04	30	THN	Y
	0.3633	0.0433	0.0000	0.0000
Borehole (Immob)	0.1	30	THN	Y
	0.1895	0.0433	0.0000	0.0000

Appendix D - Detail Base Case Rankings for Theft and Diversion

Figure D1 - Theft-Environment Ranking

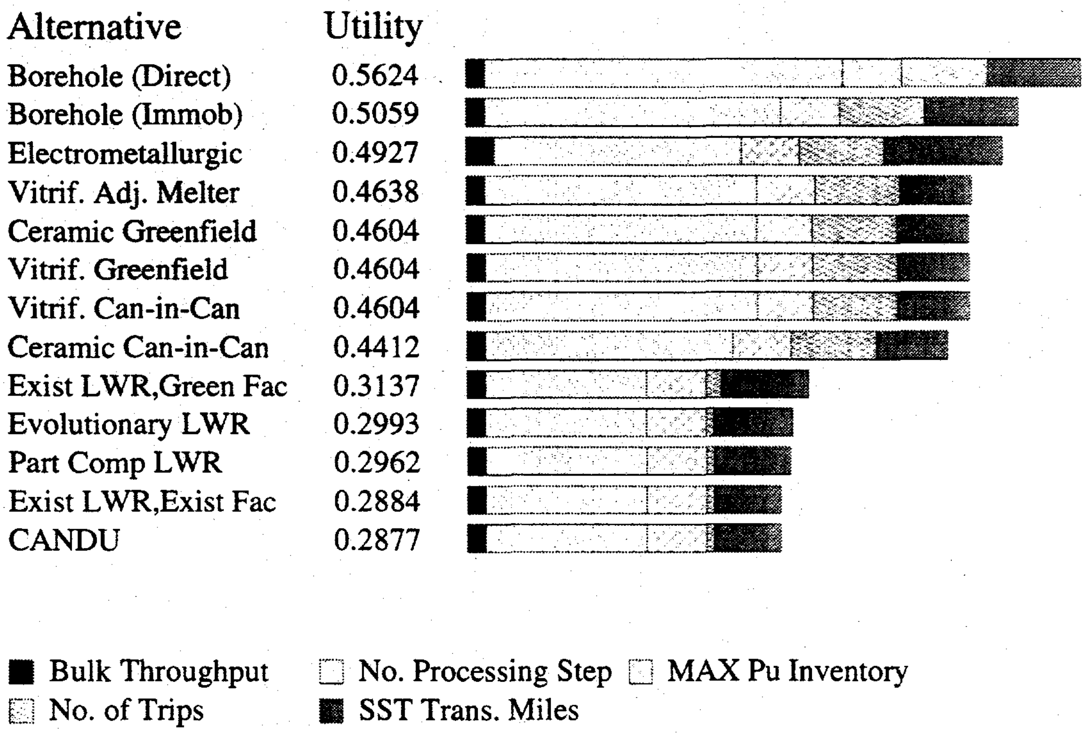


Figure D2 - Theft-Safeguards and Security Ranking

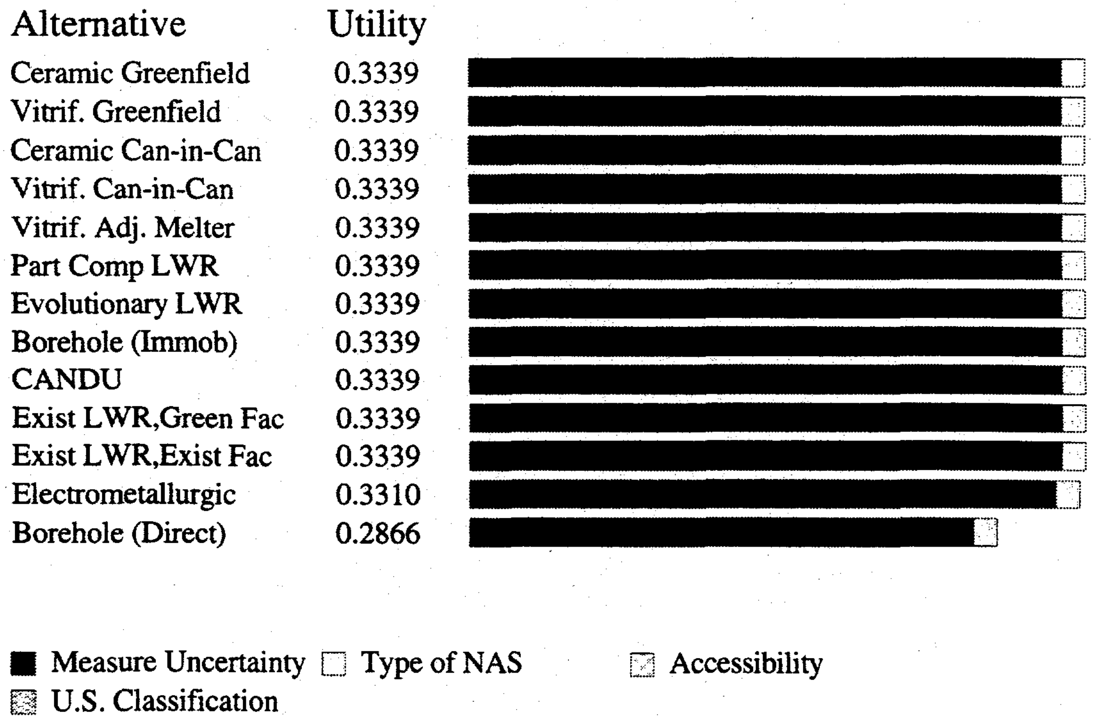


Figure D3 - Diversion-Environment* Ranking

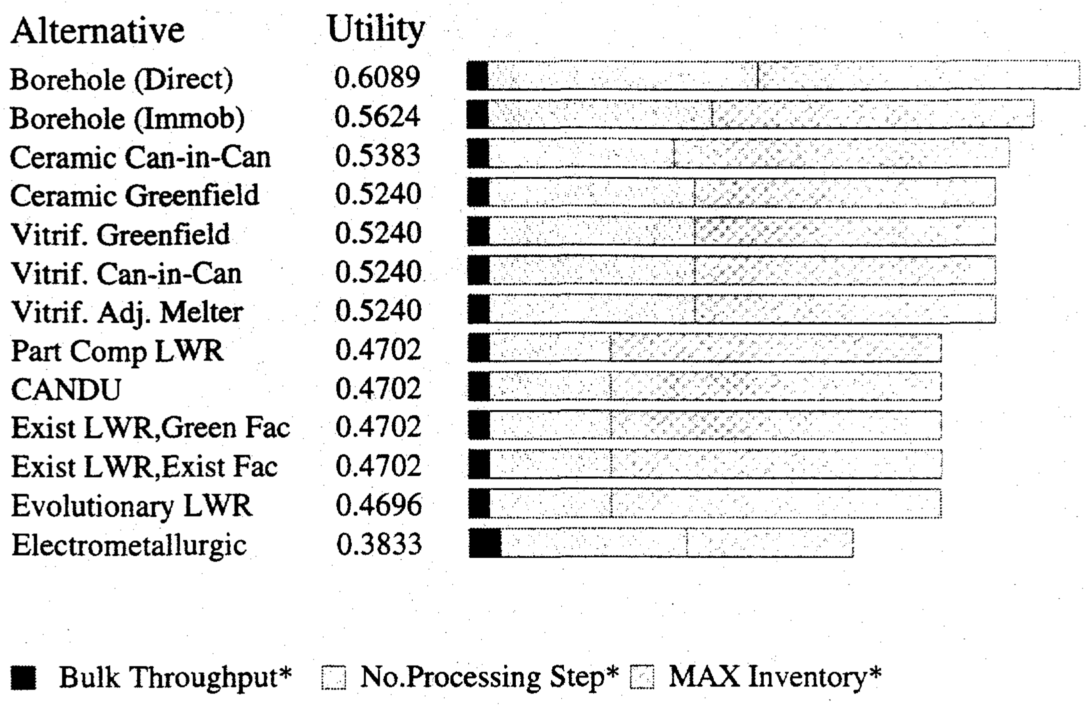
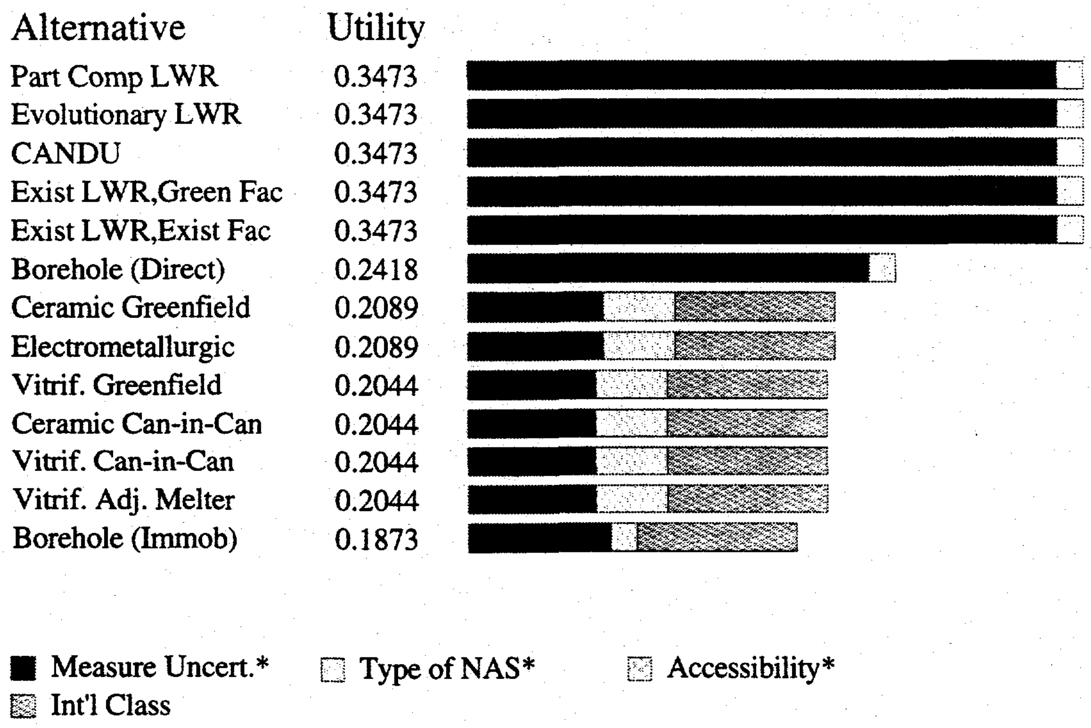


Figure D4 - Diversion-Safeguards and Security* Ranking



Appendix E - Sensitivity to the Weights on Objectives and Measures

Figure E1 - Reactor Sensitivity to Weight on Non-proliferation

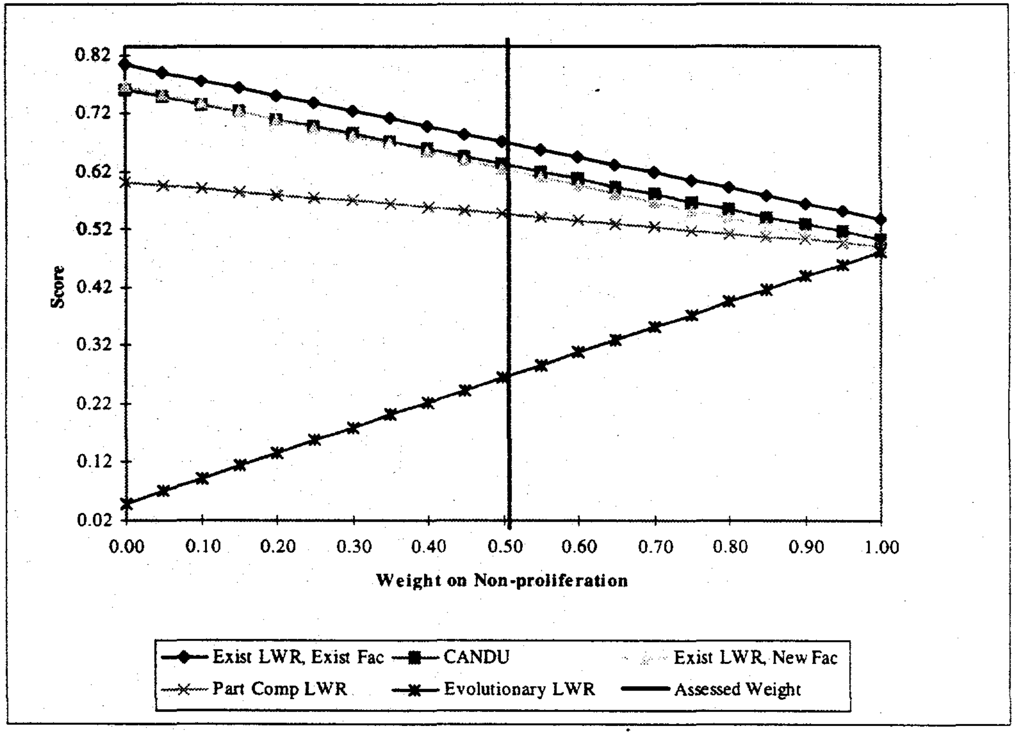


Figure E1.1 - Reactor Sensitivity to Weight on Theft

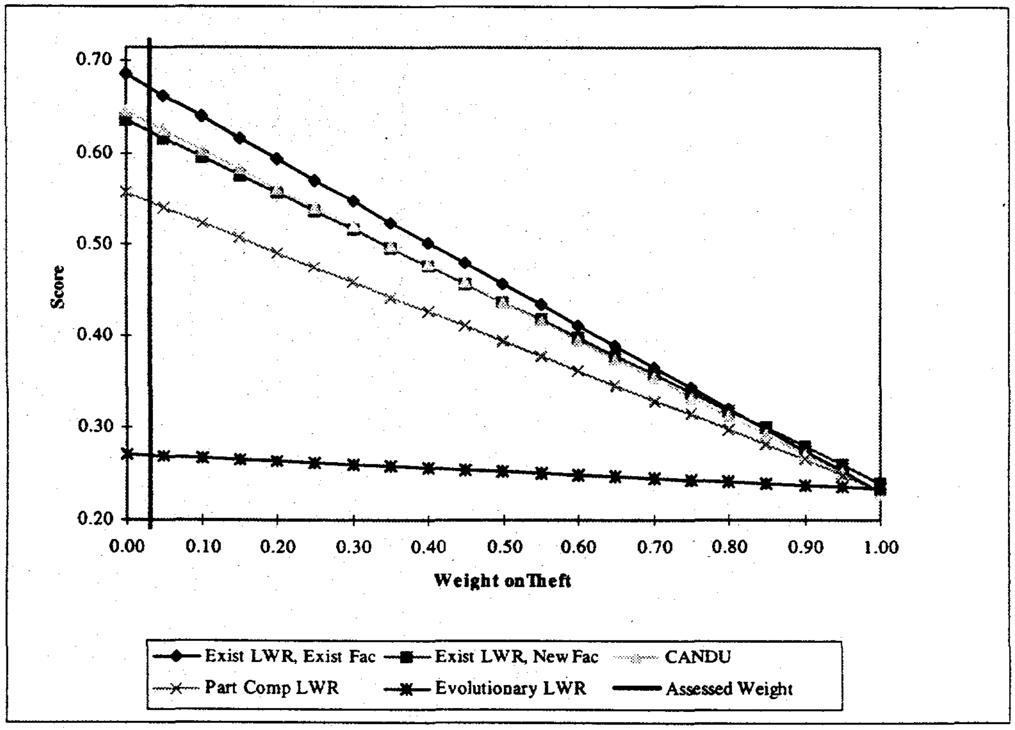


Figure E1.2 - Reactor Sensitivity to Weight on Diversion

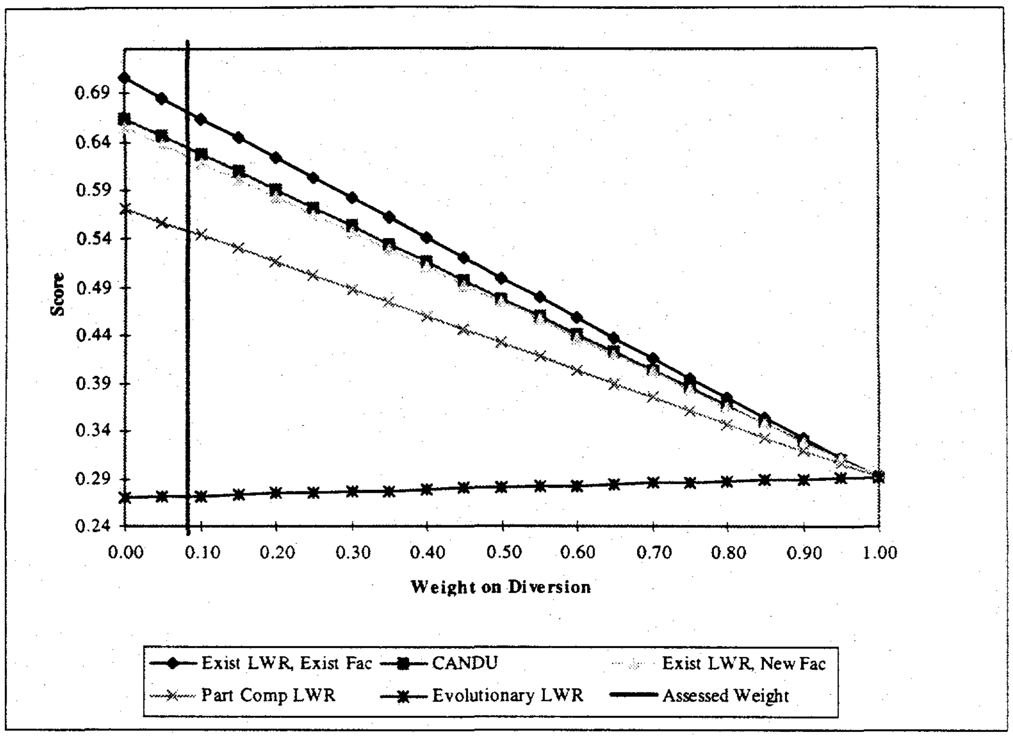


Figure E1.3 - Reactor Sensitivity to Weight on Irreversibility

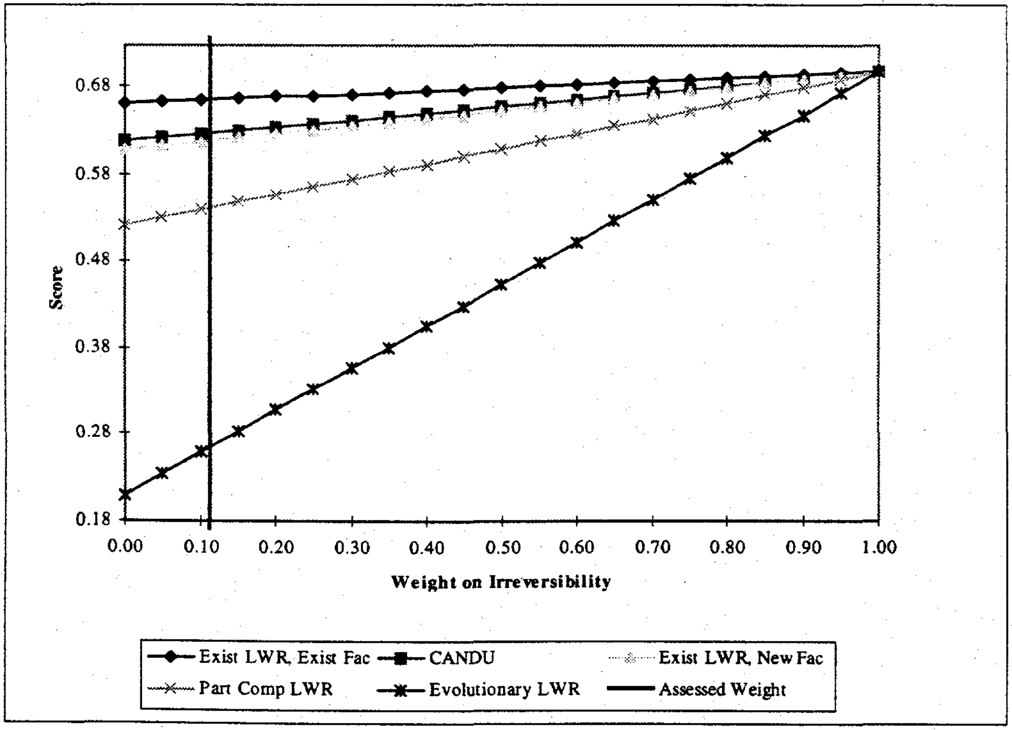


Figure E1.4 - Reactor Sensitivity to Weight on International Cooperation

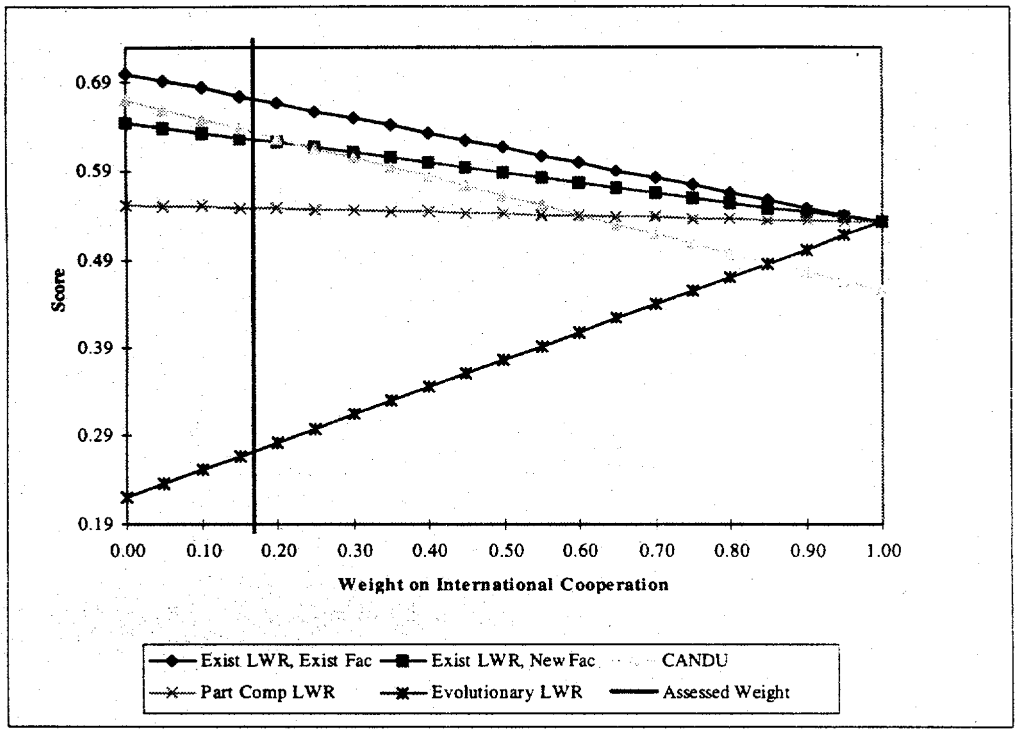


Figure E1.5 - Reactor Sensitivity to Weight on Russian Cooperation

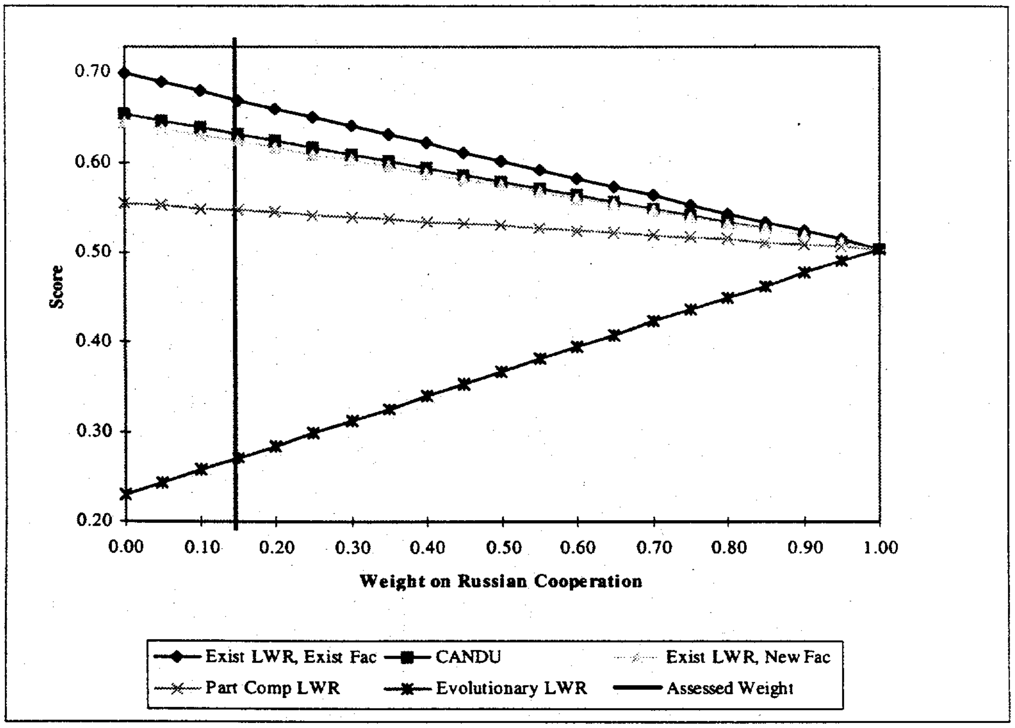


Figure E1.6 - Reactor Sensitivity to Weight on Civil Use of Plutonium

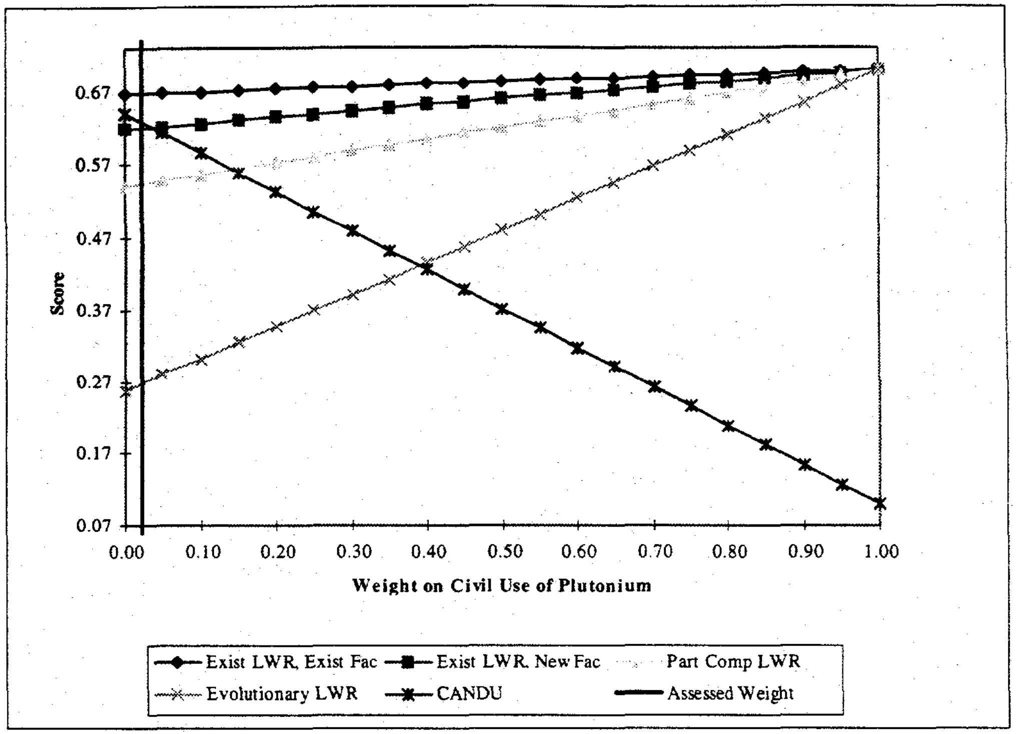


Figure E1.7 - Reactor Sensitivity to Weight on Timeliness

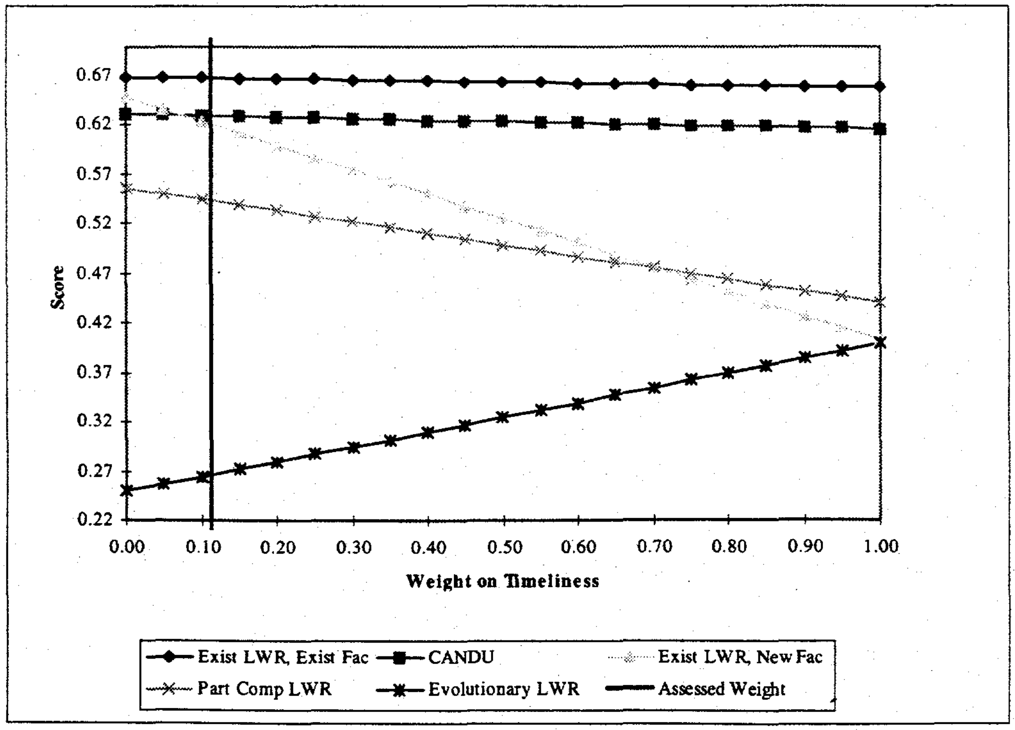


Figure E1.8 - Reactor Sensitivity to Weight on Time to Start

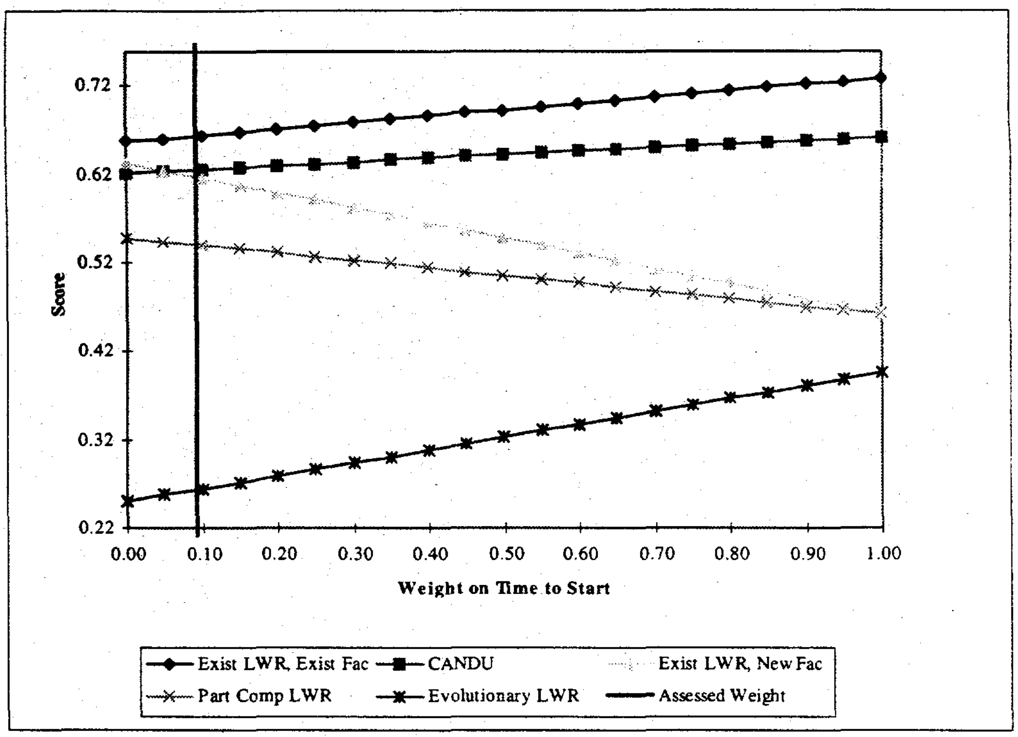


Figure E1.9 - Reactor Sensitivity to Weight on Time to Complete

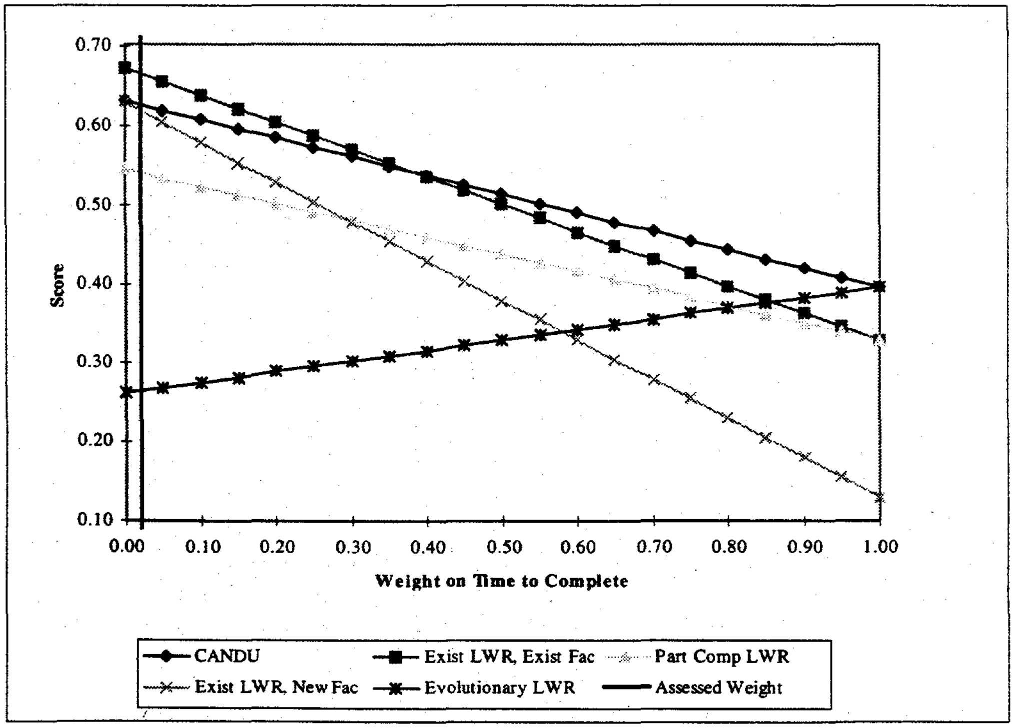


Figure E2 - Reactor Sensitivity to Weight on Operational Effectiveness

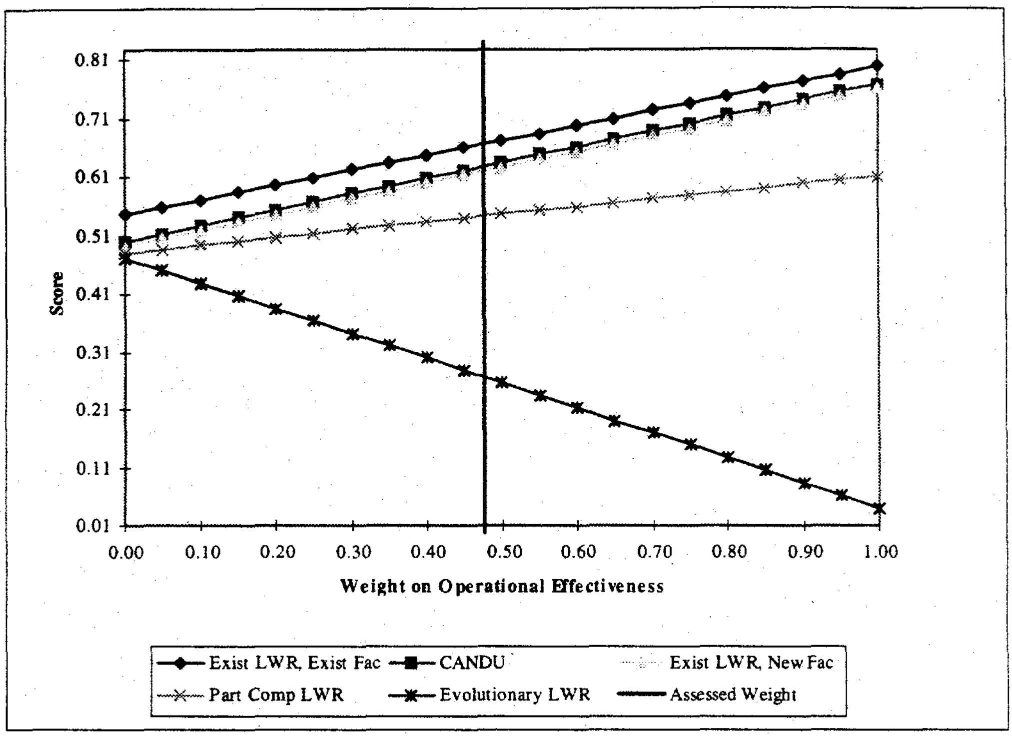


Figure E2.1 - Reactor Sensitivity to Weight on Investment Cost

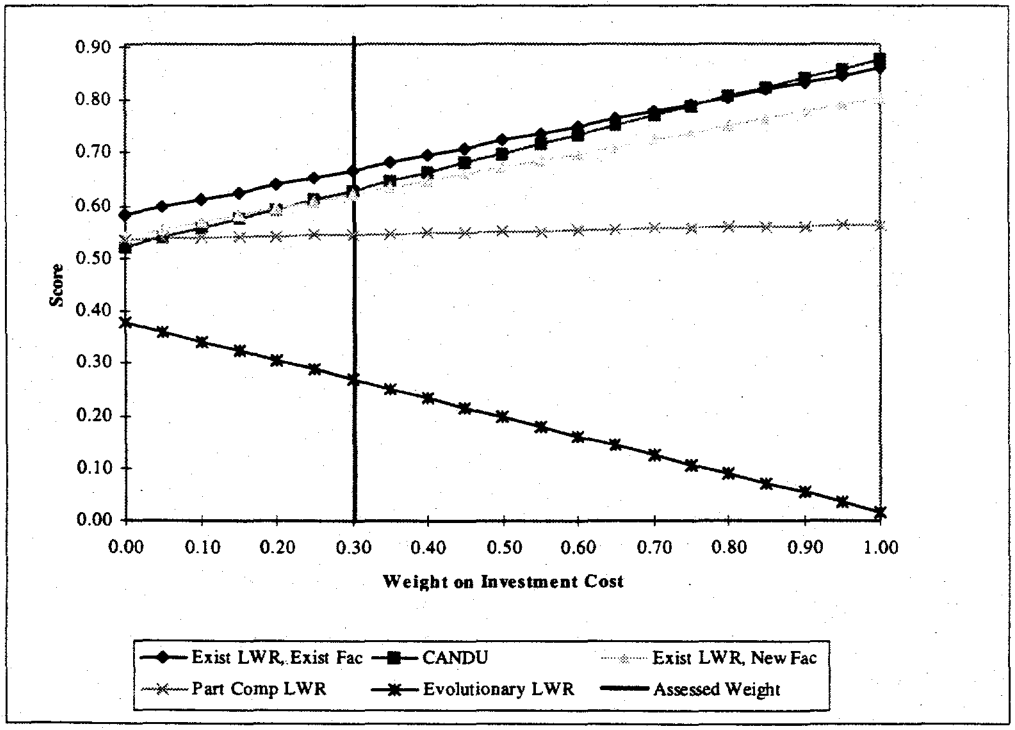


Figure E2.2 - Reactor Sensitivity to Weight on Life-cycle Cost

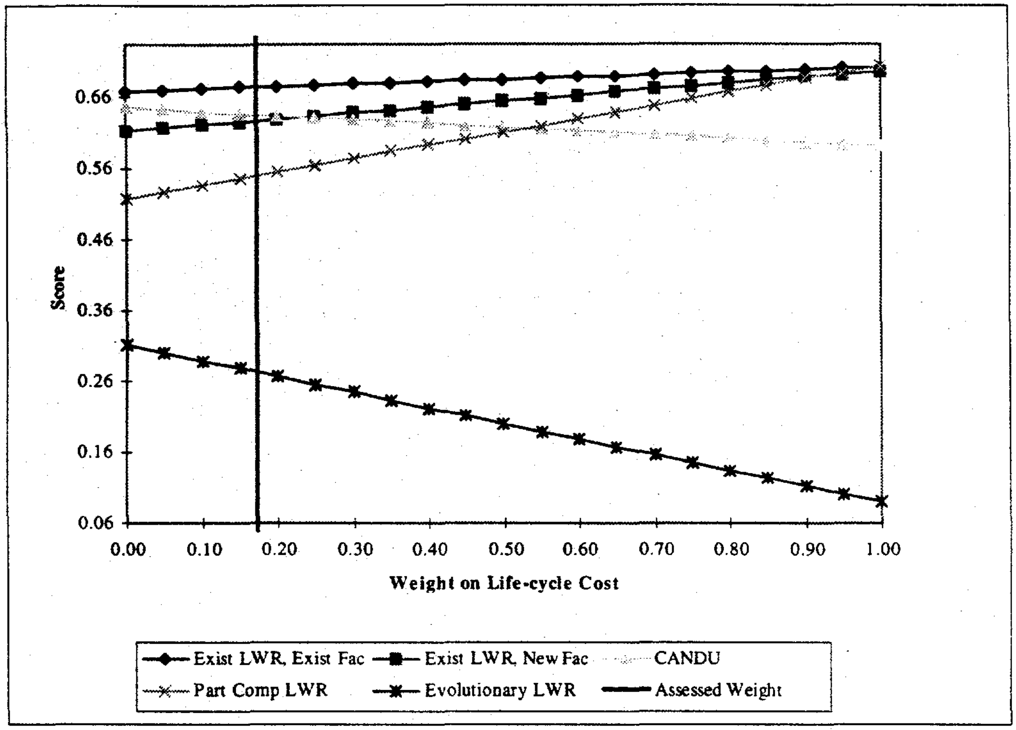


Figure E3 - Reactor Sensitivity to Weight on ES&H

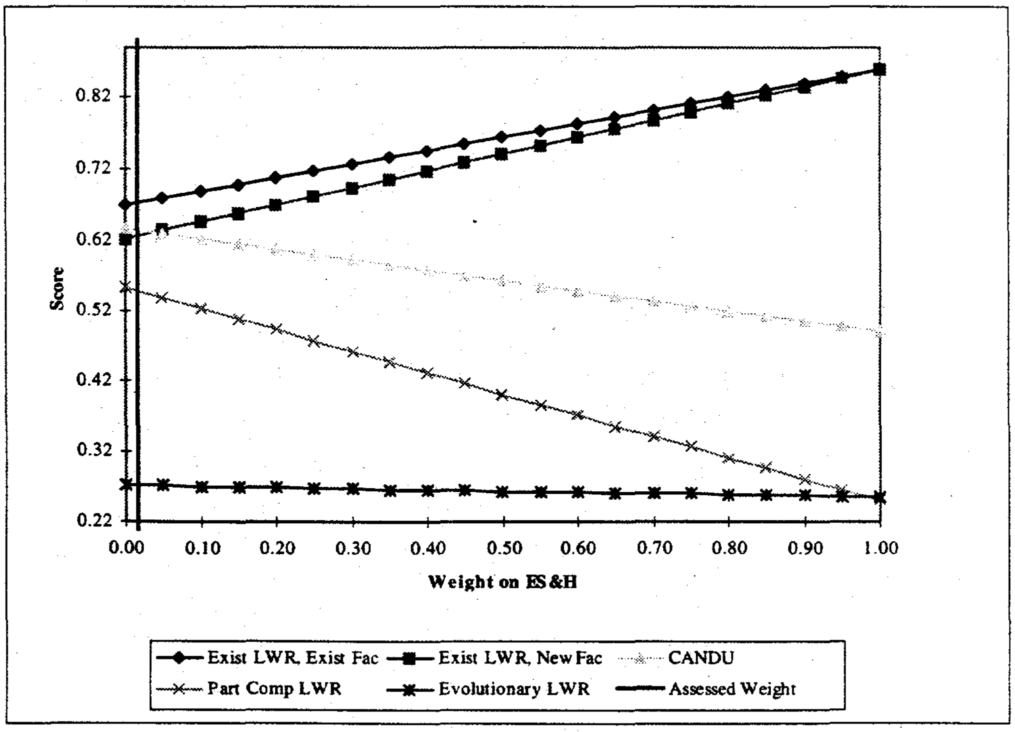


Figure E3.1 - Reactor Sensitivity to Weight on Human H&S

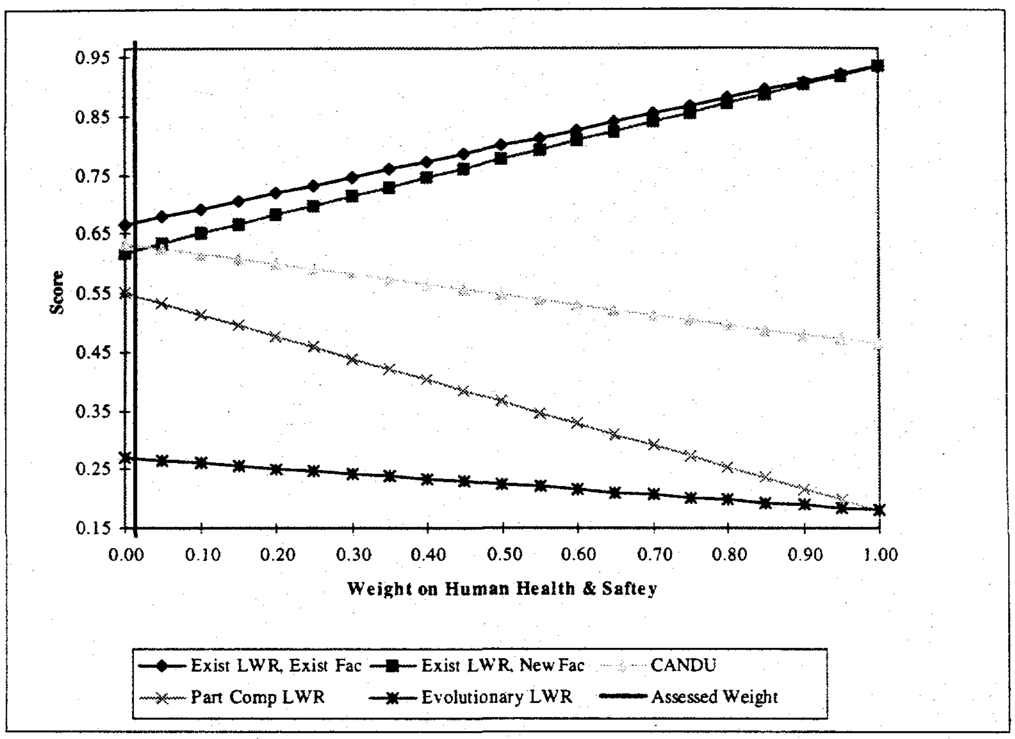


Figure E3.2 - Reactor Sensitivity to Weight on Natural Environment

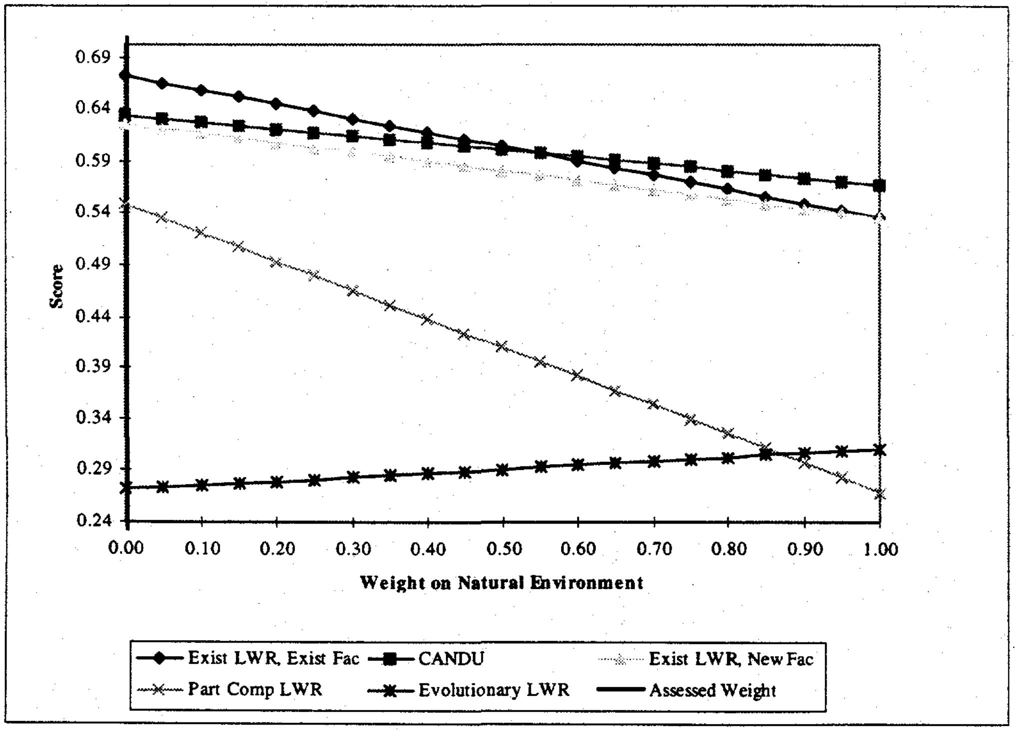


Figure E3.3 - Reactor Sensitivity to Weight on Socio-economic

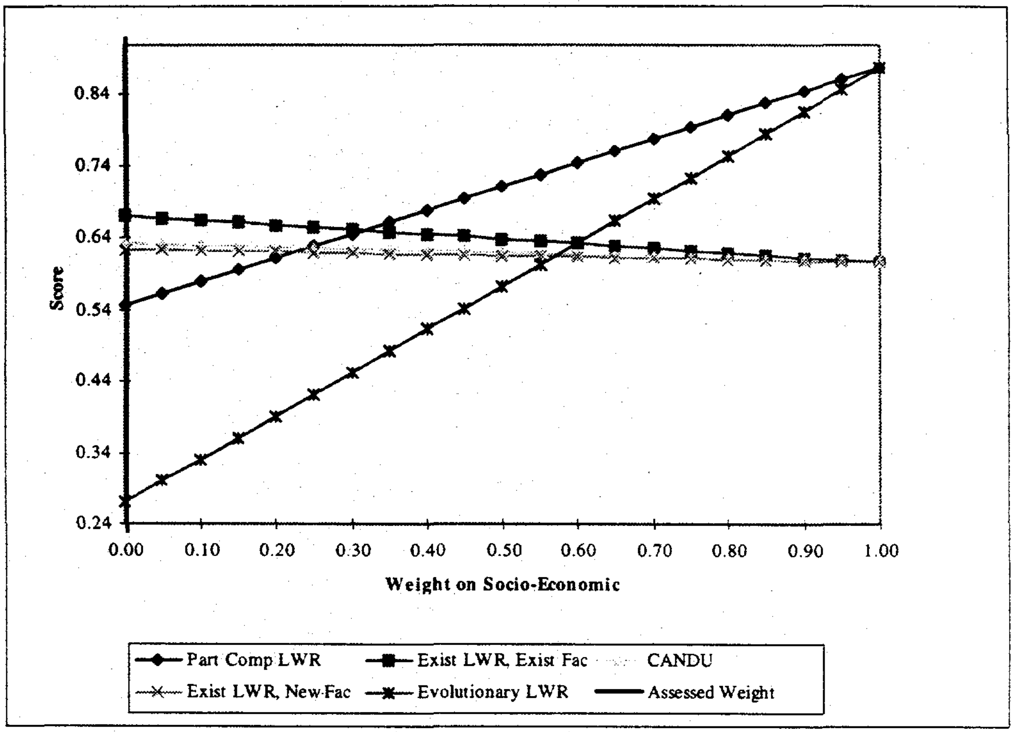


Figure E4 - Non-reactor Sensitivity to Weight on Non-proliferation

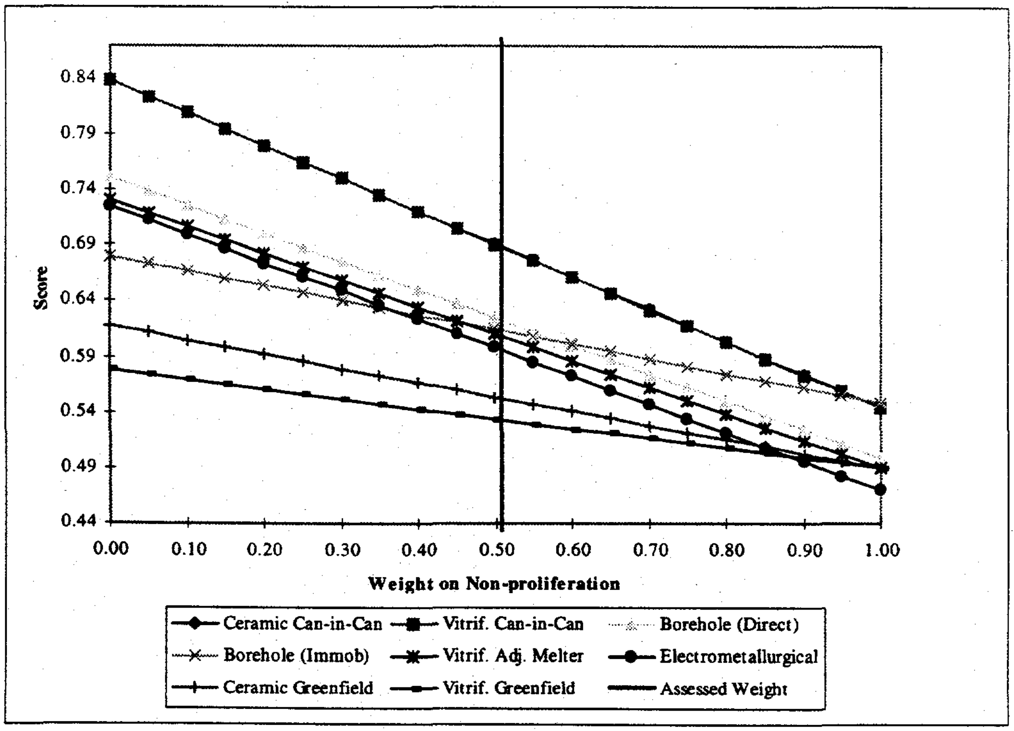


Figure E4.1 - Non-reactor Sensitivity to Weight on Theft

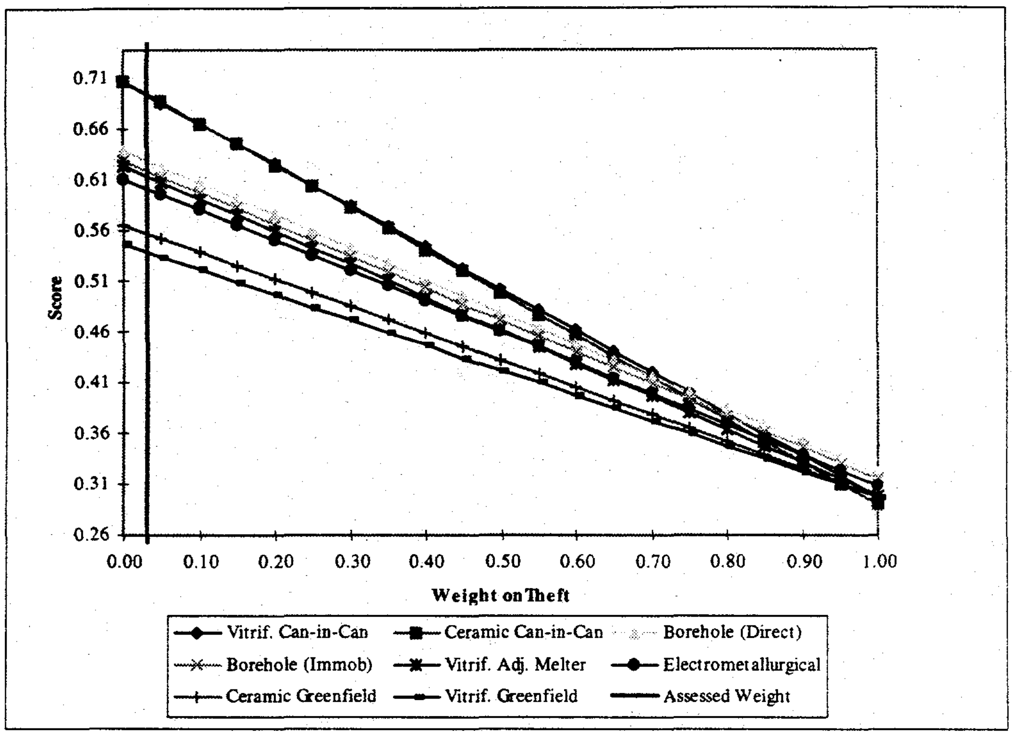


Figure E4.2 - Non-reactor Sensitivity to Weight on Diversion

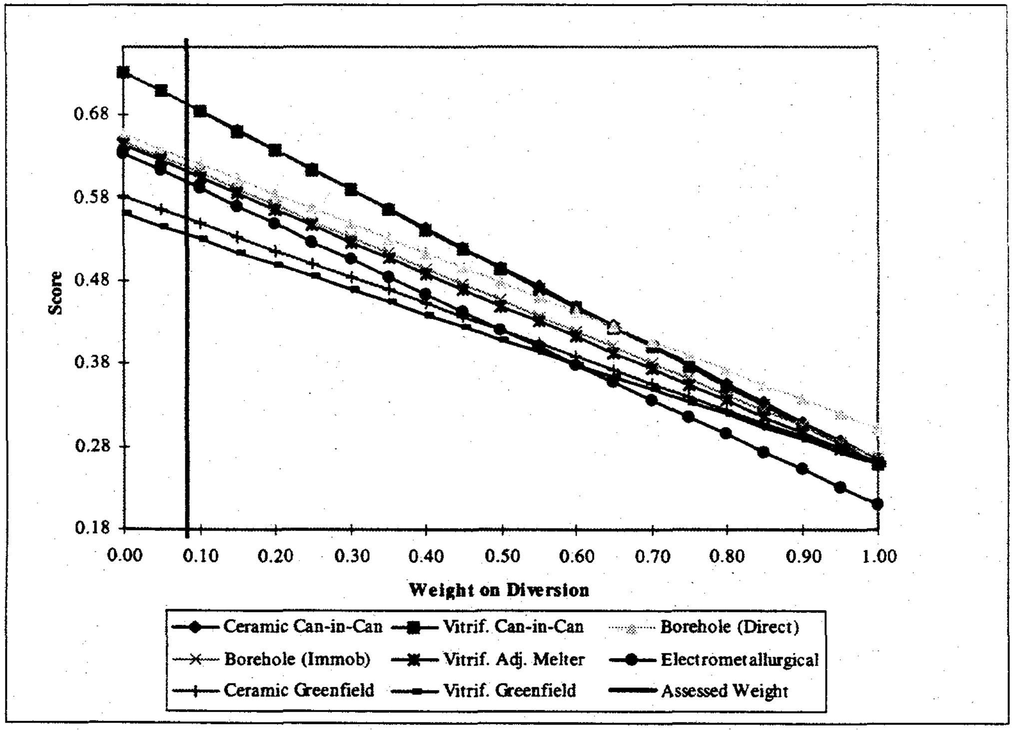


Figure E4.3 - Non-reactor Sensitivity to Weight on Irreversibility

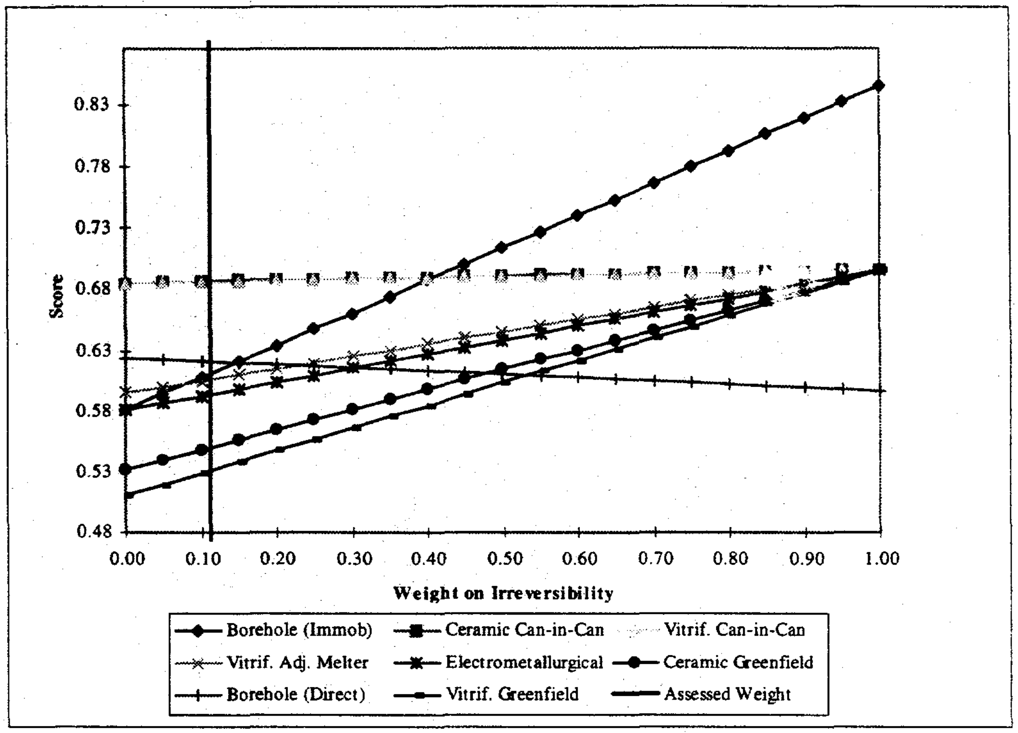


Figure E4.4 - Non-reactor Sensitivity to Weight on International Cooperation

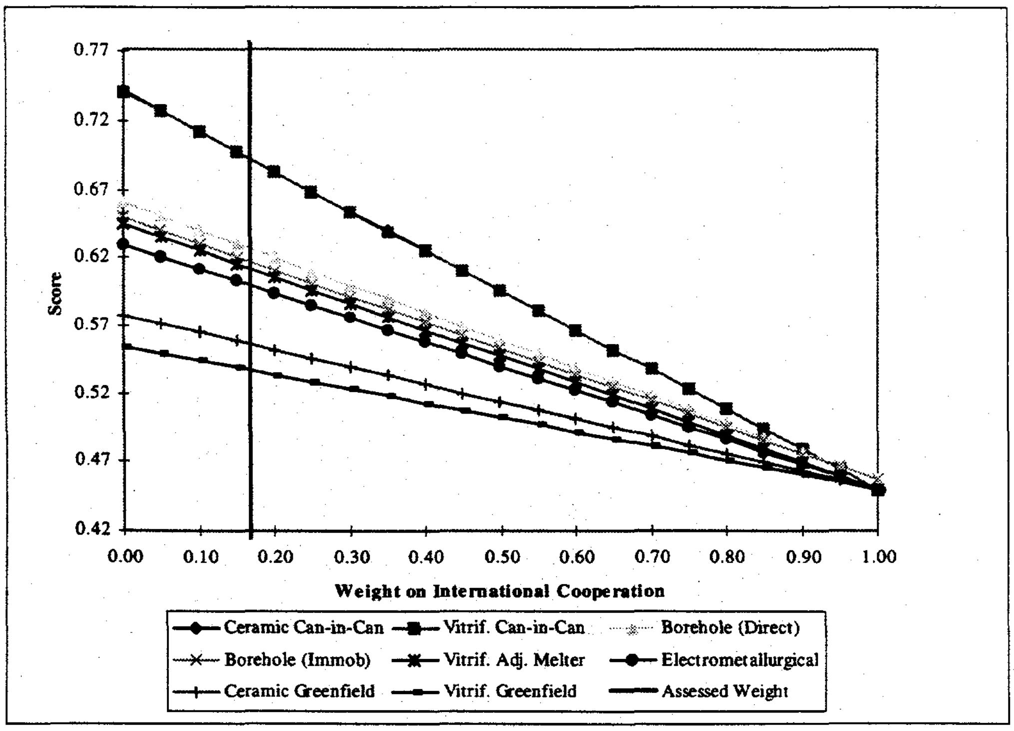


Figure E4.5 - Non-reactor Sensitivity to Weight on Russian Cooperation

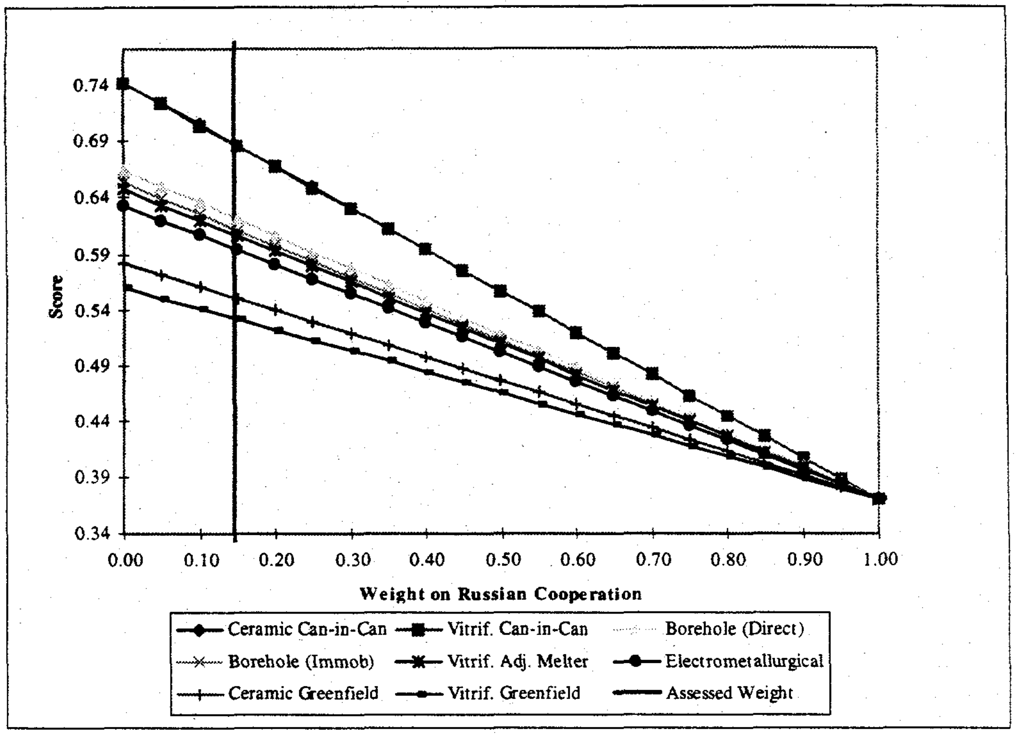


Figure E4.6 - Non-reactor Sensitivity to Weight on Civil Use of Plutonium

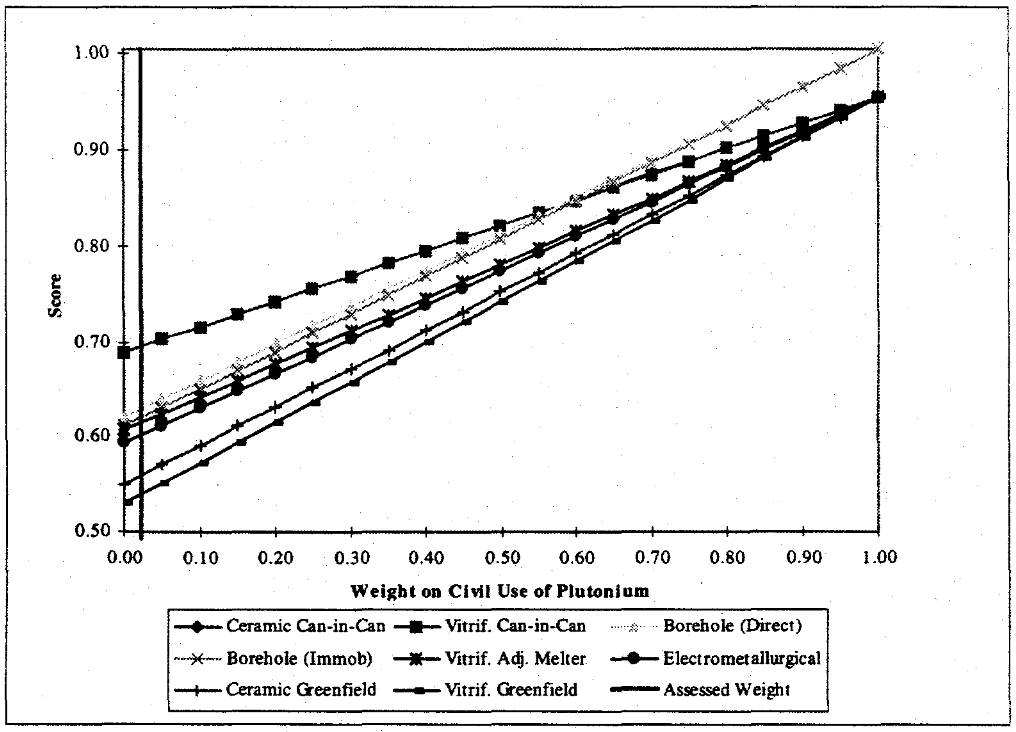


Figure E4.7 - Non-reactor Sensitivity to Weight on Timeliness

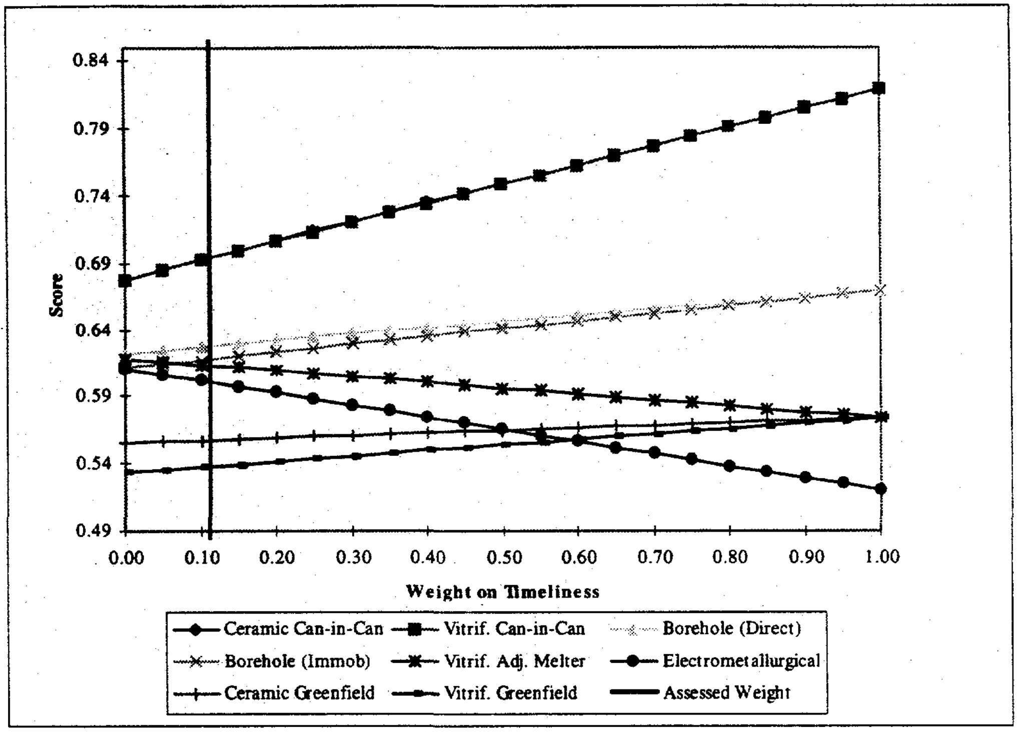


Figure E4.8 - Non-reactor Sensitivity to Weight on Time to Start

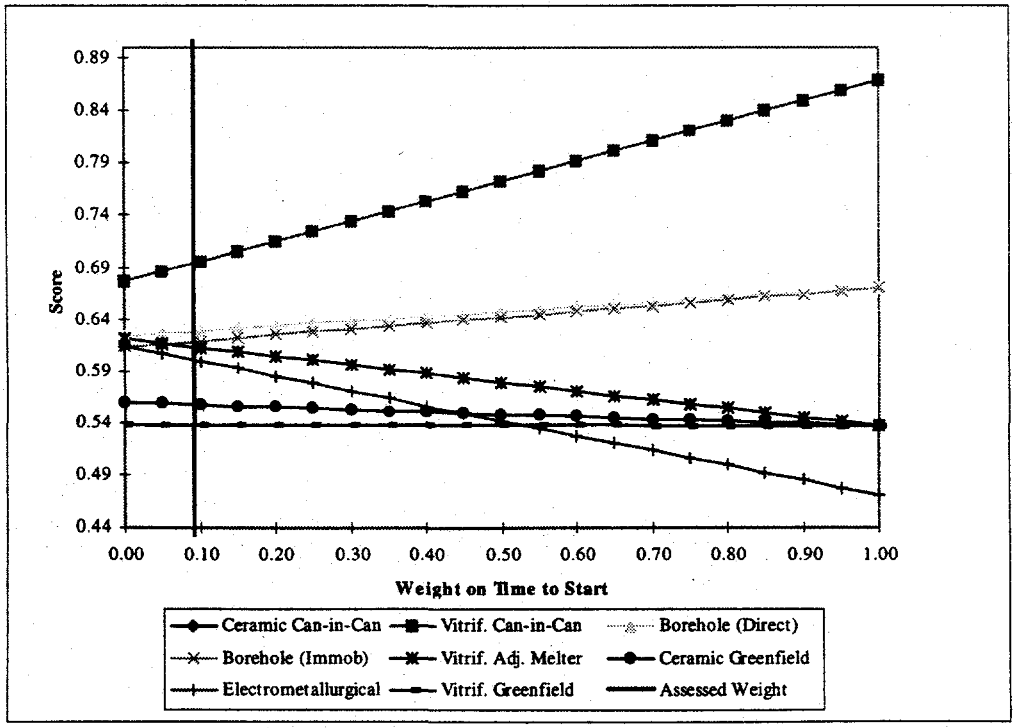


Figure E4.9 - Non-reactor Sensitivity to Weight on Time to Complete

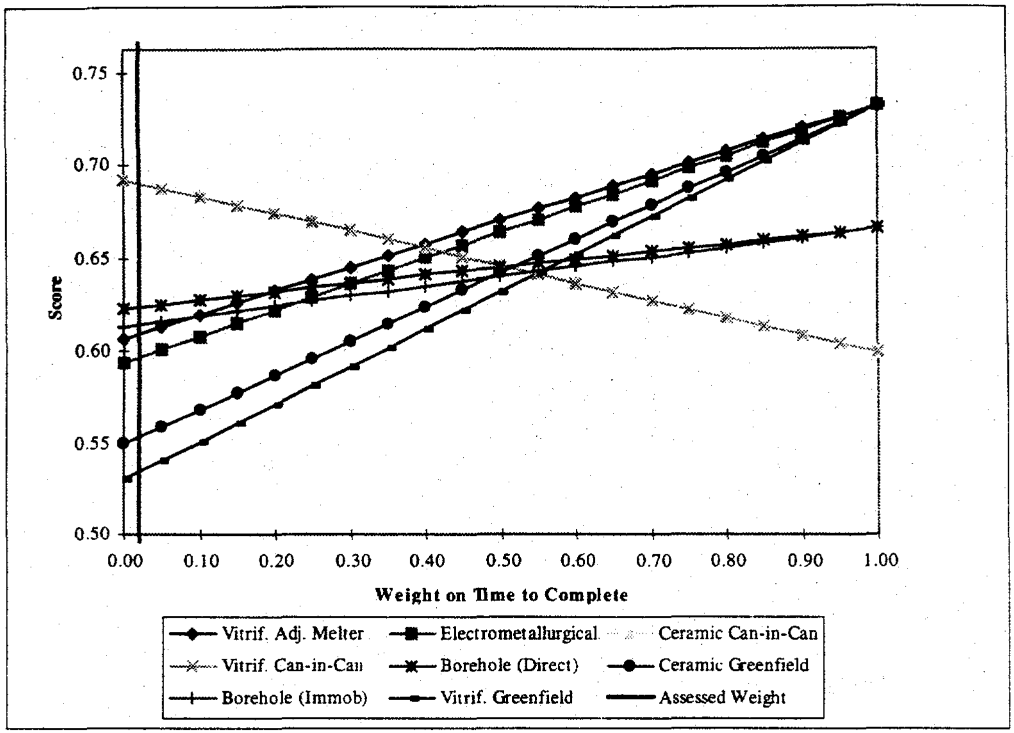


Figure E5 - Non-reactor Sensitivity to Weight on Operational Effectiveness

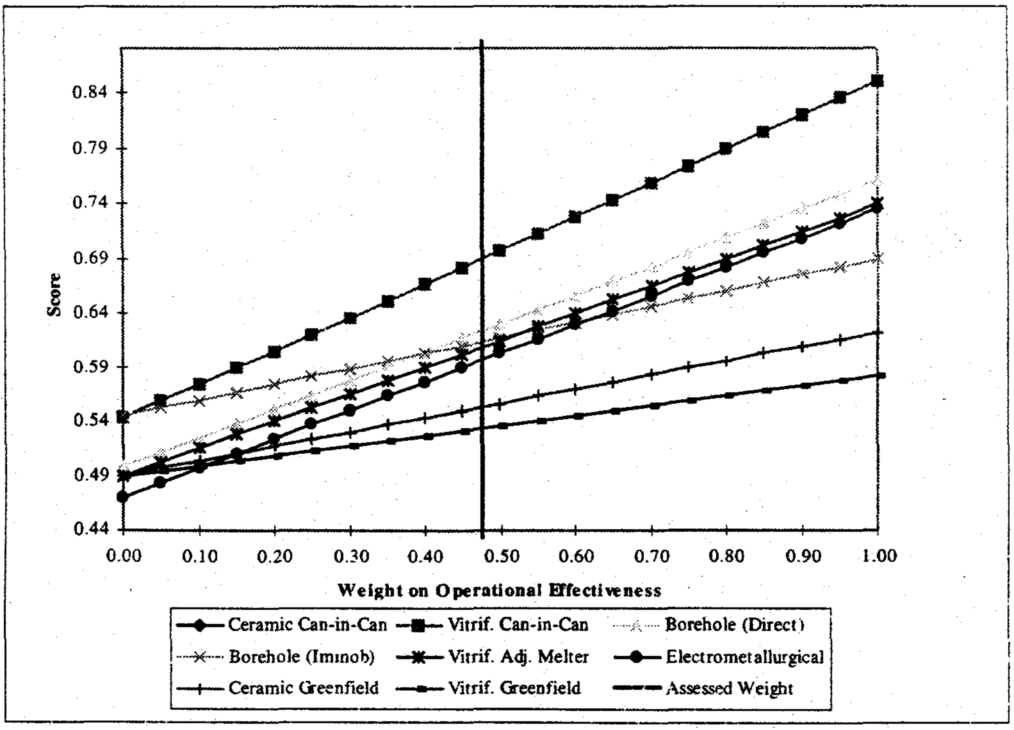


Figure E5.1 - Non-reactor Sensitivity to Weight on Investment Cost

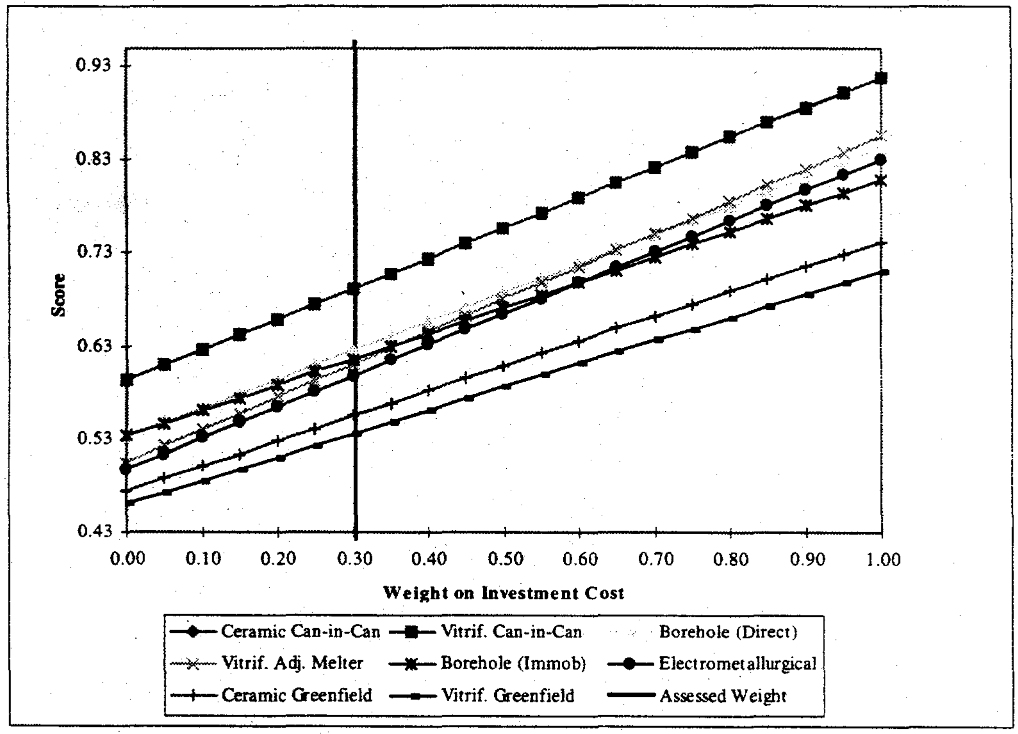


Figure E5.2 - Non-reactor Sensitivity to Weight on Life-cycle Cost

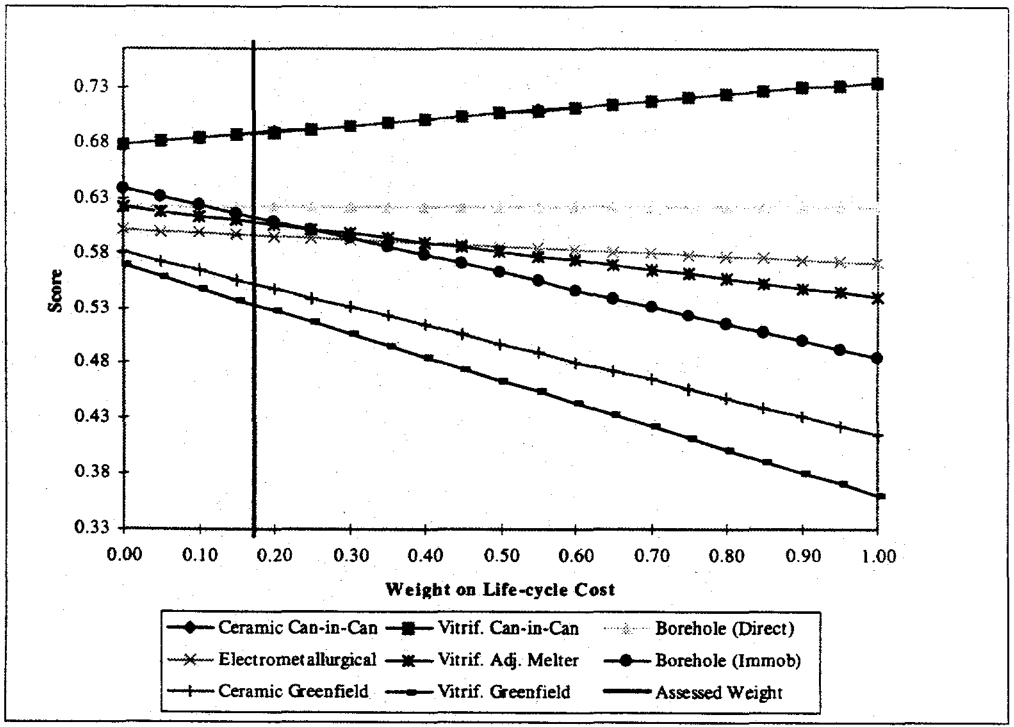


Figure E6 - Non-reactor Sensitivity to Weight on ES&H

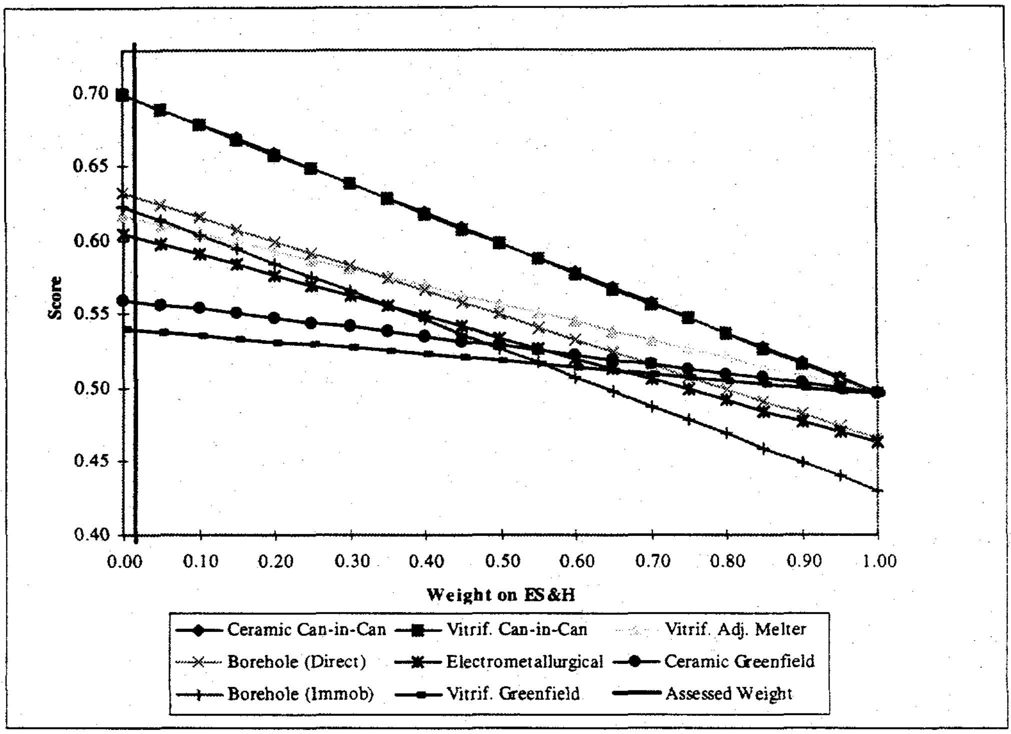


Figure E6.1 - Non-reactor Sensitivity to Weight on Human H&S

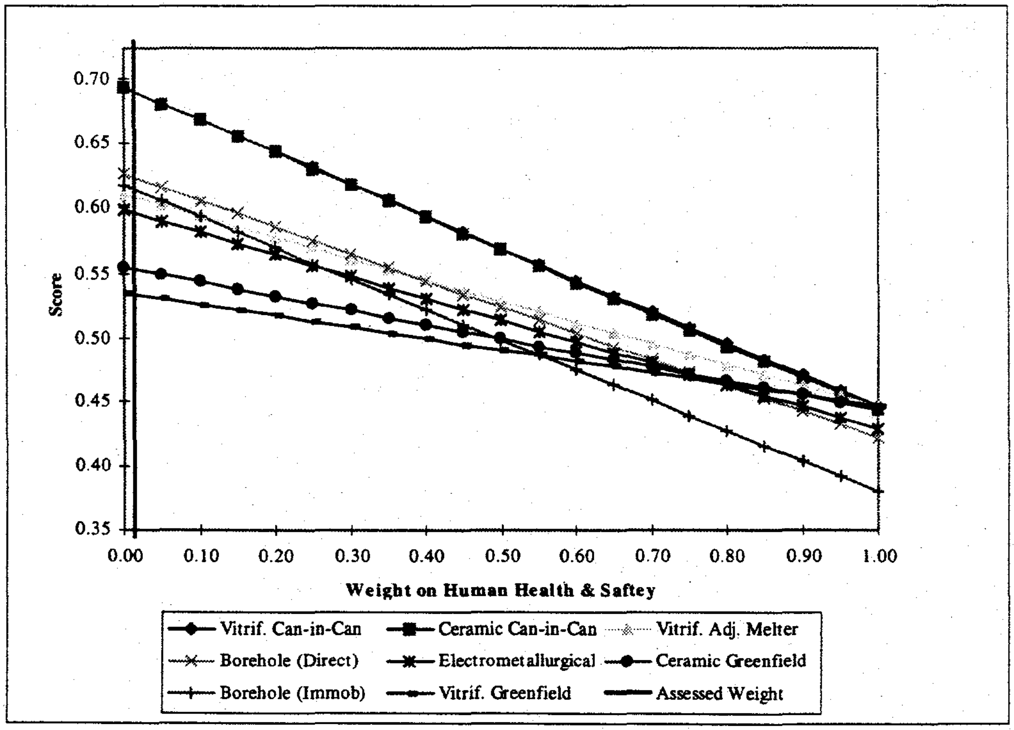


Figure E6.2 - Non-reactor Sensitivity to Weight on Natural Environment

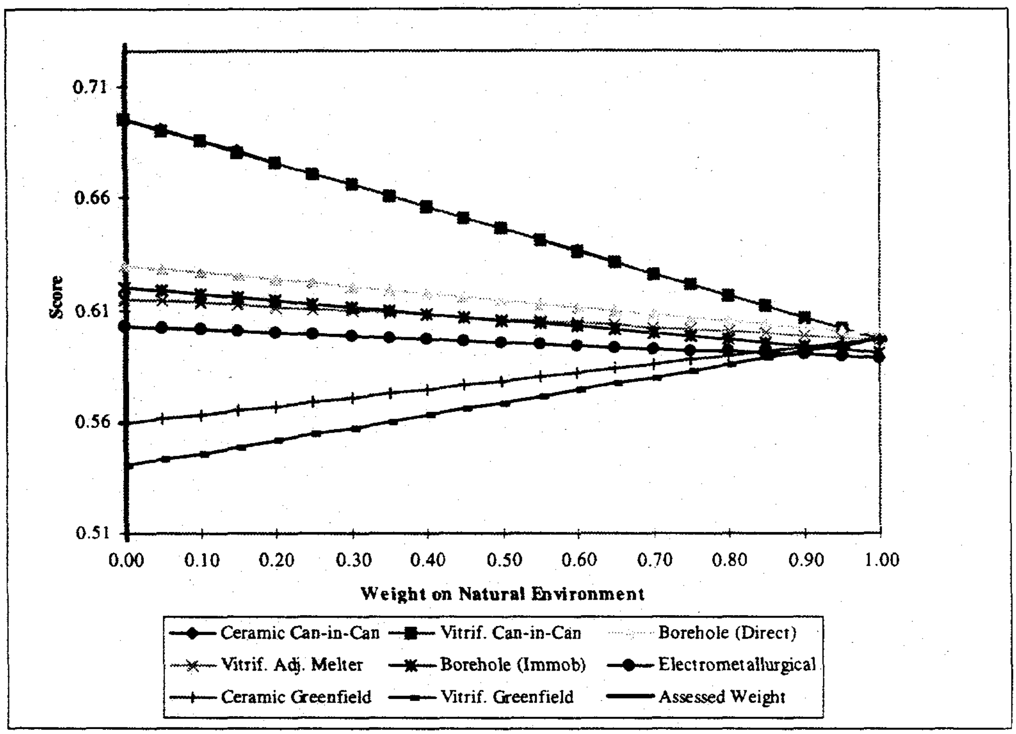
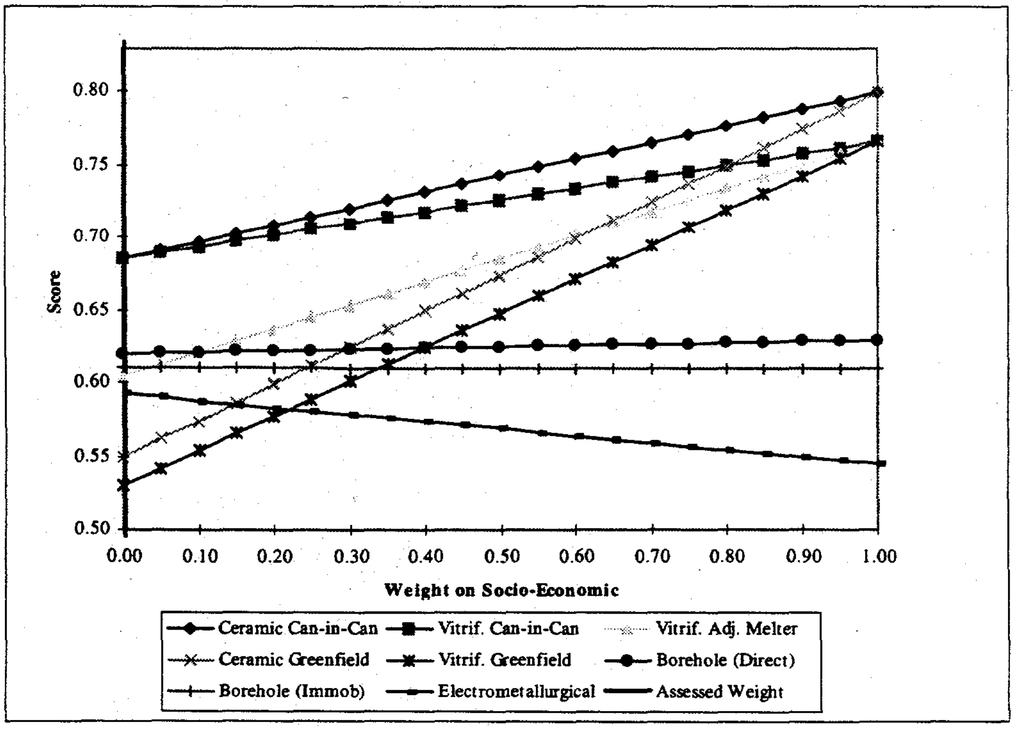
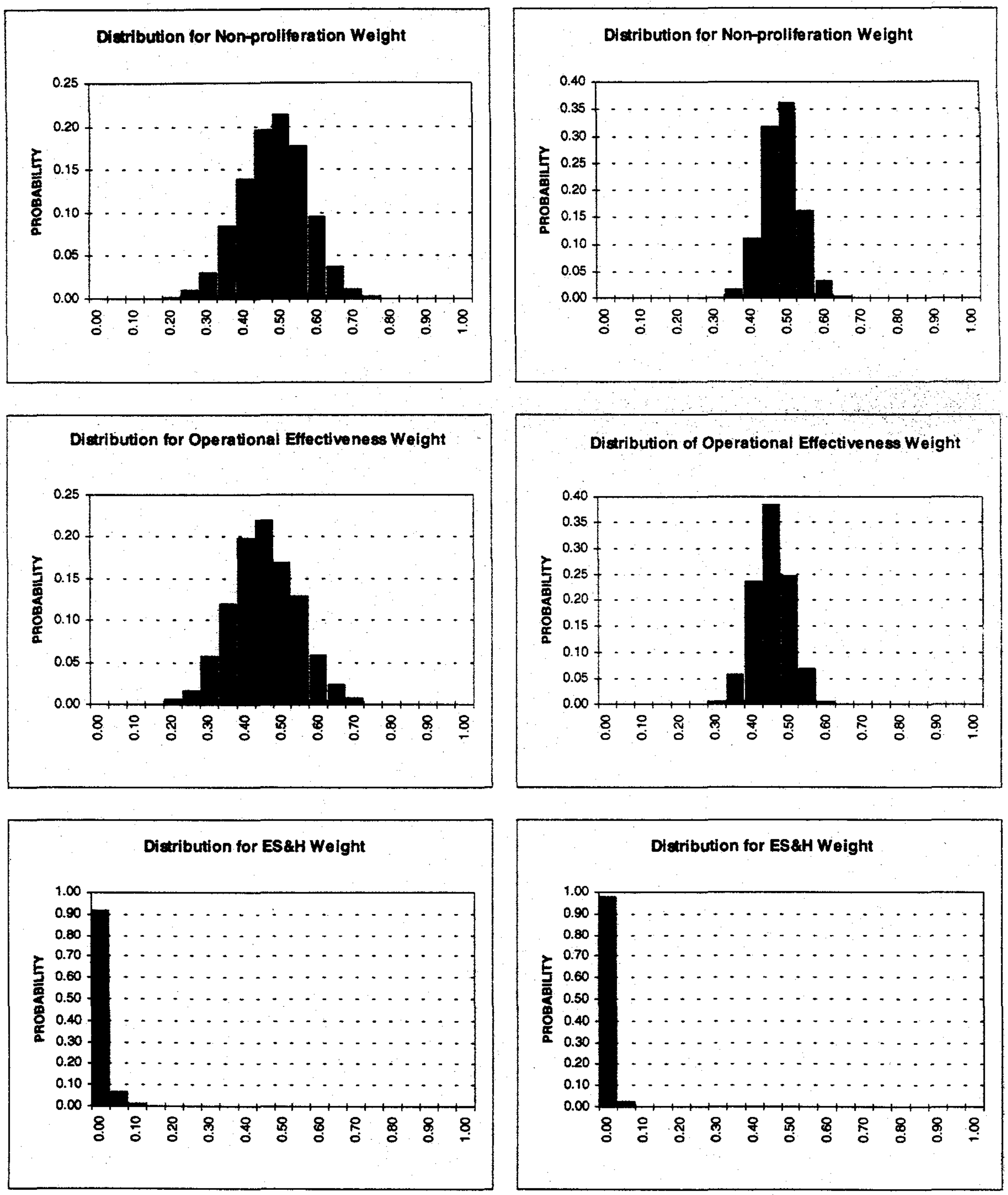


Figure E6.3 - Non-reactor Sensitivity to Weight on Socio-economic



Appendix F - Dirichlet Distributions Used in Simulation Analysis

Figure F1 - Dirichlet Weights



Sum of Parameters = 30

Sum of Parameters = 100

Distribution for Non-proliferation Weight

Distribution for Non-proliferation Weight

Distribution for Operational Effectiveness Weight

Distribution of Operational Effectiveness Weight

Distribution for ES&H Weight

Distribution for ES&H Weight

Appendix G - Computer Implementation

While a small multi-attribute utility analysis can be implemented using a hand held calculator and pen and paper, a more complicated analysis is facilitated by the use of a spreadsheet or specialty computer application. In our formal analysis, we chose to use two computer packages: Microsoft Excel™ and Logical Decisions for Windows™. We will discuss the rationale for each of these packages in the following sections.

G.1 Microsoft Excel

Microsoft Excel was chosen for a variety of reasons. An important consideration was the wide spread use of the application at the national laboratories. We anticipated a great deal of data exchange and it seemed prudent to use a package that a majority of the participants used also.

In the planning phases of the project, we assumed that the data providers would generate a single number, or at least a probability distribution, representing each measure. After meeting with the S&S team, we realized that some of the data would require additional aggregation. As previously mentioned, the S&S team provided us with data per facility rather than per alternative. Excel provided a flexible means to combine these facility measure levels into an overall measure for each alternative. We also used Excel to perform a similar facility-to-alternative aggregation for the ES&H data.

After building the Excel spreadsheets necessary to aggregate the S&S and ES&H data, we built a large composite Excel spreadsheet capable of carrying out the entire MAU analysis. Our rationale was to have two versions of the model in unique software packages to provide a means of ensuring the accuracy of the model and its results. Each of the three major criterion, Non-proliferation, Operational Effectiveness and ES&H, had a separate Excel "sheet" where the model data could be input. These sheets were often exchanged with the alternative teams to provide a system of checks and balances and to allow us to simply "paste-in" data changes and maintain data integrity.

The three major objectives each had a separate Excel sheet which scored the alternatives -- applied the appropriate value functions -- on each measure. To generate the scores for each measure, custom Excel functions were imbedded in the model. These sheets were "linked" to the raw data sheets discussed above allowing a single area for data input and further protecting the data from entry errors.

Several other worksheets were added to the model to make it a more effective analysis tool. All the tradeoffs and their implied weights were placed in a separate sheet and pulled in by the alternative scoring sheets. A summary sheet was created that pulled in the raw and scored data in a compact form for distribution to interested parties. Macros were written to aide in ranking the data and printing various pieces of the analysis. The most important worksheet, however, was one which allowed us to quickly build and update the Logical Decisions models which we will now discuss.

G.2 Logical Decisions for Windows

Logical Decisions for Windows was created by Gary Smith (Smith, 1995) to aide in the assessment and application of multi-attribute utility theory. It has several advantages over Excel in that it 1) provides a graphical means of representing the structure of the MAU model , 2) aides in the assessment of weights and value functions,

3) allows the user to specify "non-linear" and categorical value functions, 4) provides a variety of insightful ways to display results, and 5) has built-in sensitivity analyses. We will now discuss the construction and usage of the Logical Decision models.

The first step in developing a Logical Decisions model is to construct a graphic representation of the problem structure. This task amounts to creating the goals and measures of the analysis and arranging them into the desired structure. The result of this procedure is a graphic hierarchy which we have used in this report and at various briefing sessions.

The next step is to define the value functions for each of the measures in the analysis. Logical Decisions can accommodate linear scales (i.e. for Russian cooperation), piece-wise linear scales (i.e. Investment cost) and categorical scales (i.e. DOE Attractiveness). After defining the value functions, several methods are available for specifying the weight of each measure in the analysis. While it is possible to invert the order of these two processes, it is important to recognize that the weights are only valid after specifying both the value functions and the tradeoffs.

Once the model structure, value functions and tradeoffs are defined, the final step required to build the model is the definition of alternatives and inputting data for each measure for each alternative. As alluded to earlier, this process was carried out with the help of the Excel model. Logical decisions allowed us to import Excel spreadsheets into the defined structure. Therefore, we could make changes in the raw data Excel sheets and allow Excel to determine the appropriate values to import into Logical Decisions. Importing the data in this fashion provided an assurance that the data in the Excel model was accurately transferred to the Logical Decisions model and provided an efficient means for defining variants of the basic model.

As discussed earlier, we explored three possible aggregations of the S&S data. As all three were based on the same model structure and raw data, we simply allowed the Excel model to indicate which pieces of data should be imported into each Logical Decisions model. The Excel model also insured that the ES&H data were properly aggregated relative to the raw data provided and passed on to the Logical Decisions files.

We used Logical Decisions to aide in the generation of weights during several of our assessment meetings. It was particularly useful at the S&S meetings in that it provided a quick means of combining the tradeoffs and providing feedback.

Our most common usage of Logical Decisions was to score and rank the alternatives displaying the results in a graphical format. The software allowed us to aggregate that model at any level we desired. For example, we could display a bar chart of the most and/or least preferred alternatives with respect to the Resistance to theft, ES&H, or even a particular measure, say Investment cost. Logical decisions also allows the generation of "stacked" bar charts that break down an alternatives scores into component scores. These color coded charts proved to be effective communicators of the underlying model implications within our analysis team and at briefing sessions.

Another powerful feature of Logical Decisions is its built in sensitivity analyses. It allows for quick insight into the effect of changing the weights used in the model and presents the results in a graphic format. It is also possible to introduce uncertainty into the analysis by assuming a probability distribution over a measure level.