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A Multi-Attribute Utility Decision Analysis for Treatment Alternatives for the DOE/SR Aluminum-Based Spent Nuclear Fuel

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Abstract

A multi-attribute utility analysis is applied to the decision to select a treatment method for the management of aluminum-based spent nuclear fuel (Al-SNF) owned by the United States Department of Energy (DOE). DOE will receive, treat, and temporarily store Al-SNF, most of which is composed of highly enriched uranium, at its Savannah River Site in South Carolina. DOE intends ultimately to send the treated Al-SNF to a geologic repository for permanent disposal. DOE initially considered ten treatment alternatives for the management of Al-SNF, and has narrowed the choice to two of these: the **direct disposal** and **melt and dilute** alternatives. The decision analysis presented in this document focuses on a decision between these two remaining alternatives.

ES Executive Summary

The results of this multi-attribute utility analysis (MUA) indicate that, for the Department of Energy - Savannah River Site (DOE-SR), the utility for the melt and dilute treatment alternative is greater than the utility for direct disposal. This result is due largely to the DOE-SR perception of the acceptability of the treatment alternatives to peer reviewers, and to the weight that DOE-SR puts on this acceptability. Different decision-makers might well have different relative utilities.

Sensitivity analyses were performed on the model to examine the impact of different decision-maker values on the outcome. The relatively higher utility for melt and dilute was present throughout the sensitivity analyses, except when extreme changes were forced into the model. In particular, the higher utility for melt and dilute could be eliminated by removing "acceptability" from the analysis, and could be reversed by reversing the acceptability values.

ES.1 Background

The current mission of the Department of Energy Savannah River Operations (DOE-SR) with respect to aluminum-based spent nuclear fuel (Al-SNF) is *"to identify and implement appropriate actions for the safe and efficient management of spent nuclear fuel ...including placing these materials in forms suitable for ultimate disposition."* as stated in the *Savannah River Site Spent Nuclear Fuel Management: Preliminary Draft Environmental Impact Statem*ent. The proximate goal for DOE-SR is to identify the treatment alternatives for Al-SNF that achieve this mission with optimal efficiency and effectiveness. The analysis presented in this document provides a systematic decision analysis that is appropriately documented, and is based on existing data relevant to the two treatment alternatives.

DOE-SR initially considered ten treatment alternatives for the management of Al-SNF, and has narrowed the choice to two of these: the **direct disposal** and **melt and dilute** alternatives. The decision analysis presented in this document focuses on a decision between these two remaining alternatives.

ES.2 Multi-Attribute Utility Analysis

The decision analysis is a multi-attribute utility analysis (MUA). In this analysis the objectives of the decision-makers, within the context of the decision to be made, are identified, the attributes that affect the decision are defined, values for those attributes are estimated and then normalized to a scale common to all attributes. A single metric, in the form of a multi-attribute utility, is provided as input to the decision-maker. The analysis addresses uncertainties in the data by modeling uncertain parameter values. Uncertainty is expressed in the model results as a cumulative distribution. Distributions are combined by randomly sampling on each distribution of parameter uncertainty and combining the samples to generate aggregate uncertainty distributions; these resulting distributions are the multi-attribute utilities. The method can be readily modified to account for changes in the state of knowledge regarding data, treatment technologies, decision-maker values, or regulatory environment.

The multi-attribute decision analysis process employed includes the following steps:

1. Identification of the decision objectives and hierarchy.
2. Identification of the attributes.
3. Modeling the physical processes of the alternatives.
4. Identification and quantification of appropriate uncertainties.
5. Elicitation and construction of single-attribute utility functions.
6. Calculation of single attribute utilities.
7. Combining single attribute utilities using an appropriate MUA model; verification of assumptions.
8. Exercise of the model, computing expected utilities for each alternative.
9. Performing sensitivity and importance analyses.

The above steps were performed in an iterative fashion.

The ultimate decision-maker is the Department of Energy (DOE). However, the DOE management at the Savannah River Site (DOE-SR) will recommend a decision to DOE Headquarters. Thus, DOE-SR provides the substantive expertise and is acting as the *de facto* decision-maker for this analysis. Therefore, critical input was elicited from DOE-SR staff. Sandia National Laboratories (SNL) supplied only normative expertise to the decision analysis.

ES.3 Decision Attributes

Multi-attribute utilities are calculated for both treatment alternatives within the context of six decision attributes. These attributes are defined by identifying the objectives for the decision. Figure ES-1 is an objectives hierarchy showing the five major objectives that DOE-SR believes must be met. Each objective must be measured on a suitable scale in the MUA, and that scale is referred to as the *attribute* of the objective. The decision attributes considered in this decision are*:

- *Capital cost.*
- *Other costs:* maintenance and operational (M&O) cost, including transportation cost.
- *Public radiological health.*
- *Acceptability* to two major peer review panels.
- *Secondary waste.*
- *Likelihood of proliferation.*

Other issues such as worker safety and schedule were considered as concepts for potential decision objectives. However, it was determined by DOE-SR that these issues,

* The objective "Minimize Cost" is split into two attributes to reflect the different utility towards *capital costs* and operational costs)

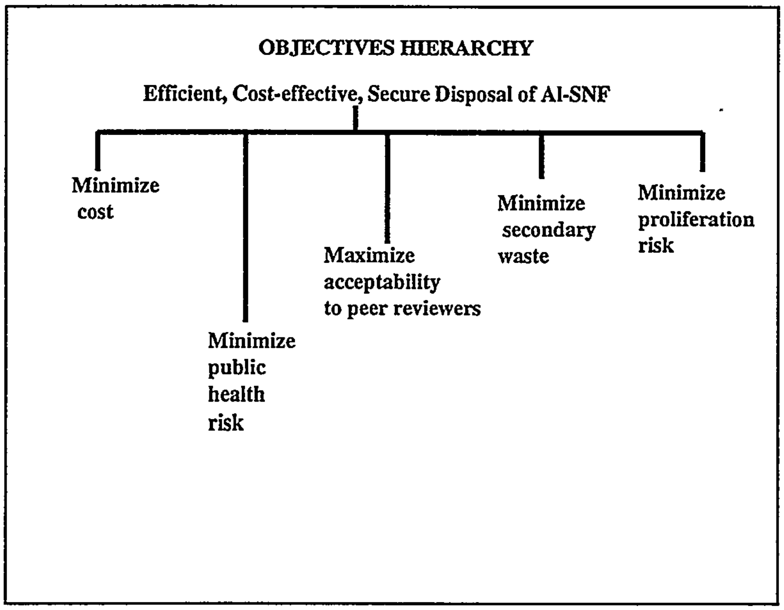

Figure ES-1 Decision Objective Hierarchy

while very important to the successful completion of DOE-SR's mission, do not represent issues that would discriminate between the two alternatives.

ES.4 Multi-Attribute Utility Results

In Figure ES-2 the multi-attribute utilities are shown for both alternatives, expressed as cumulative probability distributions. These distributions result from the incorporation of uncertainty in the values for the six decision attributes. The results in Figure ES-2 show that the multi-attribute utility for the melt and dilute alternative tends to be greater than the multi-attribute utility for direct disposal.

Direct comparisons between two cumulative distributions can be difficult. However, the ratio of the MUA estimates for each sample of the uncertainty analysis (variable parameters where sampled 1000 times) provides a direct measure of the difference of multi-attribute utility between the two alternatives. In addition, the cumulative distribution of this ratio provides a measure of the uncertainty of the difference. The cumulative distribution of the ratios is shown in Figure ES-3.

As seen in Figure ES-3, the entire distribution of the ratios lies to the right of the line defined by **(X = 1)**. Thus, for essentially all of the trials of the uncertainty analysis the multi-attribute utility is larger for melt and dilute than for direct disposal. Even when uncertainty in the parameters is incorporated, melt and dilute has greater multi-attribute utility than does direct disposal with essentially 100% confidence. A summary of major

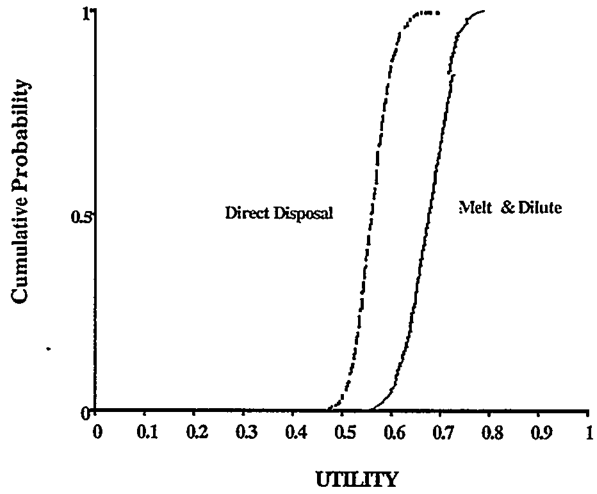

Figure ES-2 Multi-attribute utility cumulative distributions

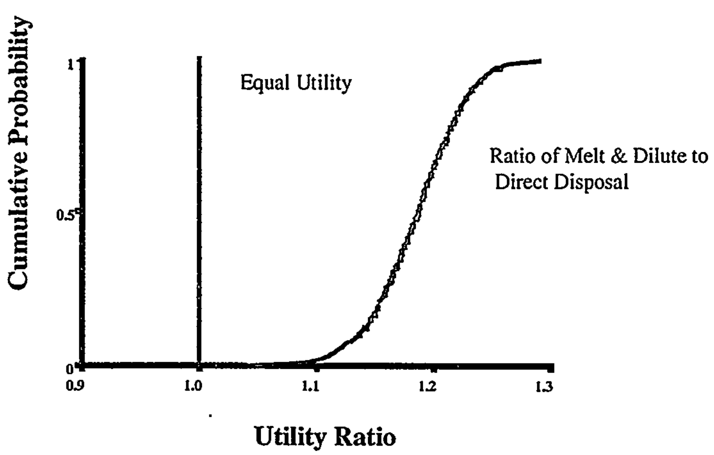

Figure ES-3 Ratio of multi-attribute utilities: melt and dilute vs. direct disposal

Table ES-1 Statistical Summary of CDF of Ratios

Min	**1.04**
Median	**1.2**
Mean	**1.2**
Max	**1.3**
Standard Deviation	**0.038**

statistics of the cumulative distribution of ratios is shown in Table ES-1. The mean value of the ratios is 1.2, which implies that the expected difference in utility between the two alternatives is 20% in favor of melt and dilute. The maximum difference in multi-attribute utility is 30%, and the minimum difference is 4%.

ES.5 Multi-Attribute Utility Sensitivity to Data, Assumptions, and Decision-Maker Values

The sensitivity of the multi-attribute utility results to changes in various elements of the decision analysis model (i.e., changes in attribute weights, removal of specific attributes from the model, variation of parameter estimates) is examined in various sensitivity case studies in the report. These sensitivities indicate that the greater multi-attribute utility estimate for the melt and dilute alternative is consistent across a range of model values for the attributes. For example, removal of the attribute *acceptability*, which has considerable influence on the base case multi-attribute utility estimate, results in essentially equivalent utilities for the two alternatives, but the preference for the melt and dilute alternative is not reversed.

The Nuclear Regulatory Commission (NRC) recently issued a review of the aluminum-based research reactor spent nuclear fuel disposition program (Knapp, 1998; Sridhar et al, 1998). The report points out a number of areas where the NRC believes that more research is needed on the materials in question: the melt-and-dilute waste form and the directly disposed spent nuclear fuel (SNF), particularly on pre-disposal impacts. However, the study concludes that both direct disposal and the waste form produced by melt-and-dilute treatment *"would be acceptable...for the disposal of aluminum based research reactor SNF in the repository."* (Knapp, 1998). Although the issues raised in the report are important to transportation and disposal considerations, these issues do not discriminate between direct disposal and melt and dilute treatment. Therefore, the relative multi-attribute utilities for the two treatment alternatives are not changed as a result of the NRC report. The report is important with regard to disposal considerations and will doubtless affect other disposal-related decisions, but it has no significant effect on the particular decision between the direct disposal and melt and dilute treatment alternatives.

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Abbreviations, Acronyms, and Initialisms

AHP	Analytic Hierarchy Process
AL-SNF	Aluminum Based Spent Nuclear Fuel
CAB	Citizens Advisory Board
CDF	Cumulative Distribution Function
D/D	Direct Disposal
DOE	United States Department of Energy
DOE/SR	Department of Energy Savannah River Operations
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
HLW	high-level radioactive waste
LLW	low-level radioactive waste
km	kilometers
m	meters
m^3	cubic meters
M&D	Melt and Dilute
M&O	Maintenance and Operations
MEI	maximally exposed individual
MLLW	mixed low-level radioactive and hazardous waste
mrem	millirem
MTHM	Metric Tonne Heavy Metal
MUA	Multi-attribute Utility Analysis
NAS	National Academy of Sciences
NUHOMS	Nuclear Horizontal Modular Storage System
NWTRB	Nuclear Waste Technical Review Board
Pu	plutonium
RBOF	Receiving Basin for Offsite Fuel
rem	roentgen equivalent man
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SRS	Savannah River Site
Th	thorium
TRU	transuranic [waste]
TSS	transfer and storage services
U	uranium
WSRC	Westinghouse Savannah River Company

Glossary

Note: According to Keeney and Raiffa (1976, p.32), there are no universally applicable definitions of the decision analysis "terms of art." In this document, the operational definitions of Keeney and Raiffa (1976) are used, and are indicated with an asterisk (*).

Activity	A project or program effort, such as melting and diluting spent nuclear fuel
Alternative*	An element of a decision; a decision is made between alternatives.
Attribute*	The metric for a decision objective; the method by which attainment of a decision objective may be met.
Constructed scale*	A surrogate, often subjective metric for an attribute that is used when no natural scale exists; e.g., acres of habitat destroyed may be a constructed scale for ecosystem damage; combined results of an opinion poll, for public confidence; cost of restoration, for defacement of historical or archaeological monuments, etc.
Decision maker*	The individual or group entity responsible for making the decision. A "decision" may be a recommendation, as in this report, in which case the "decision maker" is the entity making the recommendation.
Decision objective*	What the decision-maker wishes to achieve by making the decision.
Decision goal*	What the decision-maker accomplishes or achieves by making the decision. A goal differs from a decision objective in that a goal is actually attained.
Effective enrichment	The fraction of heavy metal in spent nuclear fuel that is fissile isotopes expressed as percent.
Enrichment	The fraction of uranium in spent nuclear fuel that is fissile expressed as percent.
Goal*	See decision goal.
Highly-enriched uranium (HEU)	Uranium that is >20% fissile uranium

Glossary – continued

Low-enriched uranium (LEU)	Uranium that is <5% fissile uranium
Natural scale*	A metric that is commonly used to measure a particular attribute, and by which the attribute can be measured objectively; e.g., dollars are a natural scale for cost, years are a natural scale for time, rem is a natural scale for radiation dose, etc.
Objective*	See decision objective.
Objectives hierarchy*	A hierarchical structure with the overall, general, all-inclusive objective of the decision at the top and more specific subordinate objectives at lower levels. The more specific the objective, the lower its hierarchical position.
Rad	Absorption of one erg of ionizing radiation per gram of absorbing material, or 0.01 joule per kg of absorber
Rem	"Roentgen equivalent -- man;" a measure of ionizing radiation dose in terms of potential biological damage. One rem is equivalent to the biological damage done by one rad of x-ray or gamma rays
Multi-attribute utility*	The overall importance or value, as determined by an appropriate combination of single-attribute utilities, that an alternative has to the decision-maker.
Single attribute utility*	An expression of importance that an alternative has to the decision-maker with respect to a single attribute; a mapping of the value of an alternative on the utility function a particular attribute.
Utility*	An expression of importance that an alternative has to the decision-maker (see single attribute utility, multi-attribute utility).
Utility function*	A function that expresses the utility of an attribute. The end points of the function are usually one and zero, or one and 100, where the upper bound is equivalent to the best possible value of an alternative, and the lower bound is equivalent to the worst possible value. The shape of the utility function between its end points is determined by eliciting information from the decision-maker.

Value* The number or quantity that a particular alternative exhibits with respect to an attribute; e.g., the cost in dollars of an alternative is the value of the alternative with respect to the attribute cost.

Weight (of an attribute)* A quantitative value of the importance of an attribute to the decision maker; e.g., if there are the three attributes cost, schedule, and radiation dose, and a decision maker says that half of the decision will be based on cost, cost has a weight of 50%. The weight of an attribute is independent of the value or utility of the attribute.

1 Introduction

1.1 Purpose

The current mission of the DOE Savannah River Site (DOE-SR) with respect to aluminum-based spent nuclear fuel (Al-SNF) is "to identify and implement appropriate actions for the safe and efficient management of spent nuclear fuel ...including placing these materials in forms suitable for ultimate disposition." (USDOE, 1997, p. iii). The proximate goal for DOE-SR is to identify the treatment alternative for Al-SNF that achieves this mission with optimal efficiency and effectiveness. This decision analysis is intended to assist DOE-SR in making such a determination.

DOE-SR initially considered ten alternatives, and has narrowed the choice to two of these. The decision analysis focuses on a decision between these two remaining alternatives.

1.2 Aluminum-based SNF Treatment Alternatives

1.2.1 Characteristics of aluminum-based SNF

DOE-managed Al-SNF includes several different types of fuel: uranium and uranium/thorium metal fuels, particulate fuels, and failed and sectioned fuels, as well as oxide fuels. Alternative methods of treating this fuel before disposal in a repository, including simply canning material with no further treatment, are being considered. In addition to the physical and chemical properties that must be accounted for in planning for disposal, most of the Al-SNF managed by DOE is highly enriched (HEU, more than 20% enriched in fissile uranium).

Figure 1-1 shows relative quantities of HEU and low-enriched (LEU) SNF to be managed at the DOE Savannah River Site[1].

1.2.2 Alternative treatment methods

Krupa (1997) examines ten alternatives that were considered for the pre-disposal treatment of Al-SNF. The ten alternatives are listed below, the first two of which are the subject of this analysis and will be described briefly in Sections 1.2.2.1 and 1.2.2.2, respectively:

[1] From the Research Reactor Spent Fuel Task Team, SNF Task, 1996).

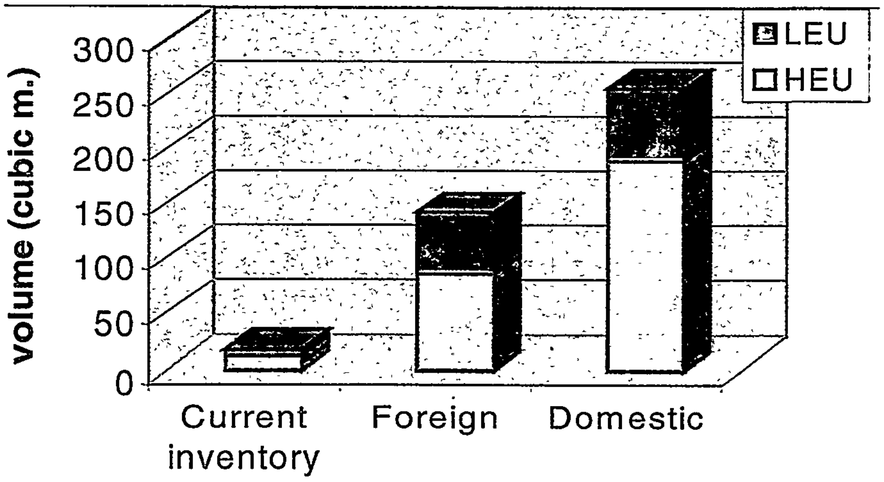

Figure 1-1 Volumetric Estimate of Aluminum-based HEU and LEU SNF to be managed at SRS

1. Direct disposal (fuel would be placed into canisters with no treatment beyond cropping and drying).
2. Melt and dilute (diluting to less than 20% enrichment by melting and blending with depleted uranium).
3. Press and dilute (diluting to less than 20% enrichment by cold pressing with depleted uranium).
4. Electrometallurgy (electrolytic separation of elemental uranium from SNF).
5. Glass Material Oxidation Distribution System (GMODS; conversion to oxide and dissolution in melted glass).
6. Plasma arc melting (dilution with depleted uranium and conversion to ceramic by plasma arc melting).
7. Dissolve and vitrify (dissolution in nitric acid, dilution with depleted uranium, and vitrification).
8. Reprocessing/recovery /melt and dilute (reprocessing in a canyon facility, dilution of recovered U to 5% enrichment, vitrification of reprocessing waste; direct disposal of fuel received after 2011).
9. Reprocessing/recovery /co-disposal (reprocessing in a canyon facility, dilution of recovered U to 5% enrichment, vitrification of reprocessing waste; melting and dilution with depleted uranium of fuel received after 2011).
10. Reprocessing/recovery (reprocessing in a canyon facility, dilution of recovered U to 5% enrichment, vitrification of reprocessing waste).

1.2.2.1 Direct disposal

Fuel will be cropped, as necessary, to remove Al end fittings. The SNF would be cropped and characterized, and canisterized so as to allow vacuum drying. The canister will be capped, filled with inert gas, welded and checked for leaks, and put into interim storage to await repository storage (Krupa, 1997, Appendix B).

1.2.2.2 Treatment by melting and dilution ("melt and dilute")

The melt and dilute process uses a single-step melting process to reduce the spent fuel volume and reduce the enrichment. The process has the following steps:

The fuel is cropped, as necessary, and melted with depleted uranium and the aluminum scrap from the cropping process. During melting, the uranium/aluminum eutectic is maintained by adjusting the relative quantities of aluminum and depleted uranium in the mixture. The resulting metallic waste form is cast in 16-inch diameter disks and sealed in a corrosion-resistant container.

1.3 Scope of Analysis

The present effort provides a systematic decision analysis that is appropriately documented, and based on existing data. Multi-attribute utility analysis (MUA) is used to evaluate attributes that affect the decision, normalize those attributes to a common scale and provide a single metric as input to the decision-maker. The analysis also addresses uncertainties. Whenever possible, data sources are published. The analysis provides sensitivity results, identifies key parameters and uncertain values, and is modifiable and readily repeatable. As knowledge about the alternatives and the regulatory environment improves, the components of the analysis, e.g. cost or schedule, can be modified to reflect new information, and revised results can be generated without an entirely new analysis effort. Data used in this decision analysis is based primarily on Krupa (1997), USDOE (1997), WSRC (1997a. 1997b, 1997c), and Cook (1997).

DOE-SR and WSRC personnel also provided unpublished information, as well as interacting with the SNL decision analysts throughout the analysis. Although the activities associated with the direct disposal and melt and dilute treatment alternatives are different, the decision analysis model is not structured differently for the two alternatives. Analogous structures of the two decision models facilitate detailed comparison between the two.

Data used as parameter values in this analysis are usually reported in the reference documents as single values (point estimates) without uncertainty quantification. Where uncertainty is quantified, a range of uncertainty is provided, but not a description of the uncertainty distribution. Therefore, engineering judgment was used to assign uncertainty distributions to many parameters of this analysis. An uncertainty importance analysis was performed to identify those parameter uncertainties to which the result is strongly correlated. This analysis is discussed in Section 3. Further investigation can be done to assess the impact of the uncertainty distributions on the MUA. The parameter estimates and their uncertainty distributions are summarized in Appendix C.

1.4 Analyzing a Decision by Multi-attribute Utility Analysis (MUA)[1].

DOE initially considered 10 alternative spent fuel treatments (Krupa, 1997), but has narrowed the candidates to two: direct disposal of SNF and melting and diluting SNF with depleted uranium ("melt and dilute"). A decision between these two treatment alternatives remains to be made. More than one basis exists for the decision; e.g. cost, radiological risk, and the amount of waste generated by the process are some of the potential bases for such a decision. Appropriate analysis of this decision recognizes that some bases may favor one alternative while other bases may favor the other alternative. For example, the one alternative may cost less than the other, but may pose greater radiological risk. The present analysis uses multi-attribute utility analysis (MUA). MUA assists the decision-maker when a decision between alternatives is based on more than one attribute, and when no single alternative has entirely favorable attributes.

The description of MUA in Sections 1.4.1 through 1.4.4 includes an introduction to some MUA terminology and methods and a discussion of risk-based decision analysis. An example of a multi-attribute decision analysis, which illustrates the application of these concepts, is found in Appendix A.

1.4.1 Terminology[2]

Decisions like the one under consideration are made between *alternatives*. These alternatives have properties or *attributes* (e.g., cost, radiological risk, and schedule). In an analysis each attribute has both a *value* and a *weight*. These and other decision analysis concepts and terms are discussed in detail in the following sections.

1.4.2 Evaluating attributes

The *value* is the number or measurement of the attribute. For example,

- the dollar cost for an alternative is its value for the attribute of cost
- time in days for an alternative is its value for the attribute of time or schedule
- dose in rem for an alternative is its value for the attribute of dose

---

[1] See Keeney and Raiffa, 1976; Keeney, 1980; and DOE, 1985 for discussions on the theory and applications of MUA.
[2] See Keeney, 1980 for in-depth discussion on these concepts and terms.

- volume of secondary waste in m^3 for an alternative is its value for the attribute of secondary waste generation

These are examples of attributes with *natural* scales. Dollars are a natural way to measure cost, rem is the natural metric for dose, and m3 is a natural metric for waste volume, and so on. If no natural scale exists, a scale is *constructed.* For example, a constructed scale can represent air pollution or index that is a combination of measured visibility interference, particle loading of the air, and meteorological stability. Scales can also be constructed subjectively, or surrogates can be used. Public "acceptance" is an attribute frequently used in environmental decisions. A scale could be constructed of percentages of people finding the alternative acceptable.

A value is preferably assigned to an attribute by consulting appropriate documents, but may be assigned by a knowledgeable person or persons. For example, the costs associated with a particular alternative can be obtained from cost studies or similar documents, or an expert familiar with the alternative and its costs can provide his or her opinion. In the present analysis, most values are representations of documented data.

1.4.3 Weighting attributes

The *weight* of an attribute is the value which that attribute has to the decision-maker; e.g., cost is twice as important as schedule; risk is four times as important as cost. Weights are assigned by the decision-maker and are independent of the assignment of value. Weights can be assigned either by a formal tradeoff analysis or by subjective assignment (e.g., of a total of 100 points, the decision maker assigns 10 to cost, 5 to schedule, 40 to risk, etc). A formal tradeoff analysis, in which the weights assigned to attributes are fully independent, is preferable, but time and resource constraints obviated its use in the present analysis. The use of the less robust subjective assignment is, however, compensated by sensitivity analysis.

1.4.4 Utility functions

Each attribute has its own characteristic scale that reflects the metric for that attribute. The attributes cannot therefore be compared directly: dollars cannot be compared directly to cubic meters. However, the attribute values can be mapped into a common space called "utility space," in which a utility function corresponds to each attribute and the value of each alternative with respect to each attribute can be expressed as a utility. The example in Appendix A describes the construction of utility functions and the derivation of utilities.

1.5 Decision Analysis Including Uncertainties

Risk is incorporated into decision analysis by incorporating uncertainty in outcomes under various alternatives. This uncertainty is represented by probability distributions on various measures of importance such as costs or waste volumes. Risk-based decision analysis uses distributions in evaluating attributes instead of point estimate values. The utilities of each attribute (single-attribute utilities) are then also expressed as distributions, as are the final measures of desirability of each alternative. Weighting is not usually done with distributed weights because of the role weighting plays in sensitivity analysis.

Instead of utilities that apply relatively simple utility functions to distributions of values, cumulative distribution functions could be used to represent attributes. This more sophisticated form of risk based decision analysis is applicable to analyses in which the alternatives are different models or different sets of equations. An example of this use is performance assessment, in which alternative assessments, or assessments using alternative parameters, are displayed as a set of cumulative or complementary cumulative distribution functions. Weighting of distribution functions is considerably more complex than weighting single attribute utilities, even when the utilities are distributed.

2 The Decision Analysis

2.1 Structure of the DOE-SR Al-SNF Treatment Decision

As discussed in Section 1, the decision to be made is a recommendation of one of the two treatment alternatives: direct disposal or melt and dilute. The treatment alternatives are distinguished by quantifiable attributes such as costs; radiation doses; and secondary waste generation. *Acceptability* (to peer review groups) and *likelihood of proliferation* are also attributes that possibly distinguish the treatment alternatives from each other. A decision analysis is usually modeled with the construction of a decision tree. This decision, however, involves only one choice between two alternatives, making a decision tree unnecessary.

The process diagram in Figure 2-1 shows two distinct paths: one for direct disposal, and one for melt and dilute. The processes are:

1) Pool storage,
2) Prepare TSS Facility,
3) SNF treatment,
4) On-site Dry Storage,
5) Transportation to the repository,
6) Disposal at the repository.

Each process in the decision path is comprised of subsidiary processes; these subsidiary processes are reflected in models that are used to calculate contributions to the attributes.

The decision analysis includes the following steps.

1. Identification of the decision goals and hierarchy
2. Identification of the attributes
3. Modeling the physical processes of the alternatives
4. Identification and quantification of appropriate uncertainties
5. Elicitation and construction of single-attribute utility functions
6. Calculation of single attribute utilities
7. Combining single attribute utilities using an appropriate MUA model; verification of assumptions
8. Exercise of the model, computing expected utilities for each alternative
9. Performing sensitivity and importance analyses

Although these steps are generally sequential, they require consistent interaction and iteration between the decision analysts and the decision-maker in order to achieve the best analysis.

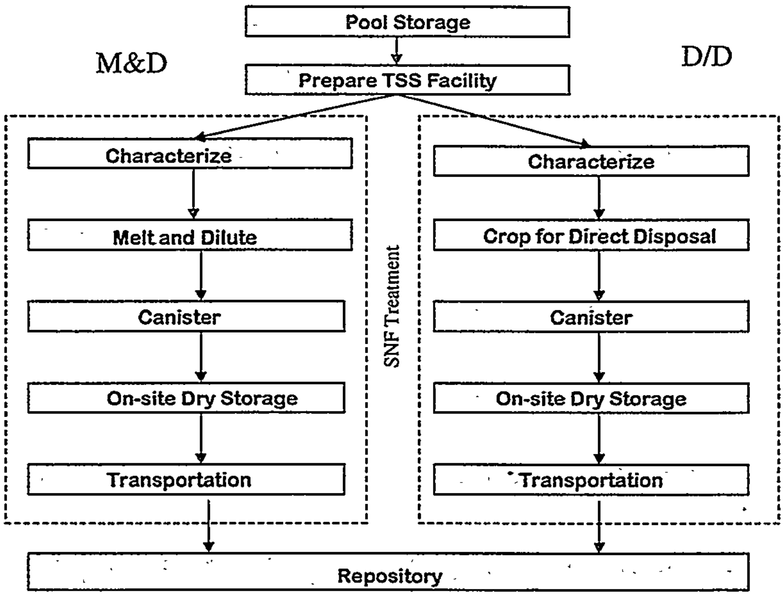

Figure 2-1 Process Flow Schematics for Direct Disposal and Melt and Dilute Treatment Alternatives

2.2 Definition of Attributes

Attributes are selected initially by identifying the decision-maker and defining the objectives of the decision. The decision maker in this case is the DOE; the DOE management at the Savannah River Site (DOE-SR) recommends a decision, provides the substantive expertise, and is acting as the *de facto* decision maker for this analysis. Therefore, the objectives hierarchy, attributes, and weighting of attributes were constructed by elicitation of, and interaction with, DOE-SR. The Sandia National Laboratories (SNL) team supplied only normative expertise to the decision analysis.

The decision's objectives, sub-objectives, and attributes are essentially those of DOE-SR. The overall objective is clearly efficient, cost-effective, secure disposal of Al-SNF. The objectives hierarchy outlines the sub-objectives through which the objectives are to be achieved. Figure 2-2 shows the initial objectives hierarchy for this decision.

Although there is not necessarily a one-to-one correspondence between sub-objectives and attributes, the sub-objectives define the set of attributes. The final attributes, and how they were determined, are described below.

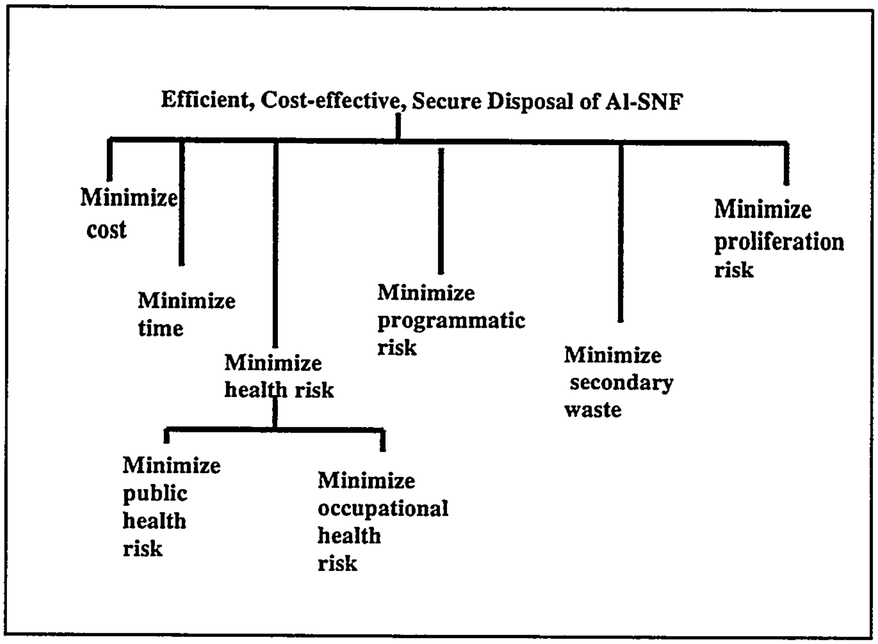

Figure 2-2 Initial Objectives Hierarchy Constructed for the Project

The analysis is based on six attributes, although more were considered initially. Each of the six attributes is described briefly in the sections that follow. Descriptions of attributes that were considered but not included in the final analysis are also presented.

2.2.1 Cost

As the decision model described in Section 2.5 and Appendix B shows a number of different costs and cost factors could play a role in this decision. Discussion with DOE-SR suggested that only capital costs would figure separately in their recommended decision; all capital cost could be considered together as a single attribute. Capital cost is singled out because funding for capital improvements requires congressional consideration and action separate from the operational budget. As a result of this separate consideration, the weighting of capital cost could be different from the weighting of non-capital cost. Consideration of the cost sub-objective resulted in two attributes: ***capital cost*** and ***other costs*** (e.g., M&O and transportation costs).

2.2.2 Time and schedule

Time (or schedule) is usually an attribute for this type of decision. Tables D-1 through D-4 of Krupa (1997) show that schedule will not discriminate between the direct disposal and the melt and dilute alternatives; both are scheduled through the entire 37-year life cycle. Therefore, because schedule is not a discriminator in this decision, there is no "time" or "schedule" attribute. Other factors outside this decision influence schedule. For this particular decision, minimizing time is not a decision sub-objective.

2.2.3 Public and occupational health and safety

Ensuring public and occupational health and safety, and minimizing threats to health and safety, are exceedingly important objectives and are mandated by law and regulation. Both the non-radiological and radiological occupational safety and health programs are maintained at the highest level of protection at SRS. Therefore, occupational safety and health, although an important factor in SRS operation, does not discriminate between the direct disposal and melt and dilute alternatives. Public non-radiological safety is potentially impacted only slightly: the number of shipments of direct-disposed Al-SNF from SRS to a repository would be about three times the number of shipments of melt and dilute-treated Al-SNF, and the frequency of ordinary, non-radiological traffic accidents is directly proportional to traffic density. However, the differential increase in traffic to and from the site due to transport of Al-SNF is negligible; non-radiological public safety is thus not an attribute in this decision. Consideration of the public and occupational safety and health objective results in one attribute: ***public radiological health***.

2.2.4 Acceptability (programmatic risk)

Acceptability to the general public and other stakeholders of each of these treatment alternatives is critically important to DOE decisions, and was therefore initially considered in the analysis. However, this particular analysis is being used by the DOE to identify the Department's preferred alternative in the final Environmental Impact Statement (EIS) for the SRS. The EIS review process provides the opportunity for the public and other stakeholders to review the analysis and provide independent input; this input may or may not recommend a different preferred alternative. Thus, acceptability to the public and stakeholders is part of a subsequent different decision, and is not an attribute of the present DOE decision.

For the decision at hand, the *acceptability* attribute is the extent to which the peer review groups that oversee the EIS process can accept either treatment alternative. In the opinion of DOE-SR, risk to the program is posed by the decisions of two peer review groups in particular: the Nuclear Waste Technical Review Board (NWTRB) and the National Academy of Sciences/National Research Council panel (this panel is referred to herein as NAS, in order to avoid confusion with the Nuclear Regulatory Commission). Moreover, the decisions or preferences of these two boards are expected to influence DOE's decision markedly. The "programmatic risk" attribute is therefore ***acceptability*** to the two peer review groups.

2.2.5 Secondary waste

Secondary waste generated by the two processes under consideration remains a discriminator in the decision and is an attribute.

2.2.6 Likelihood of proliferation

Likelihood of proliferation remains a discriminator in the decision and is an attribute.

2.3 Attributes and Final Objectives Hierarchy

The attributes considered in this decision are:

- *Capital cost*
- *Other costs:* maintenance and operational (M&O) cost, including transportation cost
- *Public radiological health*
- *Acceptability* to two major peer review panels
- *Secondary waste*
- *Likelihood of proliferation*

The attributes are described in Section 2.2. The final objectives hierarchy is shown Figure 2-3.

2.3.1 Comparison with WSRC attributes

Westinghouse Savannah River Co. (WSRC) is using the analytic hierarchy process (AHP) as a decision-aiding tool. Figure 2-4 shows a "crosswalk" between the attributes identified by WSRC and the attributes in this study. The figure indicates that all of the WSRC attributes are encompassed in the SNL study, even though they are not explicit. Time and occupational safety, which are important but do not discriminate in this decision, are indicated in the table in lighter print.

2.3.2 Weighting of attributes

Weighting the attributes is done by the decision-maker, because the relative weights are intended to reflect the value (utility) of the attribute to the decision-maker. Different decision-makers may weight the attributes differently. Weighting the attributes is also completely independent of evaluating the alternatives with respect to the attributes. An example using the attribute of cost illustrates this difference. An alternative may have a relatively low M&O cost; its *M&O cost utility* (or value with respect to M&O cost) would thus be relatively high (since minimizing cost is usually a decision objective). However, M&O cost may have less value to the decision-maker than other attributes, so that the *weight given to the attribute "M&O cost"* would be relatively low.

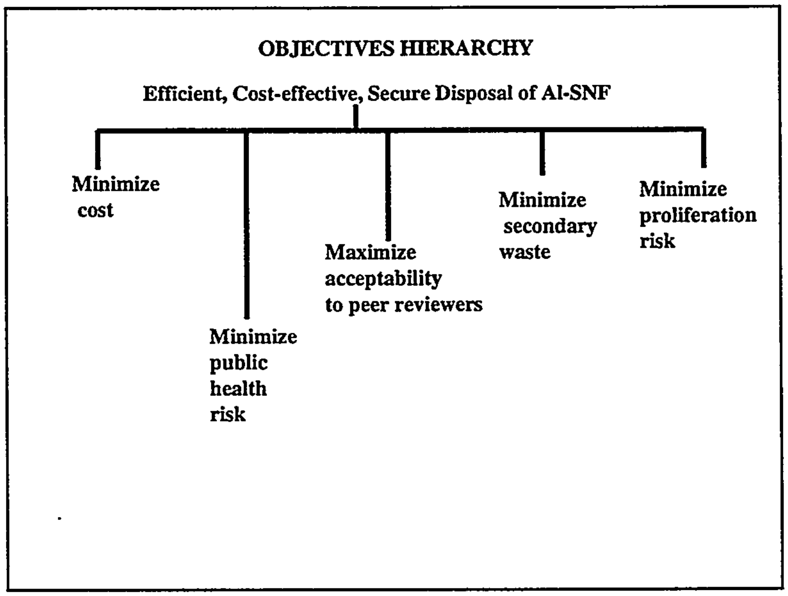

Figure 2-3 Final objectives hierarchy

SNL \ WSRC	CRITICALITY	RADIONUCLIDE RR	COMPELXITY	LICENSE	SECONDARY WASTE	MAINTAINABILITY	CHARACTERIZATION	VERSATILITY	CAPITAL COST	O&M COST	DISPOSAL COST	SCHEDULE	NGO	CSRA	PROLIFERATION	OTHER MISSIONS	OTHER DOE	SO. CAROLINA	WORKER SAFETY	PUBLIC SAFETY	ENVIRONMENT
ACCEPTABILITY	X		X	X		X	X	X					X	X		X	X	X			
CAPITAL COST									X												
PUBLIC HEALTH RISK		X																		X	
OTHER COST										X	X										
PROLIFERATION															X						
SECONDARY WASTE					X																X
SCHEDULE												X									
OCCUPATIONAL SAFETY																			X		

Figure 2-4 Crosswalk between WSRC and SNL attributes[1]

[1]Schedule and occupational safety are not shown in boldface because they were considered initially in the SNL analysis and then eliminated, for the reasons described in the text.

Attribute weights are specific to the decision at hand, and have no general or absolute significance. M&O cost, for example, could carry a relatively high weight in some decisions and a low weight in others, depending on what the other attributes of the decision are. Conversely, important aspects of a process may have low-weight attributes or no attribute at all, since, however important they may be in the absolute sense, they do not affect the decision under consideration. The present decision between direct disposal of Al-SNF and the melt and dilute alternative provides a good illustration of this phenomenon. Occupational safety is very important, but does not discriminate between the two alternatives and therefore carries no weight in this decision.

Three DOE-SR personnel (designated here as DM-1, DM-2, and DM-3) were asked to weight the attributes independently, by each distributing 100 points among the attributes. In weighting the attributes, the DOE-SR personnel knew the potential ranges for the values of each attribute (e.g., largest and smallest capital costs, the largest and smallest amounts of secondary waste, etc). Identification of these ranges was done in several iterations, and the quantitative bases for these ranges are discussed for each attribute in Section 2.4.

The resulting attribute weights are summarized in Table 2-1.

Table 2-1 Decision Attribute Weights

Attribute	Attribute Weights			
	DOE-SR Decision maker			Average for All Decision-Makers
	DM-1	DM-2	DM-3	
Capital cost	0.16	0.30	0.23	0.23
Other costs	0.11	0.18	0.11	0.13
Public Health	0.26	0.18	0.18	0.21
Secondary Waste	0.16	0.04	0.02	0.07
Likelihood of proliferation	0.05	0.06	0.12	0.08
Acceptability	0.26	0.24	0.34	0.28

This manner of weighting attributes has the disadvantage that all of the weights are not independent of each other since they sum to a predetermined amount (100 in this case). This disadvantage is offset by savings in time and resources when this method is used rather than a formal tradeoff analysis, and compensated for by sensitivity analysis. The sensitivity of the results to the weighting of each attribute, and to the individual weighting, is investigated and presented in Section 3 and Appendix D.

2.4 Structuring Utility Functions

As discussed in Appendix A, the first step in constructing a utility function is the definition of the extreme ends of the function: the values of the attribute that correspond to utilities of one and zero. The second step is construction of a utility function by eliciting an expert, who may also be the decision-maker. The third step in the present analysis is curve fitting, so that the elicited utility function is represented by an analytic function that can be used in the decision model to translate the attribute values into utilities. The actual use of the utility functions to quantify the attribute utilities is summarized in Section 2.5. Use of the resulting single-attribute utilities to quantify the ultimate result of the decision model, the multi-attribute utilities, is discussed in Section 3. The single-attribute utility functions are described in the succeeding sections.

The extremes of each utility function – the values that correspond to utilities of one and zero – are the decision-maker's estimate of the best and worst cases for each attribute. For example, the capital cost corresponding to a utility of zero is the largest capital cost possible; the figure may be limited by available budget or some other constraint. Similarly, the capital cost corresponding to a utility of one is the least amount of capital expenditure that will accomplish the task. In the present analysis, the extremes of the utility functions for capital costs, other costs, and secondary waste are the values for the best and worst case among the ten treatment alternatives considered. The public radiological health value for utility = 0 is the regulatory offsite MEI dose for 40 CFR Part 61. For likelihood of proliferation, the worst case is 100% likelihood and the best case, zero likelihood. For acceptability, the worst case is totally unacceptable, and the best is 100% acceptable. See Appendix A for a discussion on the selection of utility bounds of 0.0 and 1.0.

2.4.1 Capital cost

Capital cost has a natural scale: dollars. The capital cost recovery figures shown in the tables in Appendix D of Krupa (1997) were used to represent *capital cost*. The capital costs corresponding to utilities of one and zero were the smallest and largest capital costs, respectively, of the ten methods discussed in Krupa (1997) and listed in Section 1. One member of the DOE-SR staff was then elicited for utilities = 0.5, 0.25, and 0.75, as described in Section 2.3.2. Graphical representations of the elicited points are shown in the appropriately labeled curve of Figure 2-5. The equation that best approximates the *capital cost* utility is

Eq. 1 $U_{C\$} = 0.5\sqrt{\ln(2000/C_\$)}$

where $U_{C\$}$ = utility
$C_\$$ = *capital cost*

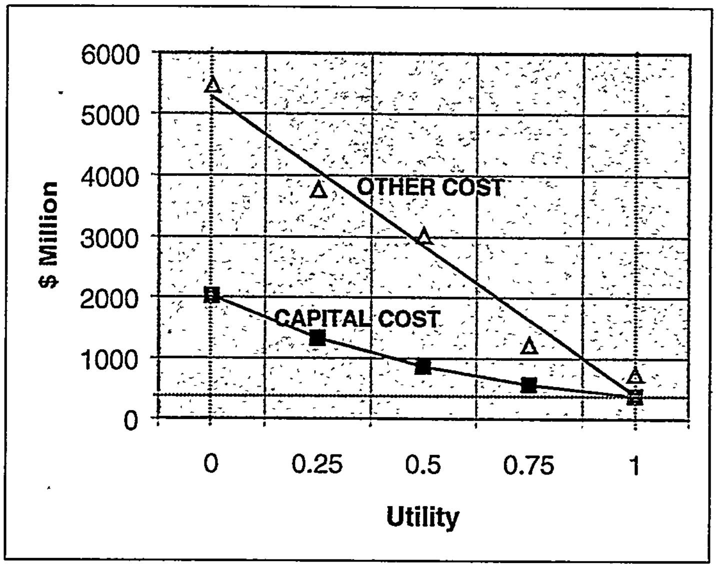

Figure 2-5 Utility functions for *capital cost* and *other cost*[1]

2.4.2 Other costs

Like ***capital cost***, ***other costs*** has a natural scale of dollars. The cost figures shown in the tables in Appendix D of Krupa (1997) were used to represent *other costs*. The "other cost" corresponding to utilities of one (smallest other cost) and zero (largest other cost) were also the smallest and largest other non-*capital cost*s, respectively, of the ten SNF treatment methods listed in Section 1.2. The same member of the DOE-SR staff was then elicited for utilities = 0.5, 0.25, and 0.75. In this case, no smooth curve could be drawn connecting these points, so the best straight line through the points was drawn, as shown in Figure 2-5. The equation for this straight line is

Eq. 2 $U_{OC\$} = 1.098 - 2.195 * 10^{-4} * OC_{\$}$

where $U_{OC\$}$ = utility
$OC_{\$}$ = *other cost*

[1] The square ( ) represents *capital costs*; the triangle (Δ) represents *other costs*, including M&O costs, transportation costs, etc.

2.4.3 Public radiological health

Public radiological health is expressed as the annual radiation dose to the maximally exposed individual located outside the SRS (the MEI dose). A natural scale of mrem/year can express annual radiation dose. The MEI dose was the composite of the offsite dose as presented in the SRS Preliminary Draft EIS (USDOE, 1997) and the dose to the MEI from transporting the SNF (or melted and diluted material) off the site. Transportation doses were calculated using INTERLINE and RADTRAN (Neuhauser and Kanipe, 1992), as described in Appendix D. The dose corresponding to a utility of 1 was the smallest MEI dose presented in USDOE (1997) for any of the ten processes. All of the offsite MEI doses are exceedingly small, so the dose corresponding to a utility of zero was selected to be the regulatory limit for offsite air emissions as given in 40 CFR Part 61: 10 mrem/year. Elicitation of the DOE-SR staff indicated that the regulatory limit was an appropriate zero utility point and that a steeply decaying exponential function would adequately express this utility. The equation for the utility function for *public radiological health* is thus:

Eq. 3 $U_D = 0.2709 - 0.1176\ln(D)$

where U_D = utility D = total annual dose to the MEI in mrem/yr.

The utility function is shown in Figure 2-6.

2.4.4 Secondary waste

Secondary waste could be evaluated using a natural scale of volume (cubic meters). However, discussion with the DOE-SR and WSRC staff elicited their estimate that secondary waste generated by either of the alternatives under consideration would be a relatively small fraction of the secondary waste generated at the Savannah River Site, identifying the metric used for *secondary waste*. This metric is calculated as described in the next paragraph.

SRS has four types of radioactive waste: high-level waste (HLW), low-level waste (LLW), mixed low-level waste (MLLW), and transuranic waste (TRU). Each of the ten methods listed in Section 1.2.2 also generates some or all of these waste types. The largest waste fraction (utility of zero) was the sum of the largest fractions of each of the four waste types generated by any of the ten methods, and the smallest waste fraction (utility of one), the sum of the smallest fractions of each of the four waste types (Equations 4a and 4b). Since the metric is a sum of fractions, the number corresponding to a utility of zero will be greater than one. DOE-SR staff were then elicited to determine the fraction sums corresponding to utilities of 0.25, 0.5, and 0.75. A function fitted to the elicited points can be represented by the following equations:

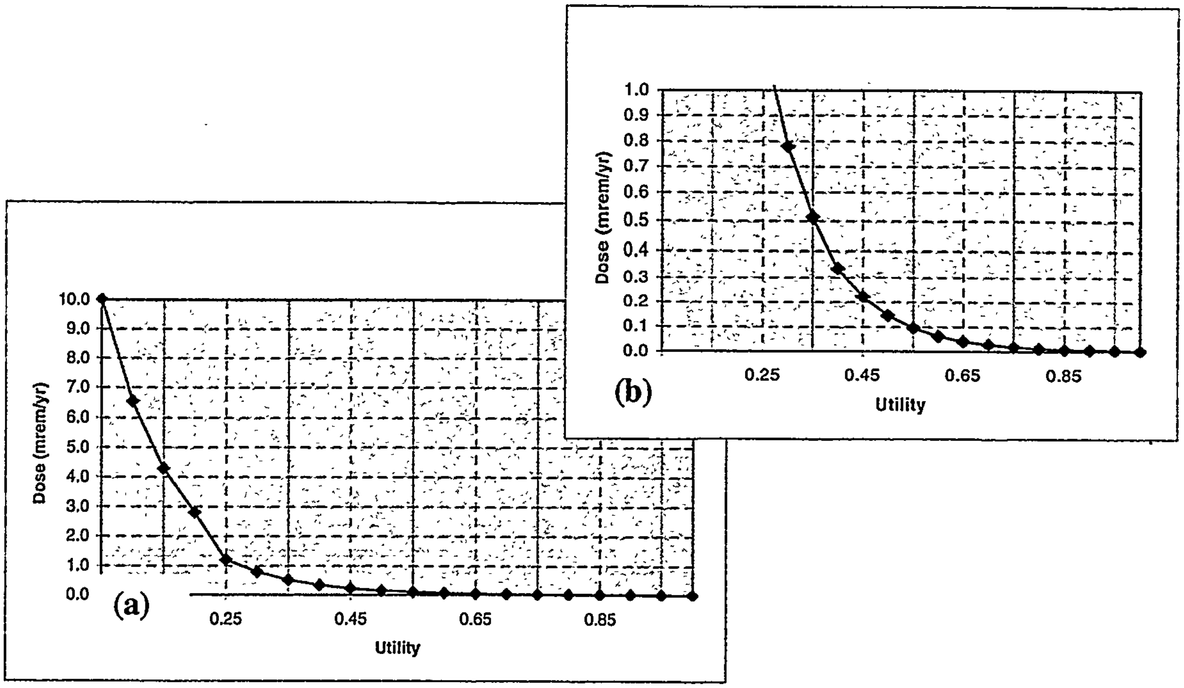

Figure 2-6 Utility function for *public radiological health*[1]

Eq. 4a $U_F = 0.2325\ln(1.0762/F)$

where U_F = utility

F = HLW fraction + LLW fraction + MLLW fraction + TRU fraction

Eq. 4b $F = \frac{HLW}{22{,}212} + \frac{LLW}{474{,}432} + \frac{MLLW}{224{,}761} + \frac{TRU}{12{,}564}$

The utility function is shown in Figure 2-7.

2.4.5 Acceptability

To DOE-SR, "acceptability" meant that the two peer review groups, the NWTRB and the NAS, would find a method acceptable without comparing it to any other method. A constructed scale is used, in which the measure of *acceptability* is the utility, and the utility function is a straight line, as shown in Figure 2-8. As discussed in Section 2.2.4,

[1] Figure 2-6(b) is an expansion of the lower part of the dose scale.

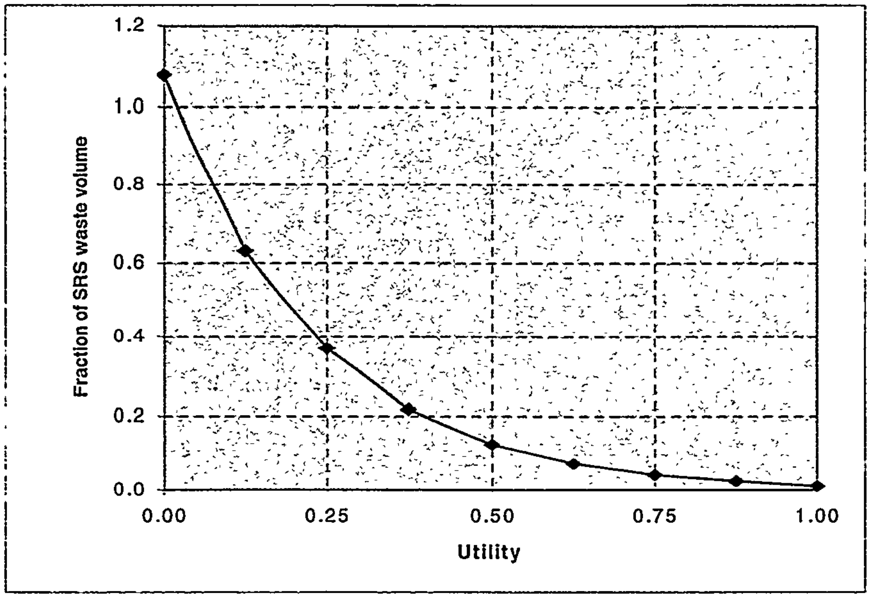

Figure 2-7 Utility function for secondary waste

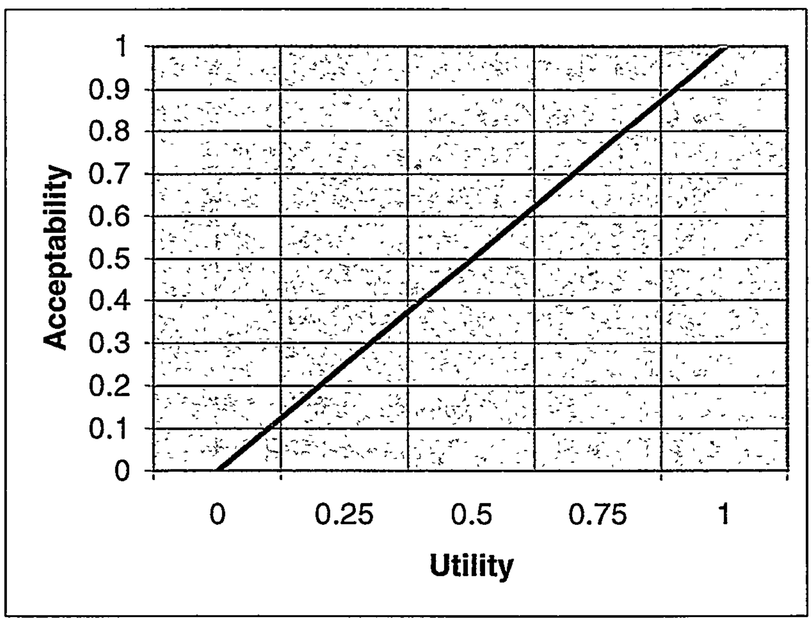

Figure 2-8 Utility function for *acceptability*

acceptability to the public and stakeholders is part of a subsequent different decision, and is not an attribute of the present DOE decision.

Acceptability is highly subjective. In this instance, not only was the utility function elicited, but also the "acceptability" of each of the two alternatives. Details of that elicitation are given here, because this is the only attribute for which a constructed, rather than a natural, scale was used. The value of the attribute on that scale was also elicited. As elicited here, it is DOE-SR's evaluation of (a) how likely NWTRB and NAS would be to approve either direct disposal of Al-SNF or the melt and dilute alternative when considering the two alternatives separately, and (b) which of these two peer groups would be more likely to influence DOE's decision. Elicitation yielded the responses shown in Table 2-2. The order of the questions was not important. Incorporation of these results into the decision model is discussed in Section 2.5.

Table 2-2 Elicitation for *Acceptability* Attribute

Elicitation Question	Response
Do you think that DOE will weigh one peer group's opinion more heavily than the other's, or will they be considered about equal?	DOE will weigh the NWTRB opinion more heavily than the NAS.
Will the NWTRB be likely to accept either of the alternatives? Can you quantify the likelihood of acceptance?	NWTRB is about 90% likely to approve the melt and dilute alternative, and is about twice as likely to approve melt-and-dilute as to approve direct disposal
Will the NAS be likely to accept either of the alternatives? Can you quantify the likelihood of acceptance?	NAS is lukewarm about both methods, and is about 60% likely to approve melt-and-dilute, and about 40% likely to approve direct disposal.

The WSRC attributes (Figure 2-4) include several other highly subjective attributes for which no natural scale exists, most notably the opinion of the State of South Carolina and of the SRS Citizens' Advisory Board (CAB). The opinion of DOE-SR is that South Carolina and the CAB both display preferences that echo those of the peer review groups, if they display any preference at all. Moreover, both of these groups are primarily interested in having SNF removed from the site to a HLW repository, and are considerably less interested in which of these two treatment methods is used. In other words, their opinion would not be expected to differentiate strongly between the two methods.

2.4.6 Likelihood of Proliferation

The likelihood of proliferation is directly related to enrichment. That is, it is generally thought that the higher the enrichment, the more potentially and readily "proliferable" the SNF. Initially, likelihood of proliferation also seemed to be directly related to the likelihood or ease of extracting or concentrating fissile radionuclides from the SNF, but this relationship appears to be too complex to use in this decision analysis. The natural scale for *likelihood of proliferation* is thus enrichment itself, although enrichment is more of a surrogate than a direct natural metric. Clearly, 100% enrichment has a utility of zero and, from the point of view of *likelihood of proliferation*, no enrichment at all has a utility of one. Because it was initially thought that the metric would be likelihood of retrieving fissile material, DOE-SR was elicited as previously described for the utilities 0.25, 0.5, and 0.75. Recognizing that the likelihood of retrieving fissile material was a surrogate for retrievability, it followed that enrichment is essentially an equivalent surrogate. Ultimately, the elicitation results were used directly in constructing the utility function. The equation for the function that best fits the elicited points is

Eq. 5

$$U_E = -0.268\ln(E)$$

where U_E = utility
E = fractional enrichment

The utility function for *likelihood of proliferation* is shown in Figure 2-9.

2.5 Estimation of Attribute Values and Utilities

The single-attribute utilities of each alternative can be determined from the utility functions described in Section 2.4 and the value of each alternative with respect to each attribute. If the values were single-valued (point estimates) the single attribute utilities could be determined directly by plotting the value of each alternative on the appropriate utility function graph, and reading the utility directly from the graph (see the example in Section A1, Appendix A). However, all of the values except one include uncertainty, and are multi-valued distributed functions instead of point estimates. This section describes the quantified uncertainty distributions (illustrated as CDFs) for the values of each of the decision attributes and the transformation of those values into utilities. Probability density function graphs for the decision attribute utilities are shown in Appendix E.

2.5.1 Capital cost

The *capital cost* data were developed by WSRC (Krupa, 1997). For each of the alternatives, WSRC has developed a five-year *capital cost* recovery period (Appendix D of Krupa, 1997), beginning with the opening date of the TSS facility. The uncertainty in the *capital cost* data is estimated as +/-30% in Krupa (1997).

Because no distribution on the uncertainty is defined the *capital cost* uncertainty is modeled using a normal distribution. The mean value is taken as the estimate in Krupa, (1997) with a standard deviation (σ) of 30% of the mean. A normal distribution was

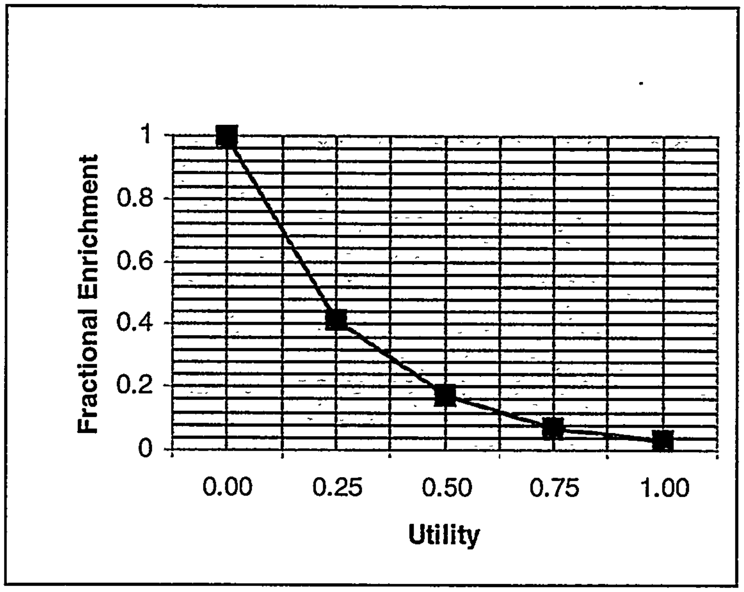

Figure 2-9 Utility function for *likelihood of proliferation*

chosen, rather than another type of distribution, in order to allow for unbounded tails in the parameter uncertainty. An unbounded uncertainty distribution is a better representation of parameter uncertainty when the extreme values of the parameter are not known accurately. Some distributions like uniform and triangular distributions bound the tails. The *capital cost* is integrated over time to provide a life cycle *capital cost* for each treatment alternative.

The *capital cost* estimates (Krupa, 1997) are based on the assumption that the operation of SRS would be privatized during the time that the Al-SNF would be treated at SRS. The privatized cost estimates are derived from non-privatized cost estimates developed for the DOE (Research Reactor Task Team Report 1996), although DOE's current intent is not to privatize management of the SRS. However, the differences between the cost estimates for privatized operations are proportional to differences between cost estimates for non-privatized operations Thus, any discriminating differences between the costs of the two alternatives would be of similar magnitude for either privatized or non-privatized management of the SRS. Therefore, the privatized cost estimates provide a valid basis on which to evaluate the *capital cost* attribute for the two treatment alternatives.

Figure 2-10 shows the cumulative distribution function (CDF) for *capital cost* value for the direct disposal and melt and dilute alternatives. The value estimates for *capital cost* were transformed into single-attribute utility estimates by the utility function in Eq. 1. The resulting CDF for *capital cost* utility is shown in Figure 2-11. Note that the CDF for the value of the melt and dilute alternative is to the left, indicating slightly lower *capital cost*, but the CDF for the utility of the melt and dilute alternative is to the right, indicating slightly higher utility.

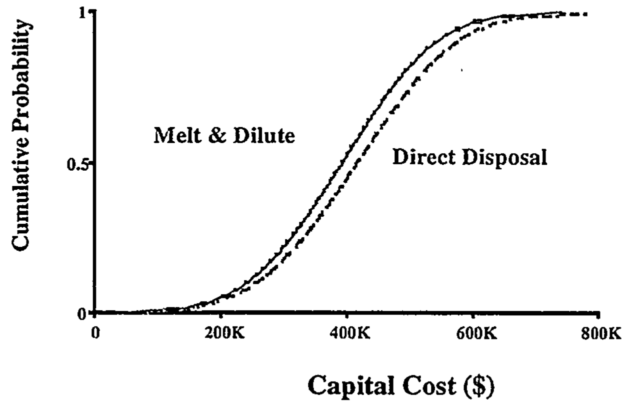

Figure 2-10 *Capital cost* **Value Distribution**

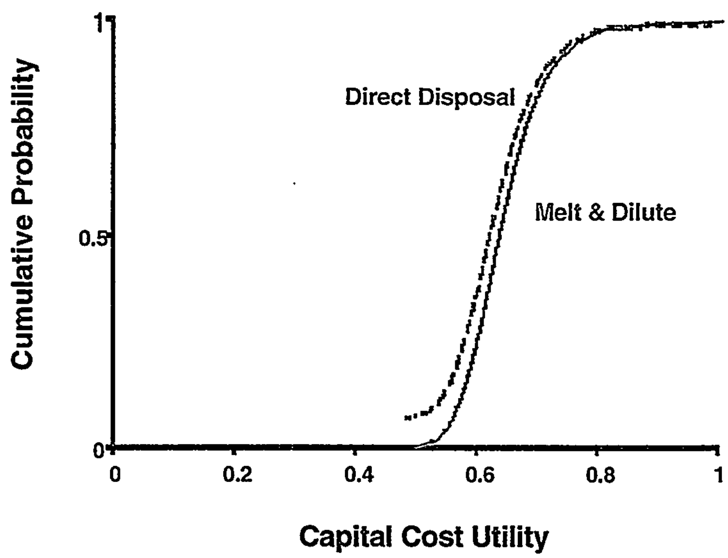

Figure 2-11 *Capital cost* **utility**

2.5.2 Other costs

The *other costs* attribute includes costs associated with typical maintenance and operation, transportation, and miscellaneous costs not associated with capital construction. Specific costs modeled as constituents of the *other costs* attribute are continued wet storage costs (operation of the L-basin and RBOF facilities), costs for operating and maintaining the TSS, labor costs, fuel treatment process costs (TSS maintenance, process materials, utilities), taxes, transportation costs, and repository emplacement costs. Estimates for each of these cost factors were developed on an annualized basis (Krupa, 1997). Annual costs estimates are integrated over time through the year 2050 to provide a life cycle operational cost estimates for both treatment alternatives. Furthermore, the individual cost constituents are dependent on the timing of various project activities, such as the startup of TSS, the removal (de-inventorying) of fuel from both wet storage basins, and the date when the repository would be available. The dependency of *other costs* on timing issues is illustrated in Appendix B (Figure B-3).

Each of the individual cost constituents of the *other costs* attribute were modeled as distributed parameters in the attribute value calculations to account for uncertainty in the estimation of costs. The resultant life cycle cost distributions for each cost constituent were summed to yield a total estimate for the *other costs* attribute uncertainty. *Other costs* are modeled using a normal distribution whose mean value is taken as the estimate in Krupa, (1997) with a standard deviation (σ) of 20% of the mean (see Appendix C for details). The uncertainty distributions for all of the individual cost constituents are correlated to maximize the uncertainty of the total *other costs* estimate. In Appendix D, examples are given for cases where the constituents of *other costs* have non-correlated distributions.

Figure 2-12 shows the CDF of the value for the *other costs* attribute. The CDF indicates significantly lower costs for the melt and dilute alternative. The value estimates for *other costs* are transformed into single-attribute utility estimates by the function in Eq. 2. The CDF of the utility of *other costs*, shown in Figure 2-13, illustrates that the melt and dilute alternative has a significantly higher utility.

2.5.3 Public radiological health

The metric for the *public radiological health* attribute is the dose to the maximally exposed individual (MEI). The MEI is the individual receiving the largest radiation dose outside the boundary of a site. This dose is defined as a maximum; therefore, parameter uncertainty is not relevant.

The MEI dose includes the dose from transportation of Al-SNF (or the melt-and-dilute waste form) from SRS to the HLW repository. The transportation dose that contributes

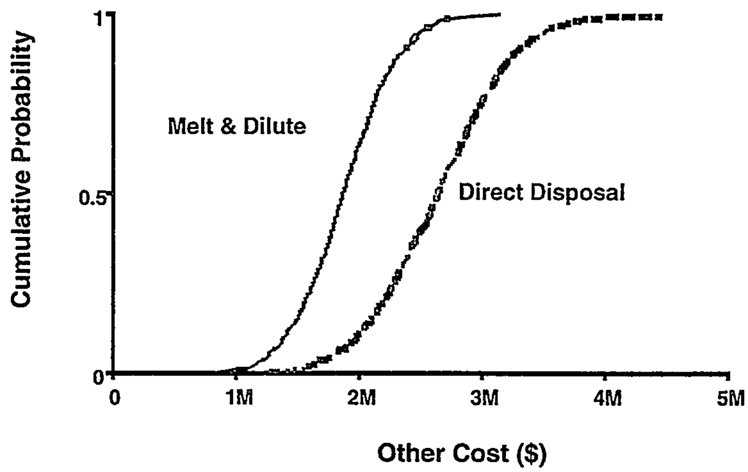

Figure 2-12 ***Other costs*** **value distribution**

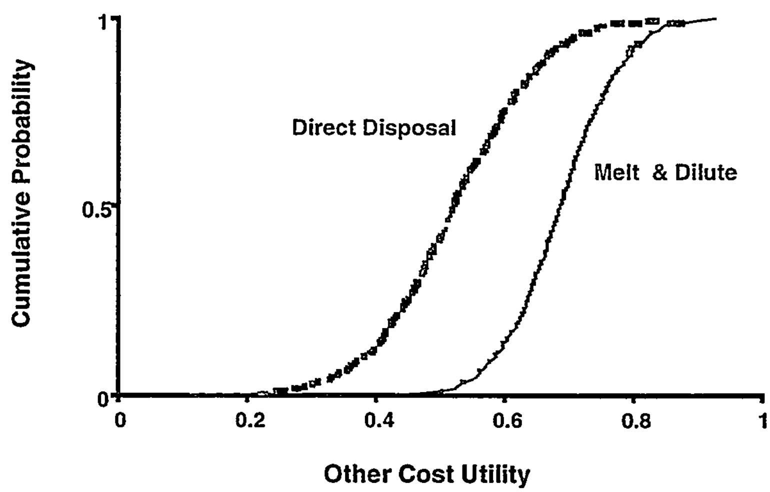

Figure 2-13 ***Other costs*** **utility**

to the MEI dose is based on an assumption that that all containers of Al-SNF being transported travel past the MEI location, so that the transportation dose adds to the offsite MEI dose. The only parameter for which there is uncertainty is the number of repository shipments per year for each alternative. The MEI dose from transportation was calculated using RADTRAN 4 (Neuhauser and Kanipe, 1992). Details of the transportation dose calculation are presented in Appendix B Section B2. The MEI dose from the operation of the TSS facility was taken from USDOE (1997).

Figure 2-14 shows the CDF for the value of the MEI annual dose estimate. The annual MEI dose estimated for the melt and dilute alternative is approximately five times greater than the MEI dose estimated for direct disposal. However the MEI doses for both alternatives are fractions of a mrem, much less than the 10 mrem/year regulatory limit of 40 CFR Part 61. The value estimates for the MEI were transformed into single-attribute utility estimates by the function in Eq. 3. The utilities of both alternatives are relatively high, because the regulatory limit defines zero utility. The resulting utilities are shown in Figure 2-15.

2.5.4 Secondary waste

The *secondary waste* volume estimates for both alternatives are taken from USDOE (1997). Estimates for the quantity of each type of waste (HLW, MLW, LLW, and TRU) that would be generated by each treatment alternative are provided. The uncertainty associated with each waste volume estimate was derived through discussions with WSRC (Krupa, 1998). The uncertainty distribution for the waste volume for all waste types is modeled as a normal distribution The point value for the waste volumes reported in the EIS were taken as mean values with a standard deviation of 50%. The volume of HLW is reported in USDOE (1997) in units of canister equivalents of vitrified (DWPF) glass. DWPF canister equivalents are converted to cubic meters in the model (See Appendix B) in order to be consistent with the other *secondary waste* types.

The point estimate volumes of each waste type from USDOE (1997) are summarized in Table 2-3.

Table 2-3 Secondary Waste Volume

Waste Type	Total m^3 at SRS
HLW	22,212
LLW	474,432
MLW	224,761
TRU	12,564

As indicated in the discussion in Section 2.4.4, the value for each alternative treatment, with respect to *secondary waste*, is expressed as the sum of the fraction of each type of

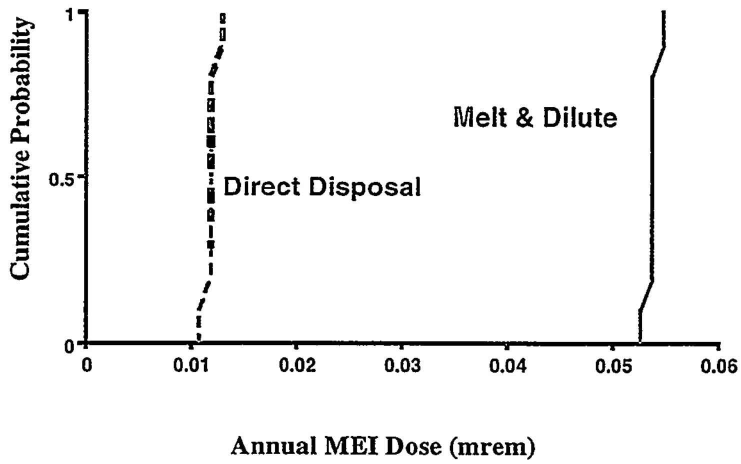

Figure 2-14 ***Public radiological health*** **value distribution**

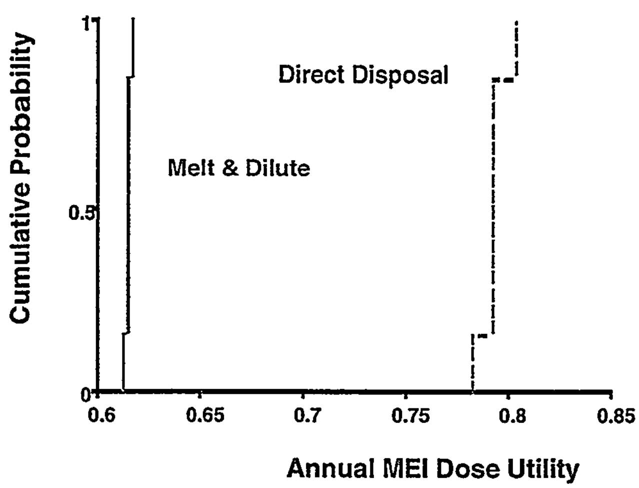

Figure 2-15 ***Public radiological health*** **utility**

waste produced by each alternative. That is, the waste produced by each alternative is divided by the site wide total for each type, and the resulting fractions summed, according to

Eq. 6 $$F = \frac{HLW}{22{,}212} + \frac{LLW}{474{,}432} + \frac{MLLW}{224{,}761} + \frac{TRU}{12{,}564}$$

where F = the sum of the waste fractions

HLW = the volume of high-level radioactive waste produced by each alternative
LLW = the volume of low-level radioactive waste produced by each alternative
MLLW = the volume of mixed low-level waste produced by each alternative
TRU = the volume of transuranic waste produced by each alternative

The CDFs for total waste fractional value are shown in Figure 2-16. The waste fraction expected from the melt and dilute alternative is estimated as approximately twice the waste fraction from direct disposal. The average waste fraction for either alternative, however, is less than 15% of the total expected waste volume inventory at SRS. The utilities for each alternative were calculated using Eq. 4. The resulting utilities are shown in Figure 2-17.

2.5.5 Acceptability

To DOE-SR, "*acceptability*" means that the two peer review groups, the NWTRB and the NAS, would find a method acceptable without comparing it to any other method. As discussed in Section 2.2.4, *acceptability* to the public and stakeholders is part of a subsequent different decision, and is not an attribute of the present DOE decision.

A constructed scale is used to calculate the value of this attribute, as described in Section 2.4.5. For this attribute, the value estimated from the constructed scale is the same as the attribute's utility.

The *acceptability* attribute estimates for both peer groups that were elicited from the DOE-SR staff are discussed in Section 2.4.5. Results of the elicitation are repeated here for the reader's convenience. Elicitation yielded the following responses:

- DOE will weigh the NWTRB opinion more heavily than the NAS.
- NWTRB is about 90% likely to approve the melt and dilute alternative
- NWTRB is about twice as likely to approve melt-and-dilute as to approve direct disposal.
- NAS is about 60% likely to approve melt-and-dilute and about 40% likely to approve direct disposal.
- NWTRB is only 45% likely to find direct disposal acceptable.

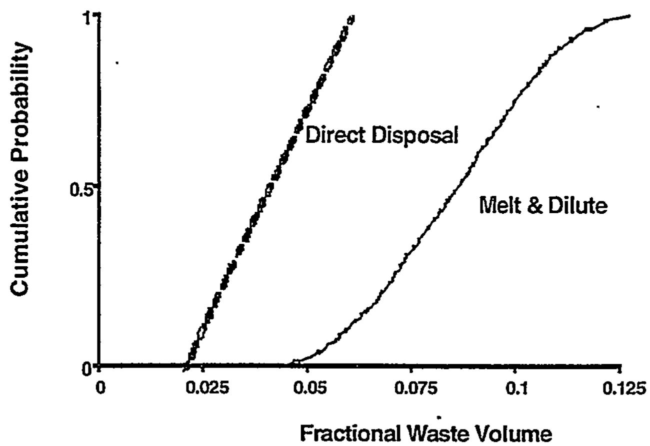

Figure 2-16 ***Secondary waste*** **value distribution**

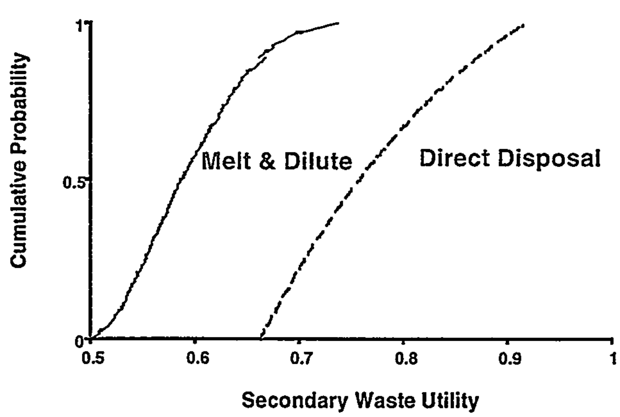

Figure 2-17 ***Secondary waste*** **utility distribution**

The *acceptability* of the two alternatives are not mutually exclusive, thus the probabilities of acceptance by a particular peer group need not add to 1.0. The results of the elicitation are summarized in Table 2-4.

Table 2-4 Likelihood of *Acceptability* for Each Treatment Alternative by Review Panels

Treatment Alternative	NAS	NWTRB
Melt and Dilute	0.60	0.90
Direct Disposal	0.40	0.45

The overall attribute value for each alternative is calculated as a weighted average of the likelihood estimates for each peer group. The weights applied to the peer groups' *Acceptability* values are unequal because, as stated above, *"DOE will weigh the NTRB opinion more heavily than the NAS."* The DOE-SR staff gave no specific weighting, so it was assumed that DOE's weighting of the NWTRB's opinion over that of the NAS would vary as a uniform distribution over the range of 1.0 to 3.0.

An additional source of uncertainty in the value of *acceptability* is the DOE-SR staffs' uncertainty regarding the peer groups' acceptance of either alternative. Thus, the values in Table 2-4 are taken to be mean values from normal distributions with standard deviations (σ) of 20% of the means. The 20% standard deviation represents the impact on a peer group's acceptance of an alternative should one panel member out of five change their own acceptance of the alternative.

The *acceptability* utilities are thus

Eq. 7 $utility = U(1-3) * (N(0.9, 0.2 * 0.9) + N(0.6, 0.2 * 0.6))$

Eq. 8 $utility = U(1-3) * (N(0.45, 0.2 * 0.45) + N(0.4, 0.2 * 0.4))$

where U(1-3) represents the uniform uncertainty distribution and N represents the normal distributions.

The CDFs for the single attribute utility of *acceptability* are shown in Figure 2-18. The utility scale for *acceptability* is the same as the *acceptability* scale itself.

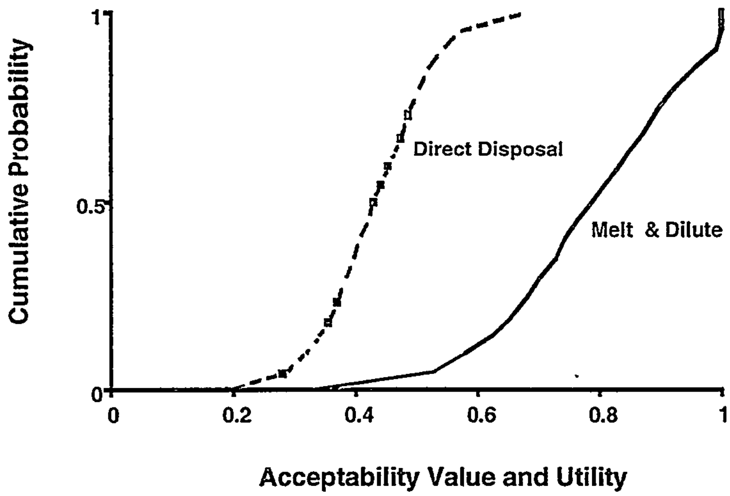

Figure 2-18 ***Acceptability* value and utility distribution**

2.5.6 Likelihood of proliferation

The *likelihood of proliferation* is considered as directly proportional to enrichment. Most of the Al-SNF to be treated at SRS is between approximately 20% and 93% enriched; the relatively small fraction of Al-SNF that is low-enriched is not accounted for in the *likelihood of proliferation* analysis. The direct disposal value is therefore assumed to vary uniformly between 0.20 and 0.93. For the melt and dilute alternative, the enrichment of the treated fuel (and hence its value for *likelihood of proliferation*) is assumed to vary as a uniform variable parameter between 0.05 and 0.20, to account for the option of diluting to 5% or to 20% fissile content.

Although the documentation on proliferation, notably USDOE (1997), finds the *likelihood of proliferation* essentially the same for the two alternatives under consideration (in the sense that all necessary measures will be taken to prevent proliferation) enrichment is used as a surrogate for likelihood of proliferation, resulting in the ranges cited. Further discussion among the DOE/DRS decision-makers suggested that likelihood proliferation was, in fact, perceived to be different for the two alternatives. The range of values was therefore chosen so that the maximum value for the melt and dilute alternative is the same as the minimum value for direct disposal.

The CDFs for *likelihood of proliferation* are shown in Figure 2-19. The attribute utilities for both alternatives were calculated with Eq. 5. The resulting utilities are shown in Figure 2-20.

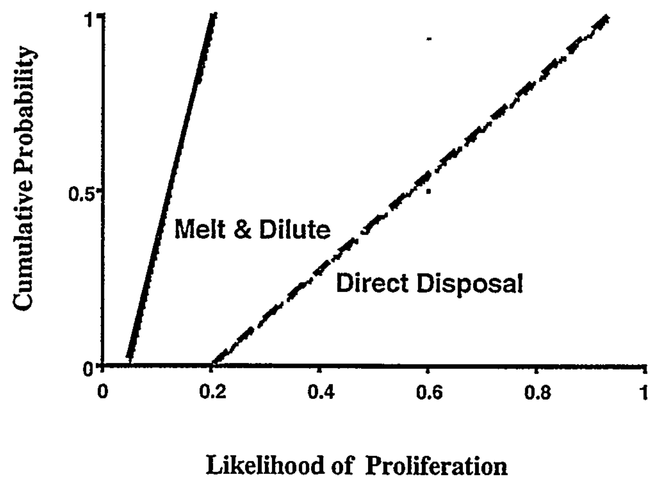

Figure 2-19 *Likelihood of proliferation* value distribution

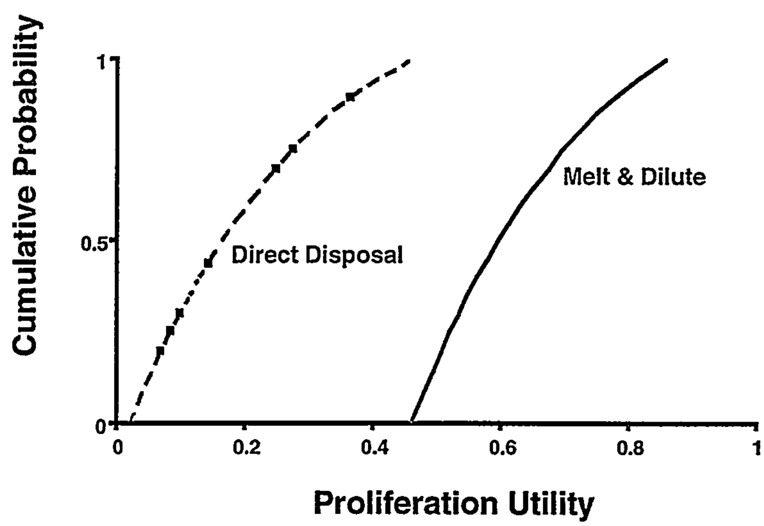

Figure 2-20 *Likelihood of proliferation* utility distribution

3 Results and Conclusions

3.1 Multi-Attribute Utility Results

The single-attribute utilities calculated in Section 2.5 are combined to yield a multi-attribute utility for each treatment alternative. This procedure is discussed in Section 1.4 and illustrated by example in Appendix A. This analysis uses a linear combination of single-attribute utilities; the attribute weights are the coefficients of the utilities. The sum of the products of weights and single-attribute utilities is a multi-attribute utility, as illustrated in the following equation:

Eq. 9 $MUA = (0.23 * U_{cs}) + (0.13 * U_{ocs}) + (0.21 * U_{d}) + (0.07 * U_{F}) + (0.28 * U_{a}) + (0.08 * U_{E})$

The mean values for the single attribute utilities in Eq. 9 (from the cumulative distributions in Section 2.4) and the weights for each attribute are summarized in Table 3-1. As seen from Table 3-1, the mean utility for melt and dilute is greater than the utility for direct disposal for four of the six attributes, with *public radiological health* and *secondary waste* having greater utility for direct disposal. The larger mean utility for each attribute is highlighted Table 3-1 to facilitate reading the table.

Table 3-1 Summary of Single Attribute Mean Utilities and Weights

	Capital costs	*Other costs*	*Public radiological health*	*Secondary waste*	*Acceptability*	*Likelihood of Proliferation*
Melt and Dilute	**0.65**	**0.69**	0.61	0.59	**0.78**	**0.61**
Direct Disposal	0.63	0.52	**0.79**	**0.77**	0.43	0.19
Attribute Weight	**0.23**	**0.13**	**0.21**	**0.07**	**0.28**	**0.08**

Figure 3-1 shows multi-attribute utilities for both alternatives. In addition to showing the MUA for each alternative, the ratio of the MUAs may be informative to the decision-maker. The ratio of the multi-attribute utility for melt and dilute to the multi-attribute utility for direct disposal was taken for each of the 1000 trials of the uncertainty analysis. The resulting CDF of the ratios is shown in Figure 3-2.

As seen in the figure, the entire CDF of the ratios is to the right of the line defined by **x = 1**, indicating that the multi-attribute utility for melt and dilute is greater than the multi-attribute utility for direct disposal across the entire uncertainty range of the results.

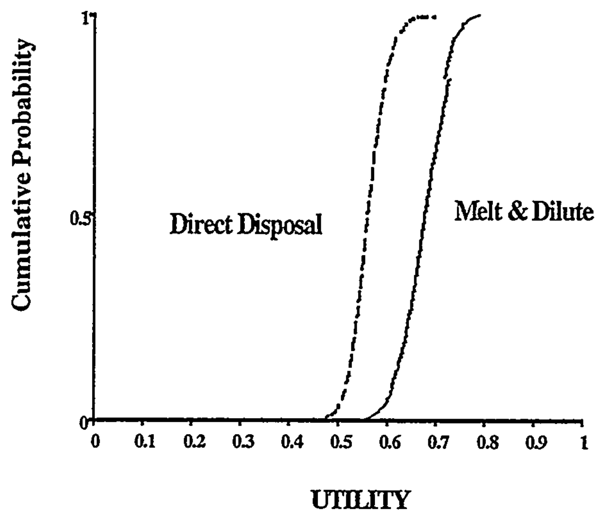

Figure 3-1 Multi-attribute utility cumulative distributions

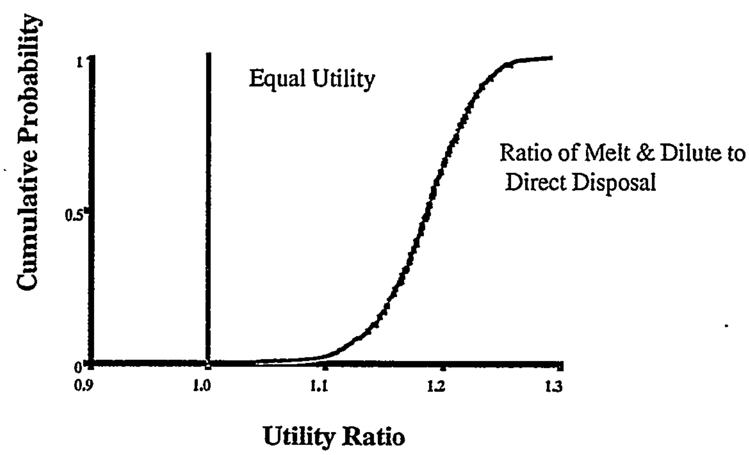

Figure 3-2 Ratio of multi-attribute utilities: melt and dilute vs. direct disposal

Given the uncertainty models incorporated into the analysis, the melt and dilute alternative appears to have a greater utility than direct disposal, with 100% confidence. A summary of major statistics of the CDF of ratios is shown in Table 3-2. The mean ratio value is 1.2, which implies that the expected difference in utility between the two alternatives is about 20%. The maximum difference in multi-attribute utility would be 30%, and the minimum difference would be essentially zero.

Table 3-2 Statistical Summary of CDF of Ratios

Min	**1.04**
Median	**1.2**
Mean	**1.2**
Max	**1.3**
Std Dev	**0.038**

Appendix D examines the sensitivity of this result to various attributes, and indicates that the greater MUA for the melt and dilute alternative appears to be consistent. Removal of the attribute of *acceptability*, which has considerable influence on the MUA, makes the utilities of the two alternatives almost equal, but does not reverse the preference for the melt and dilute alternative. Additional insight into the acceptability attribute can be gathered from the Nuclear Regulatory Commission's (NRC) recent review of the aluminum-based research reactor spent nuclear fuel disposition program (Knapp, 1998; Sridhar et al, 1998). The report points out a number of areas where the NRC believes that more research is needed on the materials in question: the melt-and-dilute waste form and the directly disposed spent nuclear fuel (SNF), particularly on pre-disposal impacts. However, the study concludes that both direct disposal and the waste form produced by melt-and-dilute treatment *"would be acceptable...for the disposal of aluminum based research reactor SNF in the repository."* (Knapp, 1998). Although the issues raised in the report are important to transportation and disposal considerations, these issues do not discriminate between direct disposal and melt and dilute treatment. Therefore, the relative multi-attribute utilities for the two treatment alternatives are not changed as a result of the NRC report. The report is important with regard to disposal considerations and will doubtless affect other disposal-related decisions, but it has no significant effect on the particular decision between the direct disposal and melt and dilute treatment alternatives.

3.2 Uncertainty Importance Analysis

Many of the parameters in the analysis have been modeled as variable parameters, and the quantification of their values has been estimated with uncertainty distributions. The uncertainty associated with any particular parameter can be a statement of either the random nature of the parameter or of the imprecise state of knowledge regarding the parameter's value – or both. Therefore, it can be very informative to estimate the importance of the uncertainty of a parameter to the uncertainty of the model results. A measure of this importance may be calculated for each variable; it is defined as the absolute value of the correlation[1] between the uncertainty in a parameter and the uncertainty in the resulting multi-attribute utility. The larger the importance, the stronger is the correlation, and hence, the greater the impact of the parameter's uncertainty upon the uncertainty of the model's results.

In Table 3-3 the importance of the uncertainty of each parameter's value to the uncertainty of the multi-attribute utility for each alternative is shown. In some cases, spurious correlations (on the order of 0.05 or less) are observed where it is know that no such correlation could possible exist (see highlighted values in Table 3-3). For example, the melt and dilute completion date has a correlation coefficient with the direct disposal multi-attribute utility of 0.043, yet it clearly can not be correlated to the direct disposal multi-attribute utility. Thus, it was decided that all correlations less than 0.10 are non-informative with regard to uncertainty importance.

Table 3-3 Importance Values for Uncertain Parameters[2]

Parameters	Direct Disposal	Melt & dilute
TSS Transportation Cask Preparation Rate	0.007	0.051
Likelihood of Peer Group Acceptance	0.707	0.885
NWTRB/NAS Weighting on *Acceptability*	0.063	0.143
Enrichment Level of Treated Al-SNF (Proliferability)	0.285	0.155
Year TSS Opens for Direct Disposal	0.013	**0.001**
Time to De-Inventory RBOF	0.017	0.023
Time to De-Inventory L-Basin	0.041	0.042
Year TSS Opens for Melt & Dilute	**0.006**	0.033
Operating Cost	0.402	0.212
Capital cost	0.444	0.331
Hazardous and Mixed Waste Volumes	0.028	0.054
LLW Waste Volume	0.135	0.063
TRU Waste Volume	0.002	0.008
HLW Volume	0.036	0.040
Melt & Dilute Activity Completion Date	**0.043**	0.056
Direct Disposal Activity Completion Date	0.055	**0.011**

The parameters whose uncertainties have the most significant impact on the variability of the multi-attribute utility for each alternative are shown in Table 3-4. The parameters listed in Table 3-4 represent those areas for which analysis, research, or data collection efforts would have greatest impact in the improvement of the uncertainty of the multi-attribute utility estimate. The parameters in Table 3-4 represent a prioritized set of data requirements from the parameter set in Table 3-3.

[1] The statistical term used is "rank correlation;" we use "correlation" here to avoid confusion.

[2] Shaded values in Table 3-3 represent spurious statistical correlations between uncorrelated parameters.

Table 3-4 Dominant Parameter Importance Measures

Parameters	Direct Disposal	Melt & dilute
Likelihood of Peer Group Acceptance	0.707	0.885
NWTRB/NAS Weighting on *Acceptability*	0.063	0.143
Enrichment Level of Treated Al-SNF (Proliferability)	0.285	0.155
Operating Cost	0.402	0.212
Capital cost	0.444	0.331
LLW Waste Volume	0.135	0.063

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Appendix A Decision Attributes, Weights, and Utilities

Appendix A Decision Attributes, Weights, and Utilities

This appendix provides details that augment the discussions of multi-attribute utility analysis in Sections 1.4 and 2, by an example that illustrates this analysis method

A.1 A MUA Example: Transportation Routes for Low-Level Radioactive Waste (LLW)

The example in this section is deliberately different from any decision involving spent nuclear fuel, and is intended only to illustrate the decision analysis method. In the example, a traffic manager must decide which of two routes to use for transporting low-level radioactive wastes.

A.1.1 Identifying and evaluating attributes

The first step in an MUA is for the decision-maker to identify the objectives of the decision in this instance, the objectives are:

1. Minimize transportation cost.
2. Minimize radiological risks to people along the route.
3. Minimize non-radiological risk
4. Minimize distance
5. Maximize public acceptance

Identifying the objectives leads to identification of attributes. The attributes are thus cost, radiological and non-radiological risk, distance, and public acceptance. It may be noted that if the decision were based only on cost – a single-attribute decision – no analysis would be necessary because the decision would be for the most favorable (usually the lower cost) route. Attributes should be as independent of each other as possible. Identification of dependencies can sometimes eliminate an attribute early in the analysis.

The attributes and their values are presented in Table A-1. The numbers in this example are fictitious, and are presented only to illustrate the method. The scales for cost, radiological and non-radiological risk, and distance are natural scales, and the values can be determined objectively. Public acceptance is a constructed scale: how likely the public is to accept transportation of LLW along this route or, alternatively, what percent of the public along the route would be likely to accept it.

A.1.2 Constructing utility functions

The values of the two alternatives with respect to each attribute are then expressed as utilities, so that they may be combined and compared. Utilities are derived from utility functions. A utility function is given values between zero and one (or zero and 100) and

Table A-1 Alternatives and Attribute Values

Route	Cost ($K)	Rad Risk (mrem)	Non-rad risk (accident frequency)	Distance (miles)	Public Acceptance
Route 1	7.8	0.0025	0.15	1040	45%
Route 2	10.4	0.0005	0.09	1080	75%

is constructed in four steps, as illustrated in Figures A.-1a through A-1d. The construction of utility functions is subjective: the decision-maker determines these functions. The values themselves, however, remain objective.

Step 1 (Figure A-1a): The highest value that the attribute could have – the most desirable situation for that attribute – is given a utility = 1.0. In this example, the lowest possible expected cost is $5000; the small diamond at the upper left shows its utility.

Step 2 (Figure A-1b): The lowest value that the attribute could have – the least desirable situation for that attribute – is given a utility = 0. In this example, the highest possible expected cost is $12,000; the small diamond at the lower right shows its utility.

Step 3 (Figure A-1c): The increment or decrement of the value of cost to the decision-maker is directly proportional to the increment or decrement in cost; that is, a dollar has the same value throughout the $5,000 to $12,000 range. The utility function is thus a straight line between the two end points.

Step 4 (Figure A-1-1d): The utilities of the costs of the two routes can then be determined from the linear utility function. The cost of Route 1($7,400) has a utility of 0.75 and the cost of Route 2 ($10,800) has a utility of 0.25.

Utility functions need not be linear. Figure A-2 is an example of a utility function for radiation dose, and illustrates that a decrease in dose from 1 rem to 0.01 rem is of considerably more value to the decision maker than a decrease from 3 rem to 2 rem. Utility functions need not be smooth curves either, but can be a series of points elicited from the decision-maker. The points on the utility function curve are elicited step-by-step; either by a decision analyst or by the decision-maker himself or herself. Figure A-3a through A-3d illustrates the construction of such a utility function, using the attribute of public acceptance from the example under discussion..

Step 1 (Figure A-3a): The decision maker determines the most and least public acceptance possible, and thereby determines the public acceptance corresponding to utilities of one and zero, respectively. In this example, a public acceptance of 90% has a utility = 1 and a public acceptance of 30% has a utility = 0.

Step 2 (Figure A-3b): The decision-maker then determines the first indifference point, which is the point of utility = 0.5. That is, the decision-maker is asked " How much

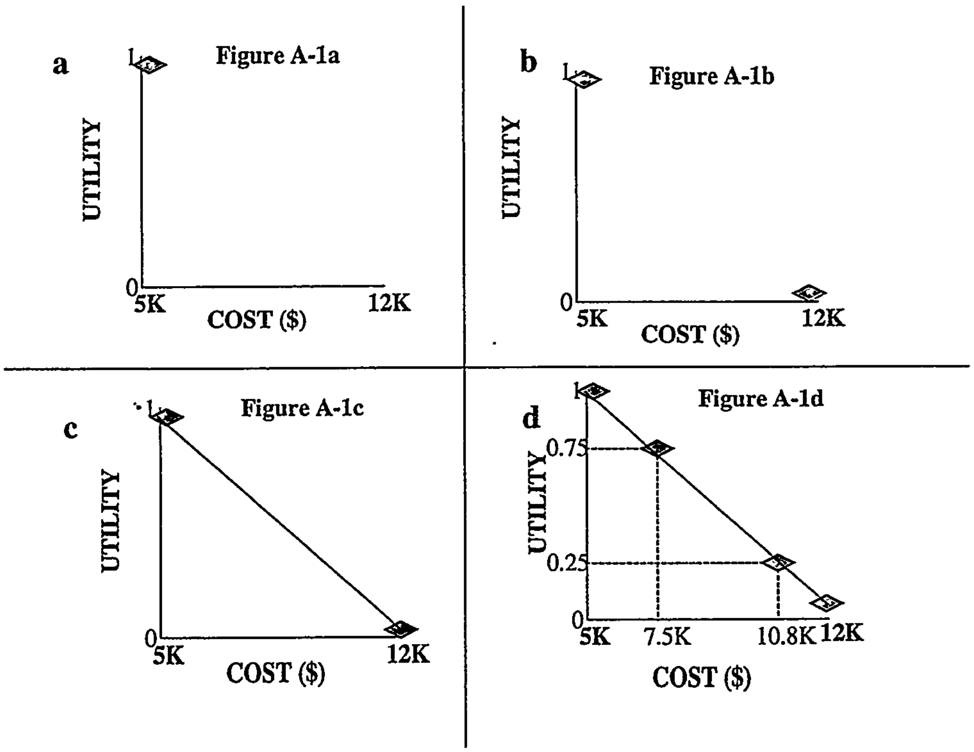

Figure A-1 Step-by-step construction of the utility function for cost

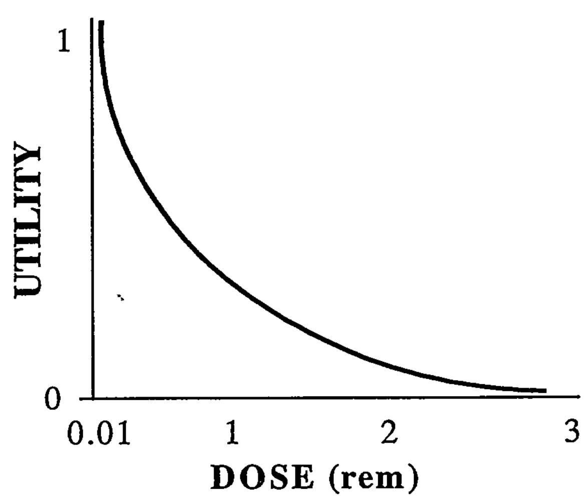

Figure A-2 Sample non-linear utility function for radiation dose

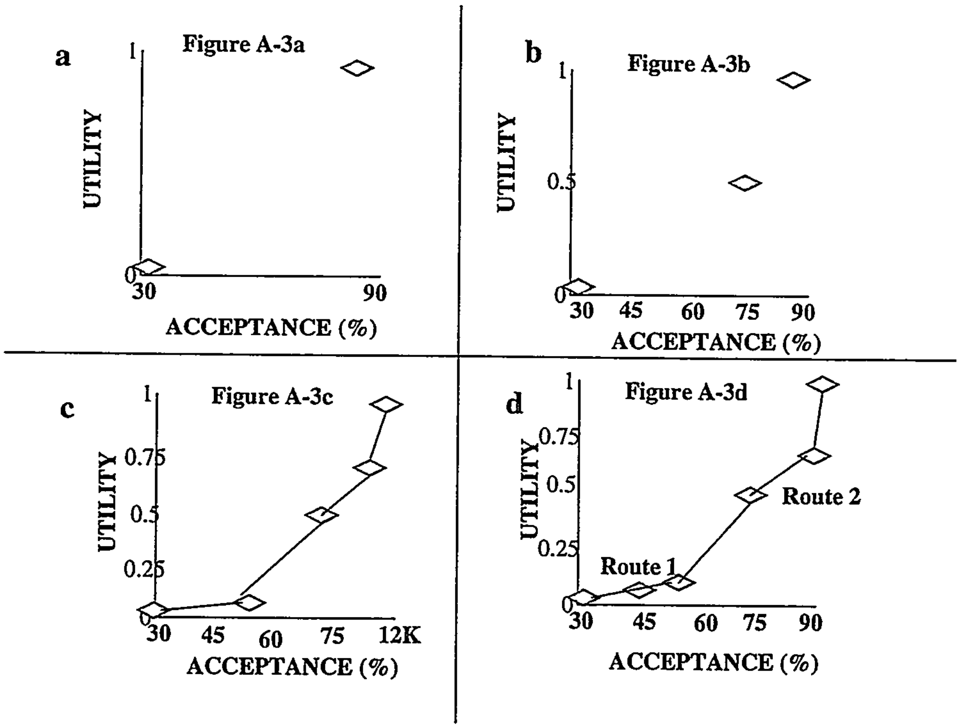

Figure A-3 Construction of an elicited utility function

public acceptance would you settle for in order to avoid a 50% probability of public acceptance of only 30%?" In this example, the decision-maker decides to settle for 75%. This may be noted as a risk-averse decision. The decision-maker tends to hold greater utility for higher acceptability (i.e, less risk of public rejection) than for lower acceptability (i.e., greater risk of public rejection).

Step 3 (Figure A-3c): By the same method as Step 2, the indifference points between 75% and 90% (utility = 0.75), and between 30% and 75% (utility = 0.25) are determined. The indifference points are connected, yielding a somewhat discontinuous utility function. If a smoother curve is desired, more indifference points may be determined or the optimum monotonic function may be obtained by curve fitting.

Step 4 (Figure A-3d): The utility values of public acceptance for Route 1 (45%) and Route 2 (75) are found on the utility function curve in the figure. These utilities are 0.05 and 0.5, respectively.

Utility functions for the other attributes can be similarly constructed, although in this example utilities were simply fabricated. Utilities for the attributes are summarized in Table A-2.

Table A-2 Attribute Utilities

Routes	Cost ($K)	Rad Risk (mrem)	Non-rad risk (accidents)	Distance (miles)	Public Acceptance
Route 1	0.75	0.75	0.85	0.6	0.05
Route 2	0.25	0.9	0.65	0.7	0.5

A.1.3 Weighting attributes

Weights are assigned to the alternatives either by performing a tradeoff analysis (Keeney, 1980, Chapter 7), by estimating relative weights, or by taking 100 "points" and distributing them. In the present example, the last method is used. Results are given in Table A-3.

Table A-3 Weights of Attributes

	Cost ($K)	Rad Risk (mrem)	Non-rad risk (accidents)	Distance (miles)	Public Acceptance
Weights	30	20	20	10	20

A.1.4 Calculating the net multi-attribute utility (value to the decision-maker) of each alternative.

A measure of the desirability or value of each alternative is then calculated by multiplying the weight by the utility:

Eq. A- 1 **Route1: 0.75x30 + 0.75x20 + 0.85x20 + 0.6x10 + 0.05x20 = 61.5**

Eq. A- 2 **Route 2: 0.25x30 + 0.9x20 + 0.65x20 + 0.7x10 + 0.5x20 = 55.5**

The decision-maker then has a result he or she can interpret. In the above case, Route 1 appears to be somewhat more desirable overall, because of the slightly larger weight given to cost than to other attributes. Changing weights may test sensitivity.

A.2. Sensitivity analysis

One method of testing sensitivity to attributes is to set the weight of an attribute to zero, normalize the weights of the remaining attributes, and gauge the change in the multi-attribute decision analysis. This type of sensitivity analysis is discussed at length in Appendix D.

Appendix B Analytica Model of Decision Process

Appendix B Analytica Model of Decision Process

B.1 Brief Description of Analytica

Analytica™ (Analytica, 1997) is the modeling software used in this analysis. This description of Analytica is intentionally brief and superficial, and presents only the highlights of the software capabilities. A prospective user of Analytica is advised to consult the cited reference. Statistical analysis of considerable sophistication may be carried out in Analytica, but that discussion is beyond the scope of this report.

Analytica screens look like influence diagrams, and the software uses an influence diagram approach. Figure B-1 shows the various symbols used in Analytica models; the figures in Appendix B are made up of these Analytica symbols.

Although the symbols are essentially empty containers that the modeler fills as he or she desires, the conventional functions suggested by Analytica are usually adhered to, and facilitate understanding of the model:

Module Node: an envelope that contains a sub-model of the overall Analytica model.
Probability Node: a node that represents an uncertainty distribution. The uncertainty distribution in a probability node can be applied to any number of variables.
Variable Node: a node that can represent any parameter. This is the general-purpose node in Analytica.
Decision Node: represents or depicts a decision parameter – a quantity or parameter that the decision-maker chooses
Result or Objective Node: depicts the results of all or part of an analysis or calculation.
Index Node: depicts an index. Analytica calculates in a series of arrays; an index is the column or row heading of an array.

Each Analytica node contains the following information:

- A description of the parameter that the node represents, e.g., cost of a facility, with the source of the information.
- An expression of the parameter, that can be a matrix, an equation, an uncertainty distribution, or a number.
- Inputs to the parameter; e.g., if the cost is a sum, inputs could be capital cost and M&O cost.
- Outputs: parameters affected by the parameter in question.
- A variable name that represents the parameter in equations.

Analytica has a library of uncertainty distributions, so that any parameter can be expressed as an uncertainty distribution. Analytica also allows a distribution to be applied to more than one parameter. Different types of distributions (e.g., normal and triangular distributions) can be combined in Analytica; combinations are made by sampling on each distribution and combining the sampled points according to the equation specified by the modeler. The modeler specifies the type of sampling (Monte

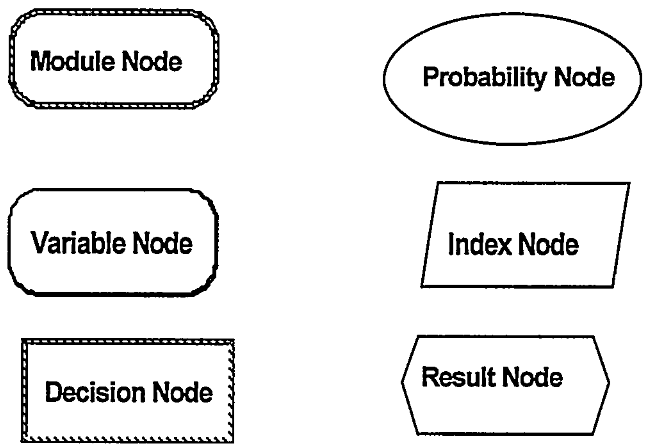

Figure B-1 Nodes (symbols) used in Analytica

Carlo, Latin Hypercube, etc) and the number of samples. In this analysis, Latin Hypercube sampling was used. One thousand observations were sample from each distribution.

Results of any model calculation can be displayed in tabular or matrix form, or graphically. Mean values, cumulative distributions, probability density distributions, and probability bands can be displayed. Input data can be changed at any point in the model and the results of changes are displayed in real time.

B.2 Relationship between the Decision Attributes and the Physical Processes of SNF Treatment

Each process step that makes up the entire Al-SNF treatment process impacts the values of one or more of the attributes of the decision. The relationship between processes and attributes is provided in Table B-1.

Table B-1 Relationship between Processes and Attributes

	Capital Cost	Other Costs	Public Rad Dose	Secondary waste	Likelihood of proliferation	Acceptability
Pool Storage		X				
Prepare TSS Facility	X	X				
SNF Treatment		X	X	X		
Transportation		X	X			
Repository		X			X	X

Cost is the only attribute associated with each process step of both treatment alternatives. Krupa (1997) provides costs on an annual basis. The attributes are evaluated on a program life cycle basis, and the cost attribute is integrated within the module over the expected project life.

B.2.1 Pool Storage

The pool storage module represents the activities involved in the continued maintenance of SNF in wet storage provided in the RBOF and L-Basin. The model diagram is provided in Figure B-2.

The only attribute affected by pool storage is *other costs*. The annual cost for continued operation of L-Basin and RBOF are provided in Krupa (1997). The model evaluates the costs for L-Basin and RBOF until each basin has been emptied (de-inventoried). Emptying of L-Basin and RBOF is assumed to begin when the TSS opens: between 2006 and 2011 for the melt and dilute alternative and between 2006 and 2009 for direct disposal. The time to de-inventory each of the basins (RBOF and L-Basin) is assumed to vary uniformly between 7 and 9 years for each. The annual wet storage costs are the sum of the costs of RBOF and L-Basin. The node "Cum Wet Storage" integrates the wet storage costs annually over the period of the study. The life cycle wet storage costs are calculated as a contributor to the attribute *other costs*.

B.2.2 Prepare TSS Facility

This module represents those activities that are to be performed before the TSS opens for operations. The TSS facility is necessary for the receipt of offsite Al-SNF and for the treatment of both offsite Al-SNF and the Al-SNF inventory from RBOF and L-Basin. *Capital cost* and *other costs* are the only attributes affected by on-site transfer. *Capital costs* recovered over a period of years subsequent to the opening of TSS, and the costs associated with the development of the technology for TSS are included. Other activities related to maintenance and operations of the TSS are located in the SNF treatment module.

The upper tier of nodes (4 nodes) in Figure B-3 represent the *capital cost* calculation. The lower tier of nodes represents the cost to develop the TSS. The cost of development is not a capital cost but will contribute to *other costs*.

Capital recovery costs are incurred over a five-year period beginning with the opening of the TSS. The date at which the TSS opens is determined in the pool storage module. Uncertainty is modeled for the cost estimate for each of the five years of recovery of TSS development costs. The result is the only contributor to *capital cost.*

Data from Krupa (1997) for annual TSS development costs is summarized in Table B-2.

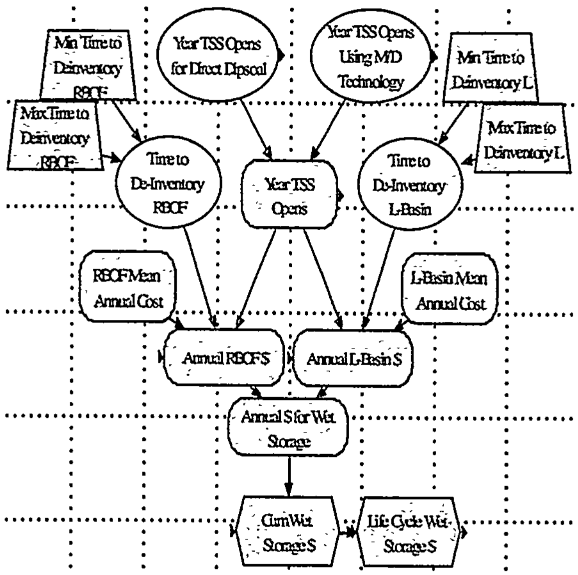

Figure B-2 Pool Storage Diagram

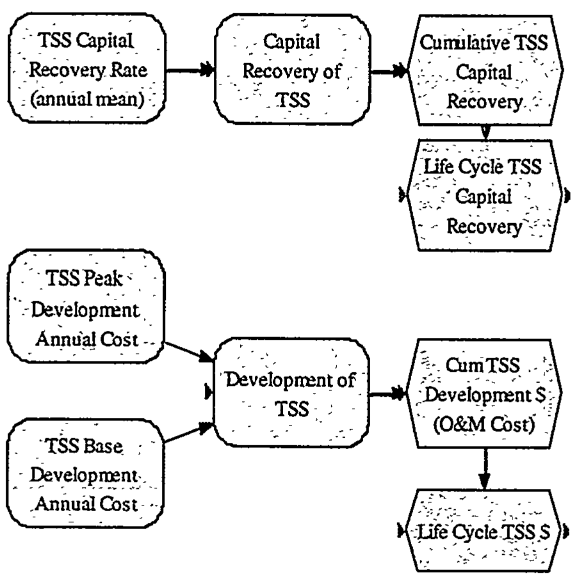

Figure B-3 Prepare TSS Facility Diagram

Table B-2 TSS Development Costs

Development Year	$ Millions
1	7.8
2	2.9
3	7.0
4	4.1
5	2.2
6	2.2
7	2.1
8	2.1
9	2.1

The approximation does not affect the decision analysis because the data for direct disposal and melt and dilute costs for this activity (Krupa 1997) are identical. Furthermore, life cycle costs are components of the *other cost* attribute, so that the annual variations in this cost component are inconsequential, as long as the cost integrated over time approximates the value of the tables.

Development cost is calculated by applying the following factor to the cost distribution:

Eq. B- 1 $$[B + (P - B) * \exp(-.55 * time)]$$

where B = the minimum TSS development cost
P = the maximum TSS development cost

The exponential coefficient 0.55 results in an empirical approximation to the nine-year total: a total of $32.74 million as compared to the data in Table D-1 of Krupa (1997) of $32.5 million. In the context of total other costs, this difference is negligible .

B.2.3 SNF Treatment

The SNF treatment process includes all activities beginning with the opening of the TSS through receipt of SNF from offsite and RBOF and L-Basin, through treatment such as cropping, melting, or canning, through characterization of the SNF, transfer to dry storage, and all associated M&O. This process module contains sub-modules for the calculation of SNF treatment contribution to *other costs*, *secondary waste* and *public radiological health.*

Cost data is taken from Krupa (1997), and waste and public health data, from USDOE (1997).

B.2.3.1 Cost elements in SNF Treatment

Figure B-4 shows the structure for calculation of costs in the SNF treatment process. Annual labor costs and manpower requirements are provided in Krupa (1997). Operations are assumed to begin with the opening date of TSS at 21 shifts per week until the RBOF and L-Basin are de-inventoried. After that time, only fuels from offsite account for the TSS process load, and operations decrease to 5 shifts per week. Treatment costs represent those costs for materials, maintenance and utilities. Taxes are calculated as described in Krupa (1997). All costs associated with SNF treatment cease when TSS fuel treatment operations are terminated.

As with *other costs*, these costs have uncertainty applied and are integrated to provide life cycle costs for inclusion in the *other costs* attribute.

B.2.3.2 Waste stream module

The relative volume of waste materials produced by each treatment alternative is estimated in this sub-module. The volumes of wastes for four waste categories; LLW, HLW, MLW, and TRU, are from USDOE (1997). A uniform uncertainty distribution on the volume of each waste type was developed in consultation with WSRC (see Appendix C). HLW is reported in USDOE (1997) in units of DWPF canister equivalents, which are converted to volume units (m^3). All other wastes are reported in terms of cubic meters.

SRS currently is in possession of waste in each of these four categories. Therefore, the metric for secondary waste generated by the treatment alternatives is not the waste volume itself but the fractional increase of the SRS inventory in each waste category. Calculation and application of the fractional increase are discussed in Section 2.5.4 of this report. Figure B-5 is a diagram of the waste stream module.

B.2.3.3 Public Radiological Health

The *public radiological health* attribute is the annual dose in millirem to a maximally exposed individual member of the general public (MEI) outside the SRS site. Non-rad risk and occupational risks are not attributes of this decision, as discussed in Section 2.2.3 of this report. USDOE (1997) provides MEI doses from site operations. *Public radiological health* includes doses from transportation; the annual doses from transportation of the SNF to a repository were calculated using RADTRAN (Neuhauser and Kanipe, 1992). The RADTRAN analysis is discussed in Section B3 of this appendix. The MEI dose for the model is the sum of the dose from site operations and from transportation. No uncertainty is applied as the MEI dose, because it is itself a maximum value.

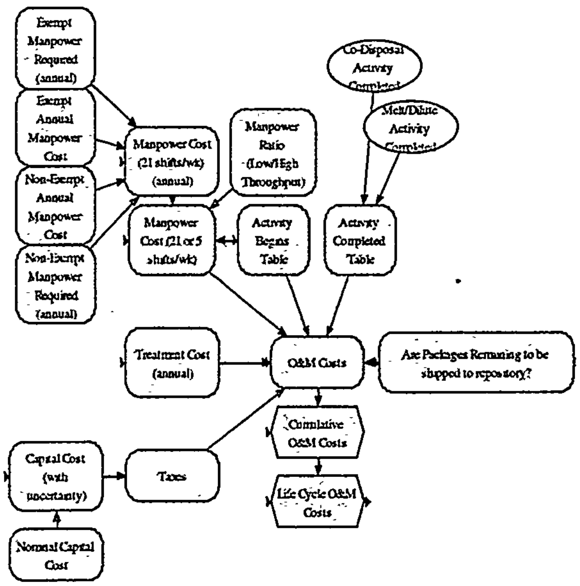

Figure B-4 Cost in SNF Treatment Diagram

B.2.4 Transportation to the repository

This module calculates contributions to *capital cost, other cost,* and public *radiological health* and consists of three sub-modules. The first is denoted "transportation breakdown" and is shown in Figure B-6.

The total number of SNF canisters and number of disposal canisters per transport package are used to determine the number of shipments required for each method over the life of the program.

The year in which the shipments to the repository begin (an uncertain and largely uncontrollable parameter) is treated parametrically and assigned the design value of 2020; it is not shown in the diagram of Figure B-6. This value is used to construct a mask (0 or 1) that acts as a constraint to not allow or allow shipments to occur in a given year. The number of disposal canisters to be shipped is then decreased according to the number of annual shipments.

The number of canisters required is provided in WSRC (1997a). The number of canisters per storage package is assumed to be 7, based on physical capacity. It is assumed that 5 storage/transport packages will be shipped per rail shipment. Krupa (1997) estimates that TSS transportation casks will be loaded at a rate of 3 per quarter, with a peak rate of 4 per quarter used to define uncertainty in the preparations rate.

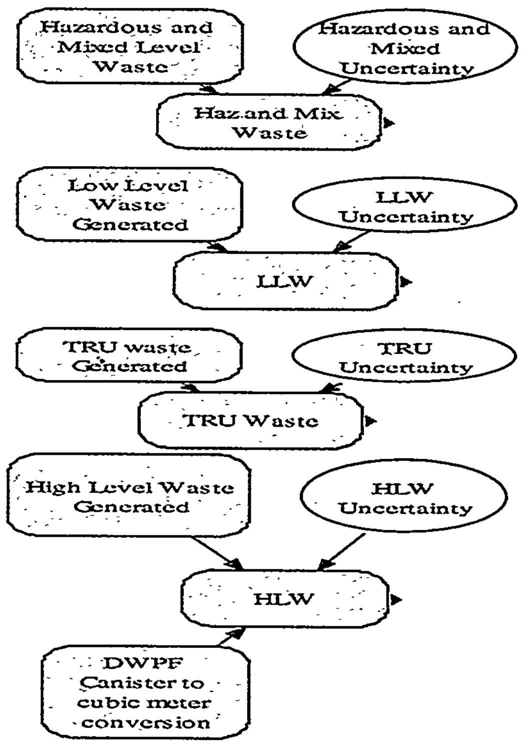

Figure B-5 Waste Stream Diagram

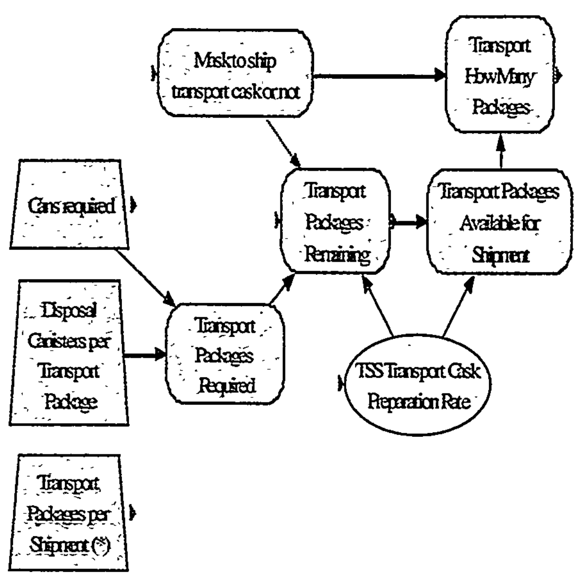

Figure B-6 Transportation Breakdown Diagram

The transportation cost module diagram is provided in Figure B-7. Krupa (1997) provides transportation cost data. Uncertainty in cost is applied on a per shipment basis. As with *other costs*, the life cycle value is calculated for inclusion in the attribute.

As indicated, transportation dose is calculated using RADTRAN and is discussed in Section B3 of this appendix.

B.2.5 Prepare TSS Facility

This module includes only the cost of NUHOMS to provide dry storage. The cost is based on the following information. The costs and quantities of NUHOMS modules cited in WSRC (1997b) are not consistent with the ratios of disposal canisters cited in the WSRC (1997a) (See object description for variable "Cans Required").

NUHOMS Horizontal Storage Module [Includes design, certification, licensing @ $6 mill/qty] (Co-disposal Option)
200 each; Total = $30,200 $FY98 Thousands

Capital cost from WSRC (1997b)

NUHOMS Horizontal Storage Module [Includes design, certification, licensing @ $6 mill/qty] (Melt and Dilute)
70 each; Total = $14,490 $FY98 Thousands
Capital cost from WSRC (1997b)

Including variables that depend on the quantity of SNF material being stored will accommodate any future changes to the modeling of storage activities.

If storage is to be in existing facilities, with no distinction between the alternatives for dry storage regardless of the quantity being stored, this contributor to cost can be disconnected from the remainder of the model.

B.2.6 Repository

Emplacement in the repository contributes to three attributes: *other costs*, *acceptability*, and *likelihood of proliferation*. The number of canisters required is multiplied by the costs per emplaced canister, and the uncertainty is applied.

Quantification of the *acceptability* attribute is discussed in Section 2.4.5 of this report. A normal distribution, with a standard deviation of 20%, is applied to the acceptability value. The distribution of *acceptability* is truncated at 1.0 on the high end.

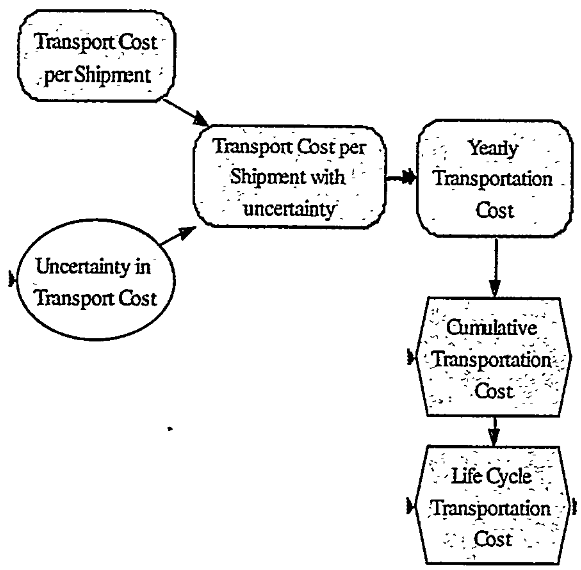

Figure B-7 Transportation Cost Module Diagram

B.2.7 Likelihood of Proliferation

Likelihood of proliferation is discussed in Section 2.4.6 of this report and is treated as equivalent to enrichment. Enrichment for the melt and dilute alternative is modeled as a uniform distribution from 5% to 20%; for direct disposal, as a uniform distribution 20% to 93%.

B.2.8 Accumulated Attributes

This module accumulates the attributes calculated for the various processes, as described in previous sections.

B.2.9 Utility Functions

Utility functions are described in Section 2.4 of this report. This module applies the utility function for each attribute to the distribution. This produces a distribution of utility for each single attribute. This conversion from dollars, millirem, etc. to utility provides a common scale for each of the attributes. Figure B-8 shows the utility function module.

The products of the single-attribute utility distributions and the relative weight of the appropriate attribute (Section 2.3.2) are added to yield the multi-attribute utility distribution for each alternative treatment.

Several alternative weightings were considered in the analysis and are discussed in Appendix D as sensitivity analyses. The module "Utility Weight Selection/Construction"

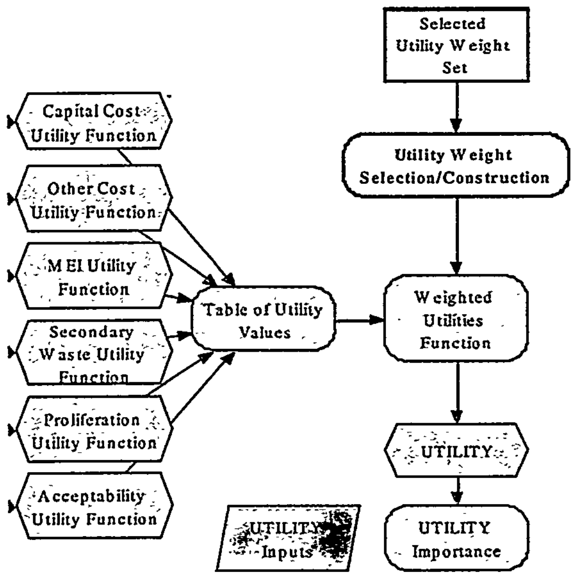

Figure B-8 Utility Function Diagram

calculates different case weights and allows the decision analyst to select all or a single weight set for evaluation of the sensitivity of the result to the different weights.

The diagram includes a node for utility importance. This is nominally a correlation analysis between the multi-attribute utility and the uncertain parameters, and identifies parameters to which the utility is strongly correlated.

B.3 RADTRAN Dose Calculation

B.3.1 General description of RADTRAN

Transportation risk is modeled using RADTRAN 4 (Neuhauser and Kanipe, 1992). Although the detailed description of the model in Neuhauser and Kanipe (1992) is not repeated here, several features of RADTRAN are worth noting. RADTRAN models incident-free transportation as a separate module from transportation accidents. In incident-free transportation, an external dose, strictly limited by regulation (10 CFR Part 71), is allowed. RADTRAN models the regulatory limit of external dose for each type of shipment, although experience indicates that the external dose (a measured number) is well below the regulatory limit in the majority of shipments, and is undetectably low for many shipments. Because the regulatory limit is the modeled dose, the modeled incident-free dose is independent of the isotopic content or radioactivity of the material being shipped. Although both gamma and neutron doses can be modeled by RADTRAN, so much of the potential neutron dose is absorbed by air that only the gamma dose is modeled in this case.

The isotopic content of the SNF and waste forms being shipped becomes important in the transportation accident module. RADTRAN models accidents as the risk of emission of fractions of the radioactive cargo into the air: this risk combines the probability of a breach of containment with the amount of material that would be leaked under a particular accident scenario. In the RADTRAN accident module, the set of all possible accidents is divided into subsets (six subsets in the present study), each with a particular probability of occurrence and aerosolized release fraction. The set of accidents always includes a subset for; no release or loss of shielding (by far the most probable case), loss of shielding only (no actual release of material), and released material that is neither aerosolized nor respirable. Doses are modeled using a Gaussian dispersion model (e.g., Wark and Warner, 1981, Chapters 3 and 4). Accident dose risks are reported in rem (like the doses from incident-free transportation); they are, however, risks rather than doses because the accident probability is incorporated.

Routes and population densities are provided by the code INTERLINE (Johnson et al, 1993). Although the census data in INTERLINE is 1990 data, it is unlikely that more recent, less reliable data would change population densities significantly. The division into rural, suburban, and urban sections of any route requires the user to specify only three average speeds, vehicle densities, accident rates, etc. Actual numbers can be used for each census tract along a route, but many RADTRAN studies have shown that such a level of accuracy does not yield significantly different results. In this analysis, in particular, because an individual dose was sought, there was no need to refine the analysis beyond the "rural, suburban, urban" division. The SRS site boundary, where the MEI would be located, is in a rural area, and thus only the "rural" dose and dose risk have any significance.

B.3.2 RADTRAN analysis of transportation risks

RADTRAN model parameters are:
1. Rail shipment is assumed, with 5 SNF casks per rail shipment
2. Direct disposed SNF requires 172 shipments; the melt and dilute alternative requires between 36 and 58 shipments, and a uniform distribution is assumed.
3. Rail route and population densities are obtained from the code INTERLINE.
4. Other parameters are from RADTRAN and are given in Table B-3.

Table B-3 RADTRAN Parameters

Parameter	Type of Route Segment		
	Rural	Suburban	Urban
Residents per sq. km	6.3	346.5	2112.1
Km	3820.5	583.2	48.8
Average speed (km/hr)	64.44	40.32	24.12
Vehicles per hr	1	5	5
Accidents per km	1 E-7	1.9 E-6	1.5 E-5

The RADTRAN risk assessment assumed that each rail car would pass by the location of the MEI. The incident-free dose is therefore the dose to a person at the side of the right-of-way as the train passes by. RADTRAN models population doses and derives maximum individual doses from the population dose model. RADTRAN results are given in Table B-4.

Table B-4 RADTRAN Results: Doses from Rural Area Transportation of SNF

Alternative	Incident-free dose (mrem)	Accident dose risk (mrem)
Direct disposal (172 trips)	0.927	2.5E-4
Melt and dilute (36 trips)	0.194	5.2E-5
Melt and dilute (58 trips)	0.313	8.4E-5

Because the doses from incident free transportation are four to five orders of magnitude higher than the modeled accident dose risks, the latter were treated as negligible.

Appendix C Data

Appendix C Data

Data were obtained from the following sources, and are summarized in Table C-1 and Table C-2:

- Informal elicitations from DOE/SR personnel (Jean Ridley, Charlie Anderson, Randy Ponik) concerning the following topics:
- – Acceptability of the Treated SNF to the Repository
- – M&O cost function utility
- – *Capital cost* function utility

- Personal communications with WSRC personnel (Joe Krupa, Natraj Iyer, Harold Peacock) and Jean Ridley/DOE-SR

- Documents reviewed or consulted:
- – WSRC, 1997a.
- – WSRC, 1997b.
- – Krupa, 1997.
- – U.S. DOE, 1997.
- – Cook, 1997.
- – USGPO, 1998.

Table C-1 Data Summary

Parameter	Description or Value	Units	Source for Description or Value	Uncertainty
Annual Treatment M&O Costs (Direct Disposal)	Maintenance/Materials/Utilities (5 shift operation): \$859/\$491/\$368; Total = \$1719	\$ Thousands	Krupa, 1997. p. 22/Table 3	Normal Distribution Mean = \$1719 σ = \$344
Annual Treatment M&O Costs (Melt and Dilute)	Maintenance/Materials/Utilities (5 shift operation): \$622/\$355/\$266; Total = \$1243	\$ Thousands	Krupa, 1997. p. 22/Table 3	Normal Distribution Mean = \$1243 σ = \$249
Technology Implementation Manpower Costs (Direct Disposal Option, 4 shifts)	Costs = (Number of positions)(annual wage) Exempt = (161)(\$91) = \$14651 Non-Exempt = (214)(\$77) = \$16478	\$Thousands	Krupa, 1997. Annual Wages, p. 22, Section 4.4 App. G, p. 1; Labor requirements	Normal Distribution Mean = \$31129 σ = \$6226
Technology Implementation Manpower Costs (Melt and Dilute)	Costs = (Number of positions)(annual wage) Exempt: (198)(\$91) = \$18018 Non-Exempt: (249)(\$77) = \$19713	\$Thousands	Krupa, 1997. Annual Wages, p. 22, Section 4.4; App. G, p. 2;, Labor requirements	Normal Distribution Mean = \$37731 σ = \$7546
M&O Cost (Direct Disposal)	Cost = maintenance/materials/utilities cost + manpower cost + taxes taxes = (0.06*0.1757* capital cost) (0.06*0.1757*\$215922) = \$2276 M&O Cost = \$1719+\$16478+\$2276 = \$20473	\$Thousands	Krupa, 1997. p. 22 Capital cost from WSRC, 1997b.	Normal Distribution For Capital Costs: Mean = \$215922 σ = \$64777
M&O Cost (Melt and Dilute)	Cost = maintenance/materials/utilities cost + manpower cost + taxes taxes = (0.06*0.1757* capital cost) (.06*.1757*\$216360) = \$2281 M&O Cost = \$1243+\$19713+\$2281= \$23237	\$Thousands	Krupa, 1997. p. 22 Capital cost from WSRC, 1997c.	Normal Distribution For Capital Costs: Mean = \$216360 σ = \$64908

Parameter	Description or Value	Units	Source for Description or Value	Uncertainty
Waste Emplacement Cost per Package	$580 per emplacement (waste package and operations) (assumes 1 canister per 5 HWL glass logs)	$Thousands	Krupa, 1997. p. 24	Normal Distribution Mean = $580 σ = $116
Mean Annual Cost for RBOF Operations	12 years operation for RBOF (assumed currently operating) Mean of $20.1M/yr	$ Thousands	Krupa, 1997. Table D-2	Normal Distribution Mean = $20.1 σ = $4.0
Mean Annual Cost of L-Basin Operations	12 years operation for L-Basin (assumed currently operating) Mean of $37.8M/yr	$ Thousands	Krupa, 1997. Table D-2	Normal Distribution Mean = $37.8 σ = $7.6
TSS Capital Cost Recovery Rate	$78.30 (M&D) $83.10 (D/D) Averaged over the 5 years of capital recovery	$ Thousands per year	Krupa, 1997. Table D-2 for Direct Disposal; Table D-4 for Melt & dilute	Normal Distribution Mean (M&D) = $78.3 Mean (D/D) = $83.1 σ (M&D)= $23.5 σ (D/D)= $25.0
TSS Development Costs	A function was developed to approximate the following annual distribution of costs for the "Receipt and Treatment Facility" Development Year Cost 1998 $7.8 1999 $2.9 2000 $7.0 2001 $4.1 2002 $2.2 2003 $2.2 2004 $2.1 2005 $2.1 2006 $2.1	$ Millions	Krupa, 1997. Table D-2	Normal Distribution Year Mean σ 1 $7.8 $1.56 2 $2.9 $0.58 3 $7.0 $1.40 4 $4.1 $0.82 5 $2.2 $0.44 6 $2.2 $0.44 7 $2.1 $0.42 8 $2.1 $0.42 9 $2.1 $0.42
Operating Manpower Ratio (5 to 21 shifts per	Total number of workers required for 5-shift/week operation divided by total number of	Workers	Krupa, 1997. Appendix G.	Applied as cost uncertainty not labor uncertainty

Parameter	Description or Value	Units	Source for Description or Value	Uncertainty
week)	workers for the 21-shift/week operation. Melt and Dilute (239/447) Direct Disposal (206/375)			
Transportation Cost	$101 per cask shipment; 7 canisters per cask	$ Thousands	Krupa, 1997. p. 24	N/A
Hazardous and Mixed Low Level Waste	90 (Melt and Dilute) 21 (Direct Disposal)	Cubic Meters	U.S. DOE, 1997. Table 2.7-3	Uniform Distribution M&D: U(45, 135) D/D: U(10.5, 31.5)
Low Level Waste Generated	Melt and Dilute: 440+20,000+5500+1100 Direct Disposal: 290+14,000+3700+110+900	Cubic Meters	U.S. DOE, 1997. Table 2.7-3	Uniform Distribution M&D: U(14000, 41000) D/D: U(9500, 29000)
TRU Waste Generated	Melt and Dilute: 351 Direct Disposal: 1 Values of <1 have been assigned a value of 1.	Cubic Meters	U.S. DOE, 1997. Table 2.7-3	Uniform Distribution M&D: U(180, 5630) D/D: U(5, 15)
High Level Waste Generated	Melt and Dilute : 1+7+2+1 Direct Disposal: 1+8+2 Values of <1 have been assigned a value of 1.	Equivalent DWPF canisters	U.S. DOE, 1997. Table 2.7-3	Uniform Distribution M&D: U(5.5, 17) D/D: U(5.5, 17)
TSS Transportation Cask Preparation Rate	Steady State: 3 Peak Rate: 4	Per Quarter	Cook, 1997. p. 26/3.1.2.5.4	+/- 1 per quarter
Time to De-Inventory L-Basin	TSS startup estimated between 2002 and 2004; L-basin de-inventory process estimated to be complete in 2009.	Years	Personal Communication J. Krupa (WSRC). Krupa, 1997. Tables D-2 and D-4: 21-shift operation for at least 7 years.	Uniform Distribution U(7, 9)
Time to De-Inventory RBOF	TSS startup estimated between 2002 and 2004; RBOF de-inventory process estimated to be	Years	Personal Communication J. Krupa (WSRC) and F. Davis (SNL).	Uniform Distribution U(7, 9)

Parameter	Description or Value	Units	Source for Description or Value	Uncertainty
	complete in 2011 .		Krupa, 1997. Tables D-2 and D-4 indicate 21-shift operation for a period of at least 7 years.	
Year TSS Opens	2006 The original reference is 2002-2004 (USDOE 1997, p. 2-4)		The value of this date has been changed, per personal communication between J. Krupa (WSRC) 2006.	Uniform Distribution D/D: U(2000.5, 2004.49) M&D: U(2000.5, 2011.49)
SRS Fuel Treatment (Direct Disposal or Melt & dilute) Activity Completed	2037 D/D: 2001/2037 M&D: 2006/2037		Krupa, 1997. p. 4, Fig. 2	Uniform Distribution Min = 2030 Max = 2044
Annual MEI Dose from Radiological Airborne Emissions	0.044 Melt and Dilute 0.00074 for Direct Disposal	Millirem	U.S. DOE, 1997. Table 4.1-25 This value was verified by comparison to the estimated maximum incremental annual doses listed in Table 4.1-3.	N/A
Annual MEI Dose from Radiological Liquid Emissions	0.000042 for Melt and Dilute 0.0014 for Direct Disposal	Millirem	U.S. DOE, 1997. Table 4.1-25	N/A
MEI Incident Free Transportation Doses	Melt and Dilute :5.39×10^{-3} Direct Disposal: 5.39×10^{-3}	Millirem per shipment.	Results from RADTRAN analyses. See Appendix B3.	N/A
DWPF Canister to cubic meter conversion	0.625	Cubic meters per DWPF canister	Per telephone conversion with J. Krupa WSRC on 4/7/98	N/A

Parameter	Description or Value	Units	Source for Description or Value	Uncertainty
Direct Disposal Canisters Required	340 for Melt and Dilute 1400 for Direct Disposal	Number of spent fuel direct disposal canisters.	U.S. DOE, 1997. Table 2.7-3	N/A
Direct Disposal Canisters per Transport Package	7 canisters per cask	Canisters per cask	Krupa, 1997. p. 24 This value has been discussed with J. Krupa (WSRC). The maximum loading per transport cask is 7 disposal canisters.	It is assumed here that the shipment of Melt & dilute Canisters has the same Transport/Disposal ratio.
Transport Packages per Shipment	5	Transport casks per rail shipment	This value has been discussed with J. Krupa (WSRC). The maximum loading per shipment is 5 casks	N/A
Uranium Enrichment	Direct Disposal: 20% to 93% Melt & dilute: 5% to 20%	Weight fraction of U235	Direct Disposal: LMITCO (1998) Melt & Dilute: WSRC (1997a)	Uniform Distribution M&D: U(.05, .2) D/D: U(.2, .93)
NAS Method Acceptability	NAS is about 0.6 (60%) likely to accept melt & dilute and about 0.4 (40%) likely to accept direct disposal.	Fraction	Section 2.2.4 (elicitation of DOE-SR)	Normal Distribution ; M&D: Mean = 0.6, σ = .12 D/D: Mean = 0.4, σ = ..08
NWTRB Method Acceptability	NWTRB prefers melt & dilute to direct disposal by about 2/1, and is about 0.9 (90%) likely to accept melt & dilute, so about 0.45 (45%) likely to accept direct disposal).	Fraction	Section 2.2.4 (elicitation of DOE-SR)	Normal Distribution ; M&D: Mean = 0.9, σ = .18 D/D: Mean = 0.45, σ = ..09
NWTRB/NAS Relative Weighting	DOE expects to weight NWTRB review more heavily than NAS	Fraction	Elicitation of DOE/SR	Uniform Distribution . U(.5, .75)
NUHOMS Horizontal Storage Module	200 each; Total = $30,200	$ Thousands	WSRC, 1997b.	N/A

Parameter	Description or Value	Units	Source for Description or Value	Uncertainty
[Includes design, certification, licensing @ $6 mill/qty] (Direct Disposal Option)				
NUHOMS Horizontal Storage Module [Includes design, certification, licensing @ $6 mill/qty] (Melt and Dilute)	70 each; Total = $14,490	$ Thousands	WSRC, 1997c.	N/A
HEU Volume %	75% of overall Al-based SNF Volume		USDOE, 1998. p. A-1: 76-79	N/A
Fissile Material Packaging Criteria	See Table C-2		Cook, 1997. p. 24/Table 3.1.2.2.19-1	N/A

Table C-2 Fissile Material Packaging Criteria

Packaging Criteria		46 cm (18 inch) (nominal) Canister		
		Direct Disposal	Co-Disposal	Melt and Dilute
Fissile-limit (Kg U-235 Maximum)	HEU	14.4	14.4	N/A
	LEU	43.0	43.0	(TBD)
	Mixed	14.4	14.4	N/A
Thermal limit (kW Maximum)		14.2	11.7	11.7

Appendix D Sensitivity Investigations

Appendix D Sensitivity Investigations

This appendix contains a number of examples in which one or more parameters of the decision analysis are changed, in order to assess the sensitivity of the decision analysis model to such changes. As is seen in each of the examples in this appendix, changes in parameters are equivalent to assigning different values or different weights to an attribute, such as might be assigned by a different decision maker.

D.1 Sensitivity Analysis of Alternative Attribute Weights

In the original case MUA analysis summarized in Section 3, the weight assigned to each attribute was the average of the attribute weight elicited from each of the three DOE-SR decision-makers, as discussed in Section 2.3.2. In this sensitivity analysis, the attribute weights elicited from each of the DOE-SR staff are considered separately. No other changes have been made in the analysis. The attribute weights are shown in Table D-1. Figures D-1, D-2, and D-3 show the multi-attribute utility results for each individual decision-maker.

Table D-1 Decision Attribute Weights

Attribute	Attribute Weights			
	DOE-SR Decision maker			Average for All Decision-Makers
	DM-1	DM-2	DM-3	
Capital Cost	0.16	0.30	0.23	0.23
Other Cost	0.11	0.18	0.11	0.13
Radiological Dose	0.26	0.18	0.18	0.21
Secondary Waste	0.16	0.04	0.02	0.07
Likelihood of proliferation	0.05	0.06	0.12	0.08
Acceptability	0.26	0.24	0.34	0.28

As can be seen from Figures D-1, D-2, and D-3, the multi-attribute utility for the melt and dilute alternative is similar for all three decision-makers, although the multi-attribute utility for the direct disposal alternative varies somewhat between the three decision-makers. However, just as with the average attribute weights, the multi-attribute utility of the melt and dilute alternative is larger than for direct disposal for each of the individual DOE-SR decision-makers. As shown in Table D-1, significant differences in weights among the three are rare: DM-1 weighted *secondary waste* considerably more than the other two, but not enough to change the relative order of the MUA results. DM-2 weighted *capital cost* slightly higher than the other two decision-makers did, but not enough to change the MUA result significantly. Although the weights for *acceptability*

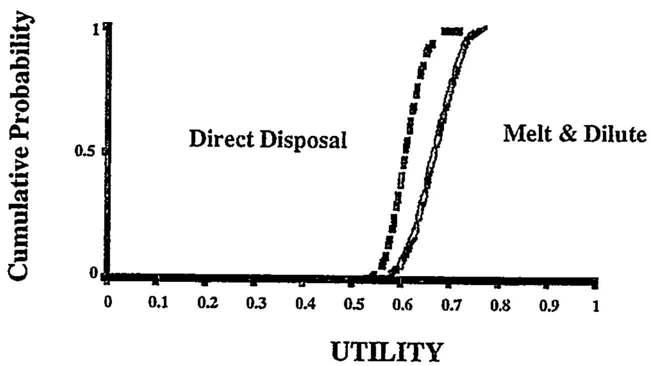

Figure D-1 Multi-attribute utility using DM-1 attribute weights

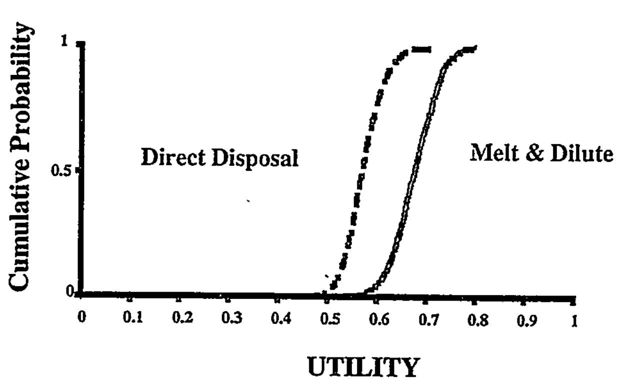

Figure D-2 Multi-attribute utility using DM-2 attribute weights

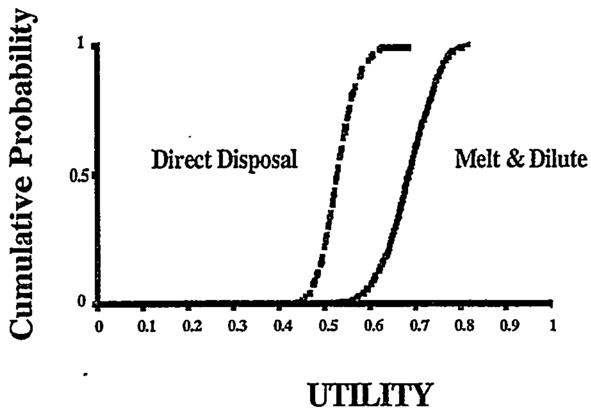

Figure D-3 Multi-attribute utility using DM-3 attribute weights

differ among the three decision-makers, all three weighted *acceptability* relatively high. Thus, the relative magnitude of the MUAs remained the same.

The model was also exercised with all attributes weighted equally. Figure D-4 shows the cumulative distribution of the multi-attribute utilities for this case. It can be seen that the relative magnitudes of the MUAs remain unchanged.

Figures D-1 through D-4 illustrate that the melt and dilute alternative has a consistently higher multi-attribute utility than the direct disposal alternative for all of the attribute weights considered here.

D.2 *Capital cost* sensitivity.

In order to represent a situation in which the capital cost of the melt and dilute alternative might have been underestimated, the value of *capital cost* was doubled for the melt and dilute alternative, while all other parameters remained unchanged. Figure D-5 shows the multi-attribute utilities using the average attribute weights from Table D-1. Doubling the capital cost of the melt and dilute alternative does increase the relative multi-attribute utility of direct disposal, as one might expect. However, the MUA for the melt and dilute alternative is still larger than for direct disposal. If the value of the melt and dilute capital cost were increased much more (e.g., quadrupled), the relative MUAs could perhaps be reversed. Modeling a series of capital cost values would give a better idea of the sensitivity of the result to the *capital cost* attribute.

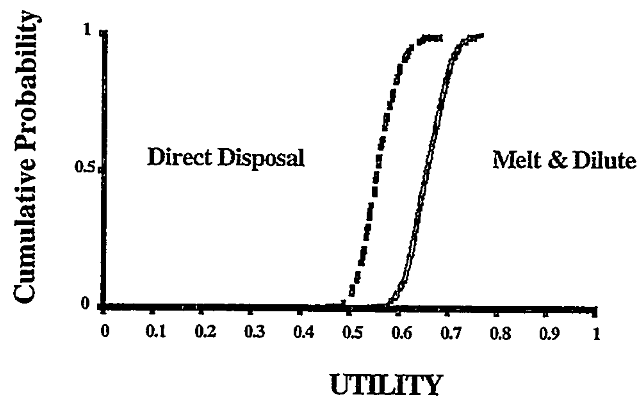

Figure D-4 Multi-attribute utility using equal attribute weights

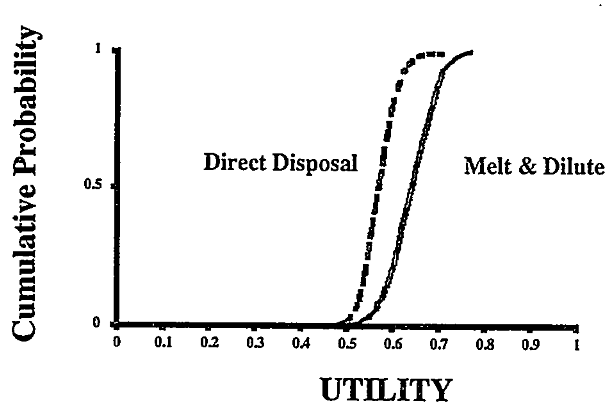

Figure D-5 Multi-attribute utilities for the *capital cost* sensitivity

D.3 Removal of attributes from the decision model

In order to simulate cases in which the decision-maker would have chosen a somewhat different set of attributes, six separate sensitivity analyses are conducted. Each of the six attributes is removed from the model and the multi-attribute utility analysis is recalculated using only the remaining five attributes. The average weights from Table D-1 are adjusted by setting the weight of the attribute removed to zero and renormalizing the remaining five attribute weights. As is evident in Figures D-6 through D-11, the multi-attribute utility for the melt and dilute alternative remains larger than for direct disposal. The relatively higher MUA for melt and dilute for each of these six sensitivity analyses is expected. The single attribute utilities for the various attributes are greater for melt and dilute than for direct disposal for four out of the six attributes. Thus, regardless of which attribute is removed from the model, the decision analysis will still be dominated by a majority of attributes for which the single attribute utilities favor melt and dilute. The two attributes for which the single attribute utility favors direct disposal are *public radiological health* and *secondary waste.*

Because of the large weight assigned to *acceptability*, one might expect that the model's sensitivity to the removal of this attribute might be the most significant for all of the attributes. Figure D-11 shows that in this case the two multi-attribute utilities almost coincide, but the relative MUAs are not reversed. One may conclude in this case that the two MUAs are essentially the same within the bounds of their uncertainties, and that, for these particular decision-makers, the *acceptability* attribute is the primary driver in the difference between the MUAs for melt and dilute and direct disposal. Sensitivity of the model to the *acceptability* attribute is discussed further in Section D.5.

D.4 Increase *secondary waste* attribute weight.

Secondary waste is one of the two attributes for which the single attribute utility for direct disposal is larger than the single attribute utility for melt and dilute (Section 2.5.4). Therefore, the increase in the value of the attribute weight for *secondary waste* that would be needed to drive the MUA for direct disposal to a greater value than the MUA for melt and dilute was investigated. Starting with the average attribute weights from Table D-1, the attribute weight for *secondary waste* was increased, and other attribute weights were normalized from the average values in Table D-1. This procedure was repeated until the multi-attribute utilities for the two alternatives coincided. The attribute weights used to produce this distribution are listed in Table D-2. Figure D-12 shows the resulting multi-attribute utility. As is evident from Table D-2, the weight of *secondary waste* must be increased by a factor of almost 6.5 in order for the model to estimate equivalent multi-attribute utilities for the two alternatives. The effect on the relative multi-attribute utilities of this re-weighting is much the same as the effect of removing acceptability as an attribute.

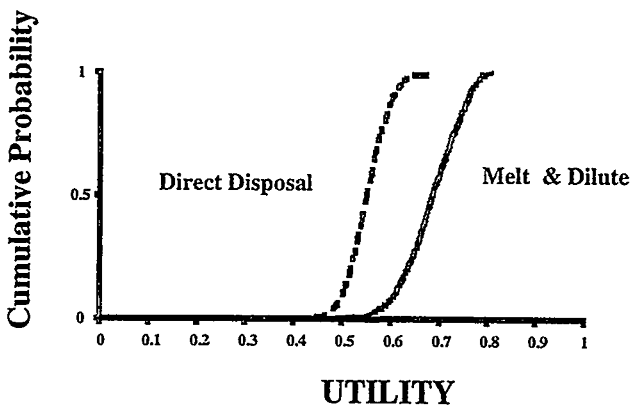

Figure D-6 Multi-attribute utilities without *capital cost*

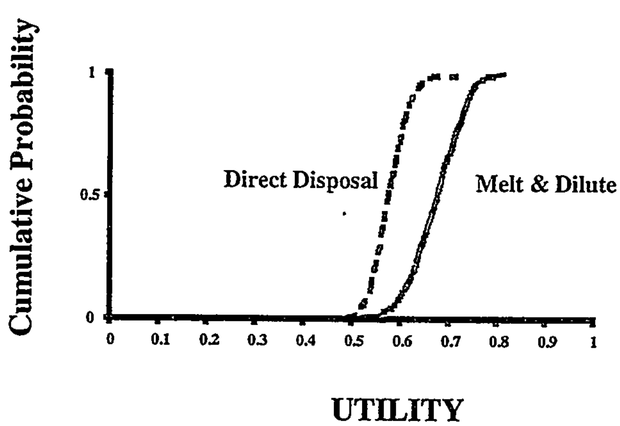

Figure D-7 Multi-attribute utilities without *other costs*

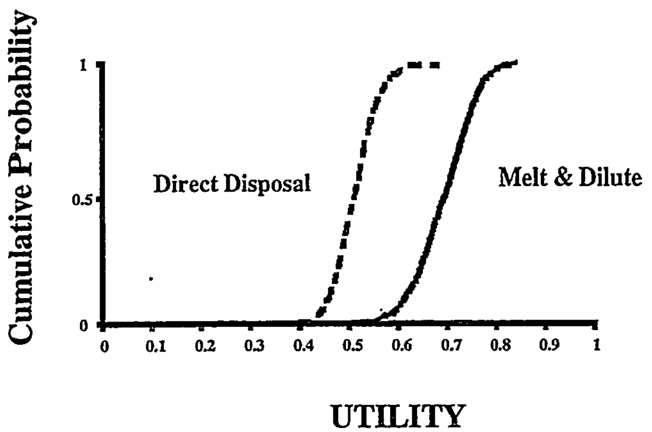

Figure D-8 Multi-attribute utilities without *public radiological health*

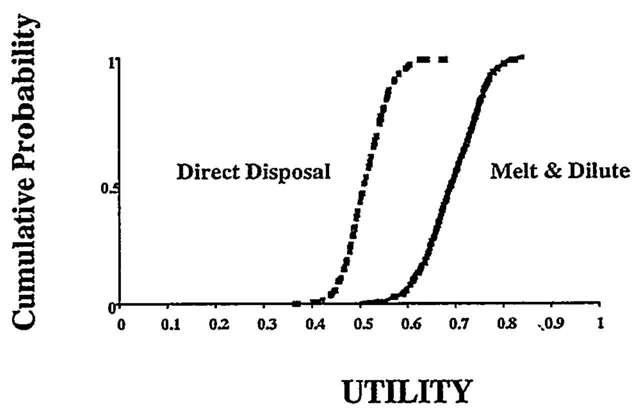

Figure D-9 Multi-attribute utilities without *secondary waste*

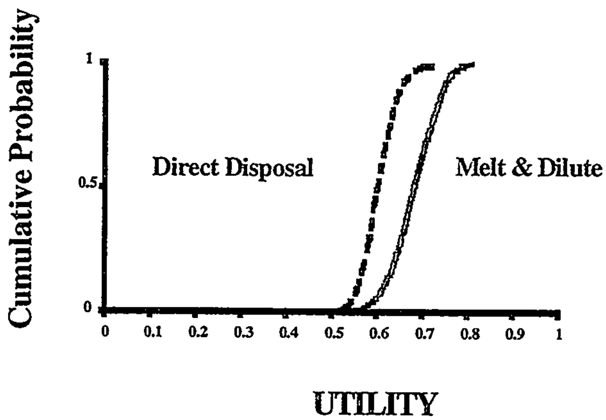

Figure D-10 Multi-attribute utilities without *likelihood of proliferation*

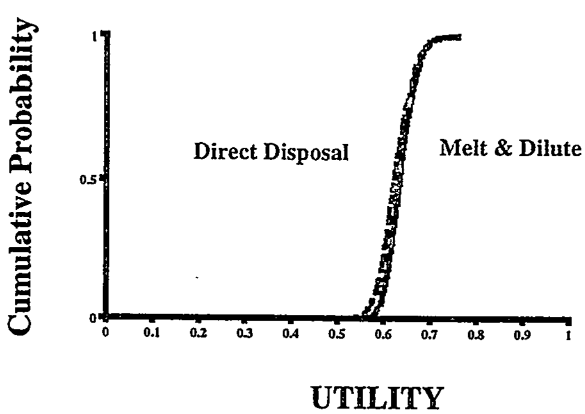

Figure D-11 Multi-attribute utilities without *acceptability*

Table D-2 Weights Required For *Secondary Waste* to Change the Preference for Melt and Dilute

Attribute	Weight
Capital Cost	0.13
Other Cost	0.08
Public Radiological Health	0.12
Secondary Waste	0.45
Likelihood of proliferation	0.06
Acceptability	0.16

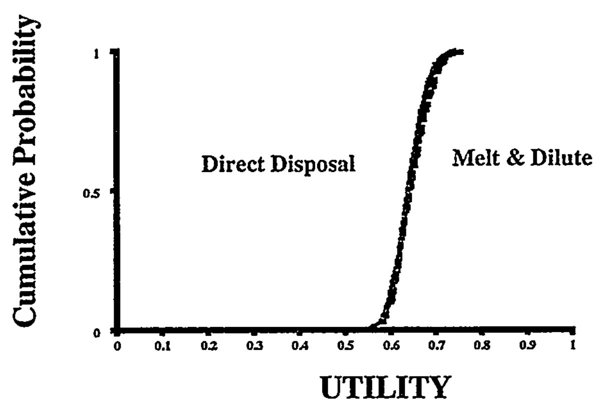

Figure D-12 Multi-attribute utility with *secondary waste* attribute weight increased

D.5 Sensitivity to the *acceptability* attribute value

Acceptability has no natural scale, and its values are captured in a constructed scale based on elicitation of the three DOE-SR decision-makers. Furthermore, no objective data used in estimating these values. As was discussed in Section 2.5.5, the values assigned to *acceptability* of the two alternatives were the DOE-SR estimates of the acceptability of each alternative to two peer review groups (NWTRB and NAS), combined with the DOE-SR estimates of the relative importance of these groups' assessment to DOE. Therefor, the sensitivity of the model to changes in the value of the *acceptability* attribute is investigated as follows: it is assumed that the DOE-SR decision-makers have incorrectly assessed the NWTRB and NAS preferences and, as an example, the values of the NWTRB and NAS *acceptability* are reversed. This sensitivity differs from the sensitivity case studied in Section D.3 and illustrated in Figure D-11, wherein the *acceptability* attribute was removed from the model, representing the case of a decision-maker to which *acceptability* is unimportant. The sensitivity analysis here assesses the case where the *acceptability* attribute remains important to the decision-maker, but its values, and hence its single attribute utilities, are differently valued than for the original case.

Table D-3 shows both the original and the reversed *acceptability* attribute values. The impact of reversing the attribute values is significant, as shown in Figures D-13 and D-14. The distributions for the multi-attribute utilities of the two alternatives in Figure D-13 indicate that direct disposal would now have the larger multi-attribute utility. As seen from the CDF of the ratios of the MUA estimates for the two alternatives in Figure D-14, this result would hold throughout the entire uncertainty range of multi-attribute utility estimates.

Table D-3 Likelihood of *Acceptability* for Each Treatment Alternative – Original Case and Sensitivity Case

Treatment Alternative	Original Case		Sensitivity Case	
	NAS	NWTRB	NAS	NWTRB
Melt and Dilute	**0.60**	**0.90**	**0.40**	**0.45**
Direct Disposal	**0.40**	**0.45**	**0.60**	**0.90**

Unfortunately no documentation of the preferences of these two peer review groups was available at the time of this writing. When such documentation becomes available, a reassessment of the *acceptability* attribute that incorporates such documentation would be very informative for the decision-maker.

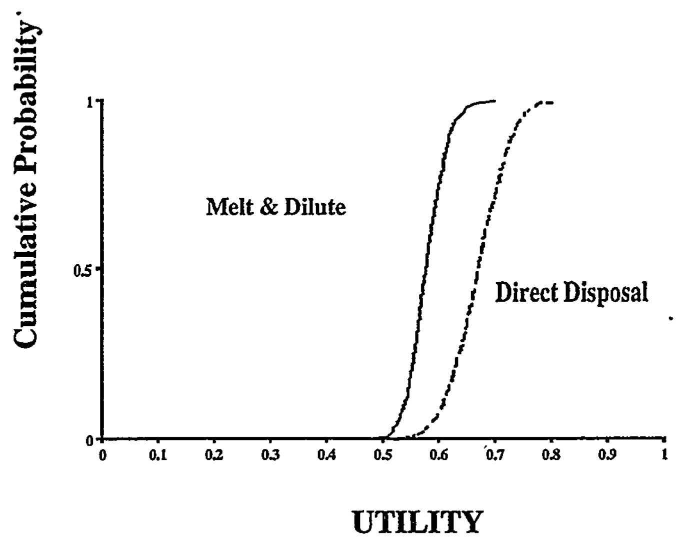

Figure D-13 Reverse *acceptability* values for both NWTRB and NAS

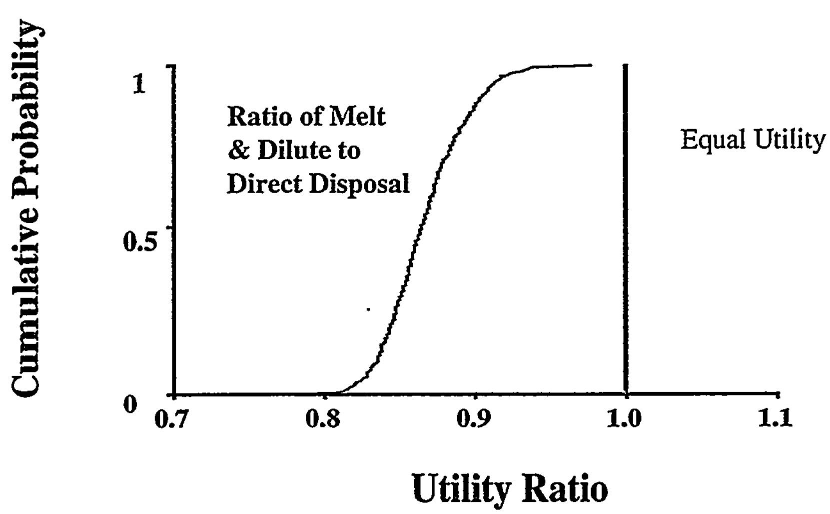

Figure D-14 Multi-attribute utility ratios when *acceptability* values for both NWTRB and NAS are reversed

Appendix E Single Attribute Utility Probability Densities

Appendix E Single Attribute Utility Probability Densities

The figures in this appendix are the single attribute utilities displayed as probability densities instead of as cumulative probabilities.

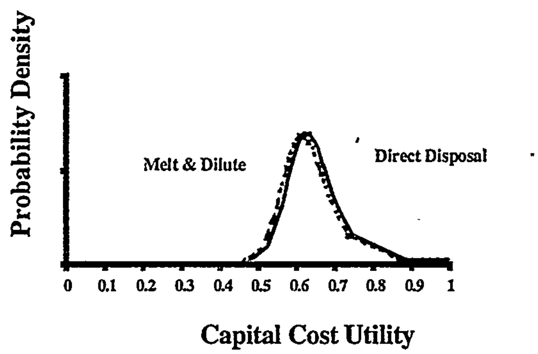

Figure E-1 *Capital Cost* **Single Attribute Utility Probability Density**

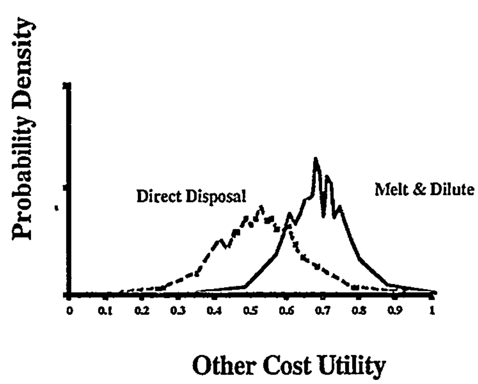

Figure E-2 *Other Costs* **Single Attribute Utility Probability Density**

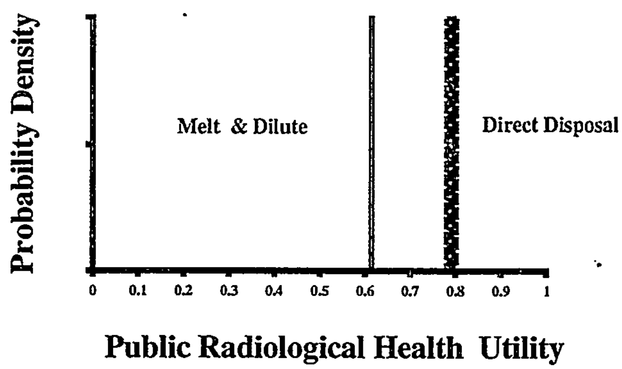

Figure E-3 *Public Radiological health* Single Attribute Utility Probability Density

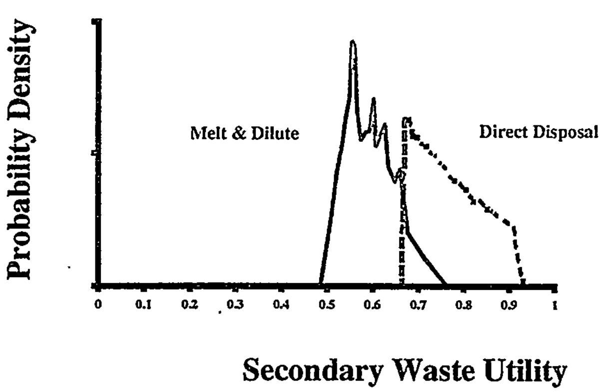

Figure E-4 *Secondary Waste* Single Attribute Utility Probability Density

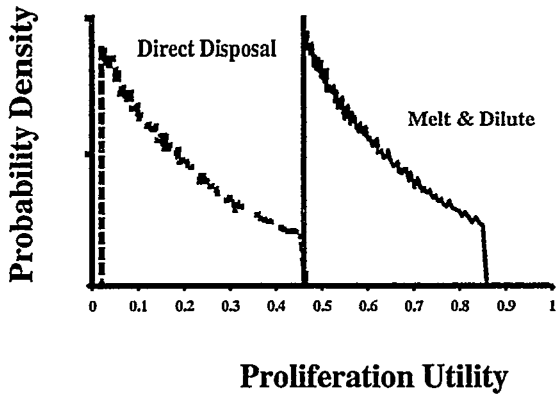

Figure E-5 ***Likelihood of Proliferation*** **Single Attribute Utility Probability Density**

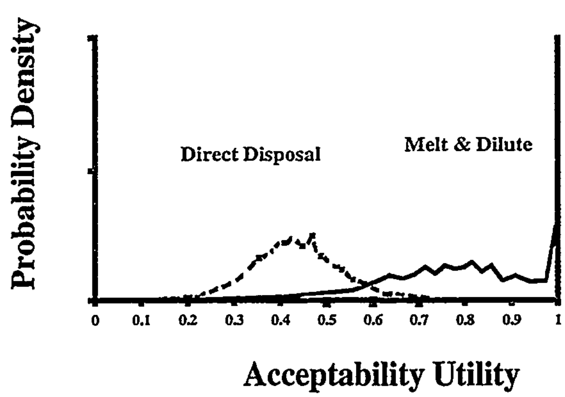

Figure E-6 ***Acceptability*** **Single Attribute Utility Probability Density**

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