

A MULTI-ATTRIBUTE UTILITY DECISION ANALYSIS FOR TREATMENT ALTERNATIVES FOR THE DOE-SR ALUMINUM-BASED SPENT NUCLEAR FUEL

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ABSTRACT

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 Statement*. The proximate goal for DOE-SR is to identify the treatment alternatives for Al-SNF that achieve this mission with optimal efficiency and effectiveness. A multi-attribute utility decision analysis (MUA) was performed to address this decision. The results of the MUA indicate that, for 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. 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.

INTRODUCTION

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.”* The proximate goal for DOE-SR is to identify the treatment alternatives for Al-SNF that achieve this mission with optimal efficiency and effectiveness.

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.

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, using the modeling tool Analytica¹. 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 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

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. "Minimize Cost" 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*:

* The objective "Minimize Cost" defines two separate cost attributes to reflect the decision-makers' different utilities towards *capital costs* and *operational costs*)

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

THE DECISION ANALYSIS

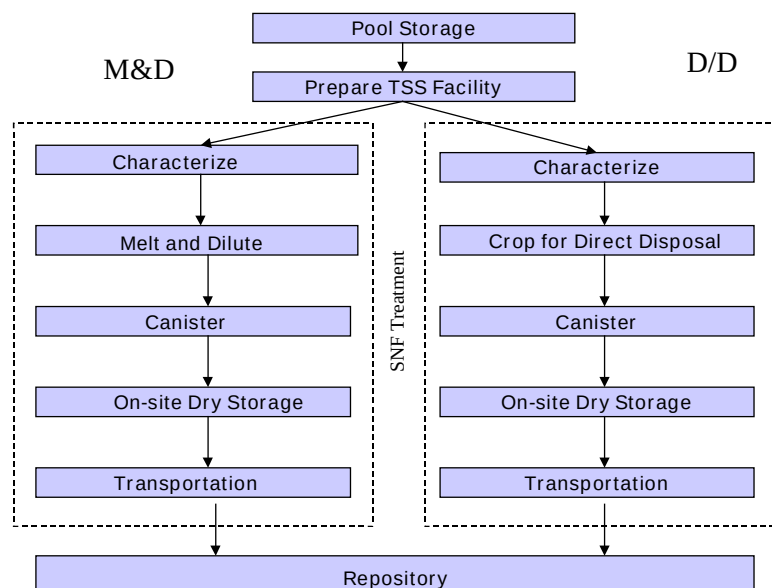


Figure 1. Process Flow Schematics for Direct Disposal and Melt and Dilute Treatment Alternatives

The Attributes

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).

Time (or schedule) is usually an attribute for this type of decision. Tables D-1 through D-4 of Krupa ² 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.

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 AI-SNF from SRS to a repository would be about three times the number of shipments of melt and dilute-treated AI-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 AI-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**.

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 SRS³. 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.

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

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

Attribute Weights

Attribute weights are specific to the decision at hand, and have no general or absolute significance. 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. The resulting attribute weights are summarized in Table I.

Table I Decision Attribute Weights

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

Structuring Utility Functions

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 extremes of each utility function – the values that corresponds 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 value 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 at hand. 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 was 100% likelihood and the best case, zero likelihood. For acceptability, the worst case was totally unacceptable, and the best was 100% acceptable.

Capital cost has a natural scale: dollars. The capital cost recovery figures shown in the tables in Appendix D of Krupa² 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. One member of the DOE-SR staff was then elicited for utilities = 0.5, 0.25, and 0.. The elicited points are shown in the appropriately labeled curve of Figure 3. The equation that provides the best fit for the *capital cost* utility is

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

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

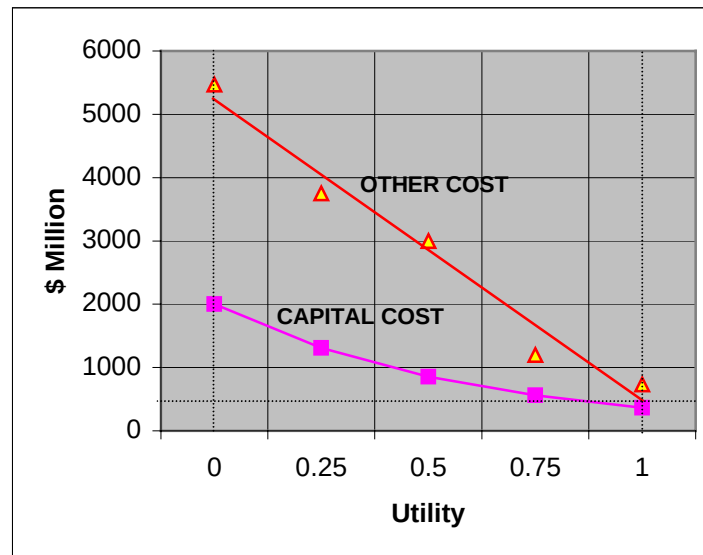


Figure 2 Utility functions for *capital cost* and *other cost*.¹

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

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

cost” corresponding to utilities of one (smallest other cost) and zero (largest other cost) were also the smallest and largest other non-*capital costs*, respectively, of the ten SNF treatment methods. 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. The equation for this straight line is

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

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

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 EIS³ 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 Kanipe⁴). The dose corresponding to a utility of 1 was the smallest MEI dose presented in reference 3 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:

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

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

The utility function is shown in Figure 3.

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 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:

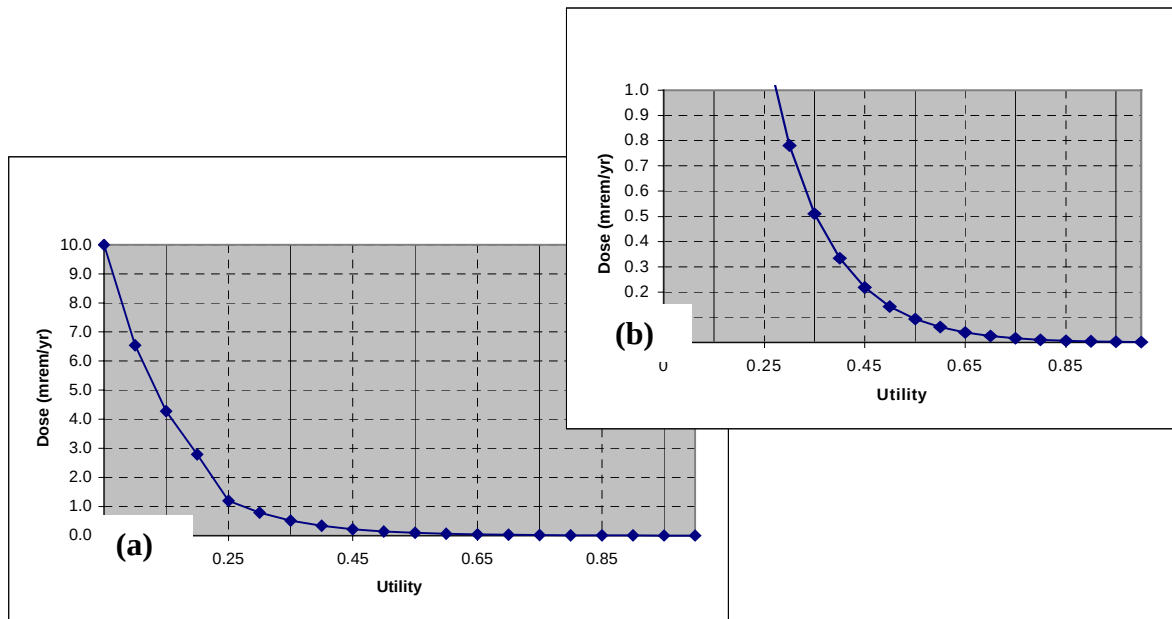


Figure 3 Utility function for *public radiological health*¹

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

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.

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

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

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 AI-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 II. The order of the questions was not important.

Table II 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 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

ESTIMATION OF ATTRIBUTE VALUES AND UTILITIES

The single-attribute utilities of each alternative treatment can be determined from the utility functions 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. However, all of the values except one include uncertainty, and are multi-valued distributed functions instead of point estimates. Uncertainties were modeled as normal distributions .

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 4. Note that the CDF for the utility of the melt and dilute alternative is to the right, indicating slightly higher utility.

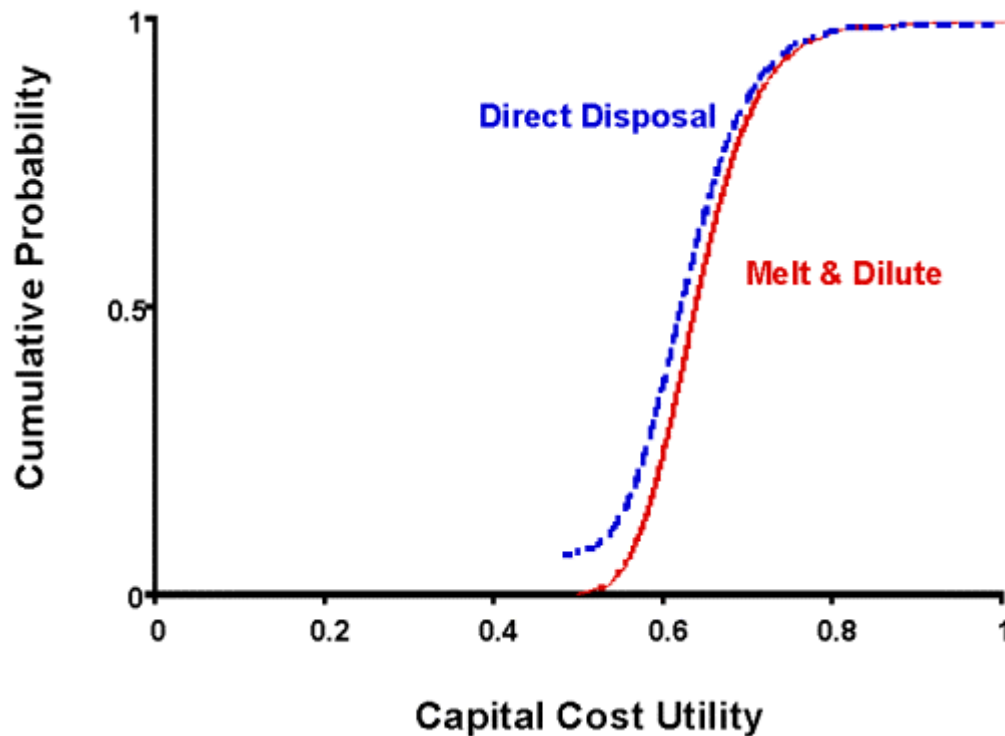


Figure 4 *Capital cost utility*

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. The uncertainty distributions for all of the individual cost constituents are correlated to maximize the uncertainty of the total *other costs* estimate. The CDF of the utility of *other costs*, shown in Figure 5, illustrates that the melt and dilute alternative has a significantly higher utility.

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

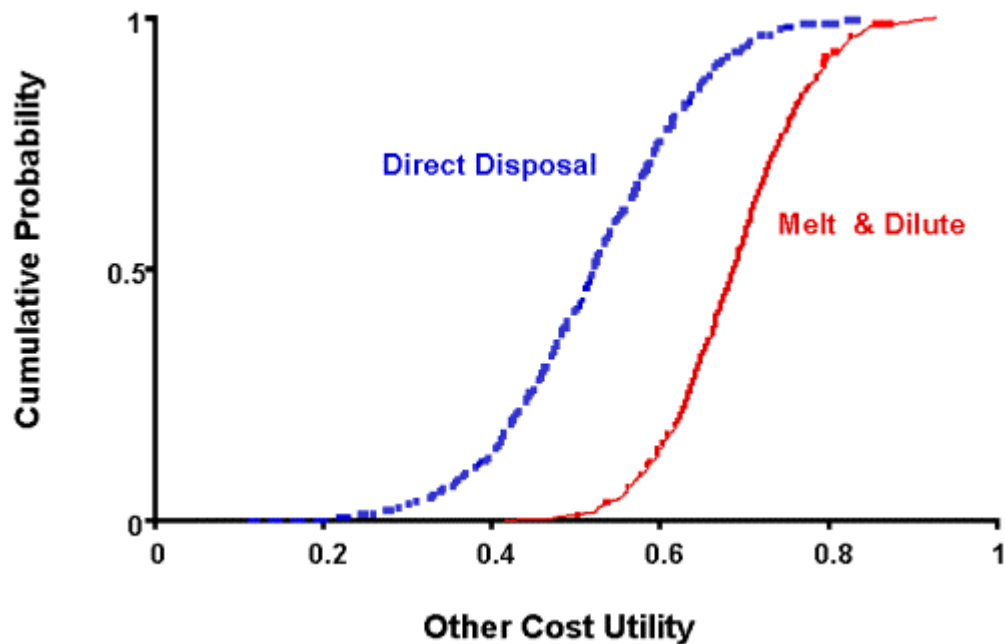


Figure 5 *Other Costs Utility*

to the MEI dose is based on an assumption that that all containers of AI-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). The MEI dose from the operation of the TSS facility was taken from USDOE (1997).

The *secondary waste* volume estimates for both alternatives are taken from USDOE (1997). 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 value for each alternative treatment, with respect to *secondary waste*, is expressed as the sum of the fraction of each type of 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

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

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

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 *acceptability* attribute estimates for both peer groups were elicited from the DOE-SR staff and were:

- 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.

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 III.

Table III 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 values in Table III 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

$$\text{Eq. 7} \quad \text{utility} = U(1-3) * (N(0.9, 0.2 * 0.9) + N(0.6, 0.2 * 0.6))$$

$$\text{Eq. 8} \quad \text{utility} = U(1-3) * (N(0.45, 0.2 * 0.45) + N(0.4, 0.2 * 0.4))$$

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 6. The utility scale for *acceptability* is the same as the *acceptability* scale itself.

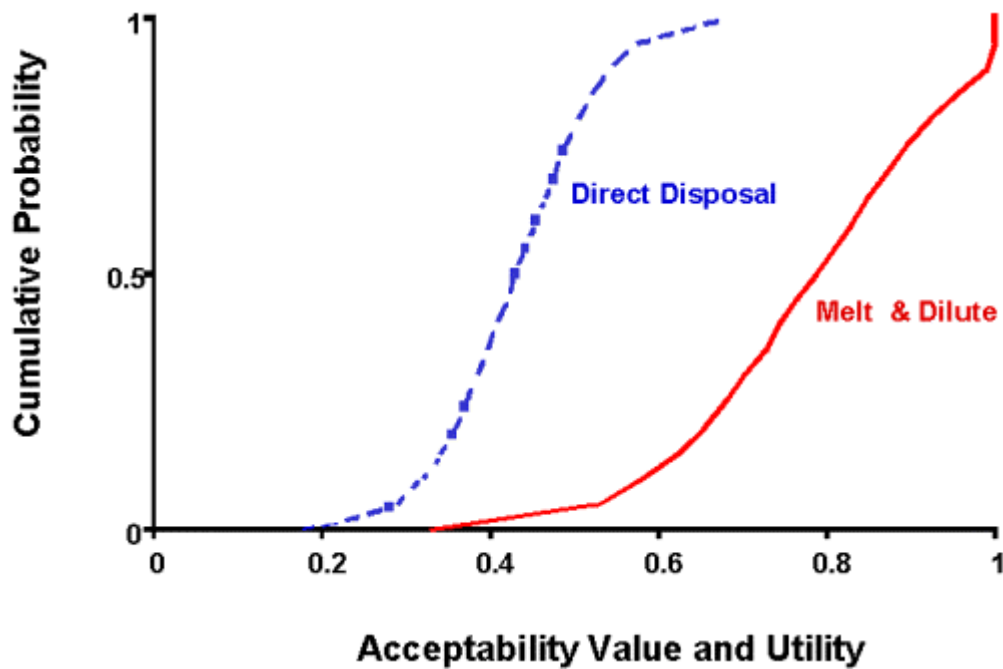


Figure 6 *Acceptability value and utility distribution*

Most of the AI-SNF to be treated at SRS is between approximately 20% and 93% enriched; the relatively small fraction of AI-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. The range of values was chosen so that the maximum value for the melt and dilute alternative is the same as the minimum

value for direct disposal. The attribute utilities for both alternatives were calculated with Eq. 5.

MULTI-ATTRIBUTE UTILITY RESULTS

The results of Figure 7 show that the multi-attribute utility for the melt and dilute alternative is larger than the multi-attribute utility for direct disposal.

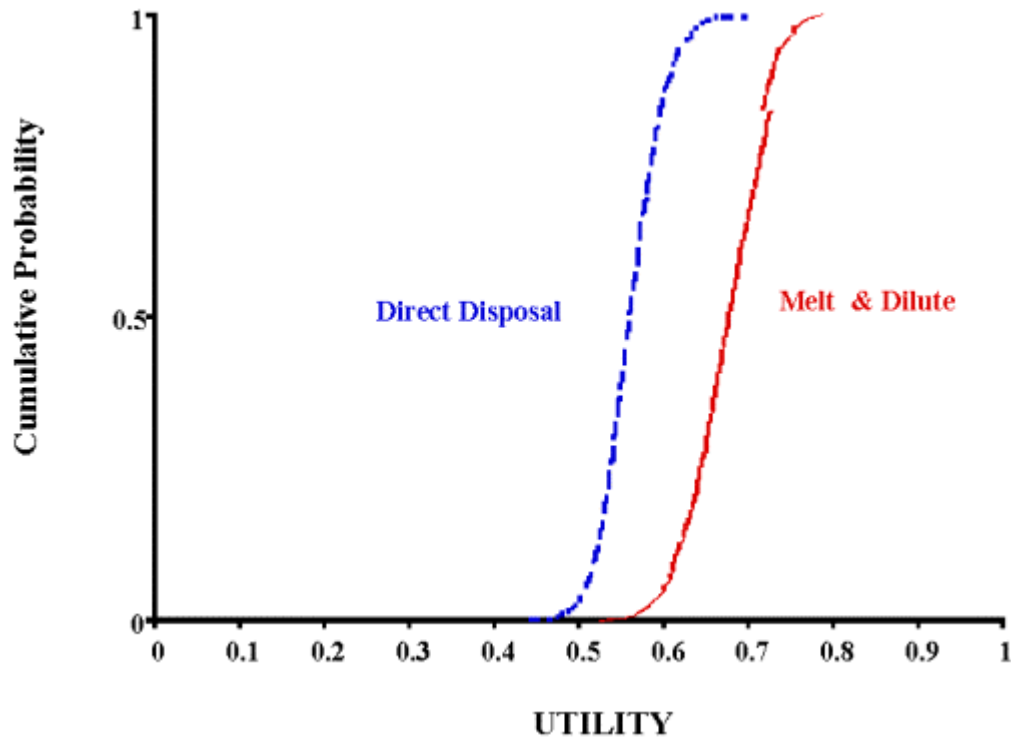


Figure 7. Multi-attribute utilities.

MULTI-ATTRIBUTE UTILITY SENSITIVITY

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.

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