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 a decision process 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 formal decision process used to evaluate these two remaining alternatives.

Introduction

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. Sandia National Laboratories (SNL) has conducted a decision analysis to assist DOE-SR in making such a determination.

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).

DISCLAIMER

Ten alternatives were initially considered for the pre-disposal treatment of Al-SNF. These alternatives were:

1. Direct disposal
2. Melt and dilute
3. Press and dilute
4. Electrometallurgy
5. Glass Material Oxidation Distribution System
6. Plasma arc melting
7. Dissolve and vitrify
8. Reprocessing/recovery /melt and dilute
9. Reprocessing/recovery /co-disposal
10. Reprocessing/recovery

From these 10 alternatives, the two alternatives that were selected for a more formal evaluation were direct disposal and melt and dilute;

- For the direct disposal option, fuel will be cropped, as necessary, to remove Al end fittings. The SNF would be characterized and canistered 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.

- 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.

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. 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. 19997b, 2997c), and Cook (1997). Full details of this analysis are provided in Davis (1998).

DOE-SR and Westinghouse Savannah River Company (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.

This paper will present the MUA methodology used for this decision analysis as follows:

- Development of process steps for the two alternatives
- Identification of attributes and weights
- Development of utility functions
- Analysis
- Results

Development of the Process Steps for the Two Alternatives

The process steps involved for each alternative were defined as shown in Figure 1. The steps were defined through iterative discussions with the DOE-SR decision-makers and with technical staff at WSRC.

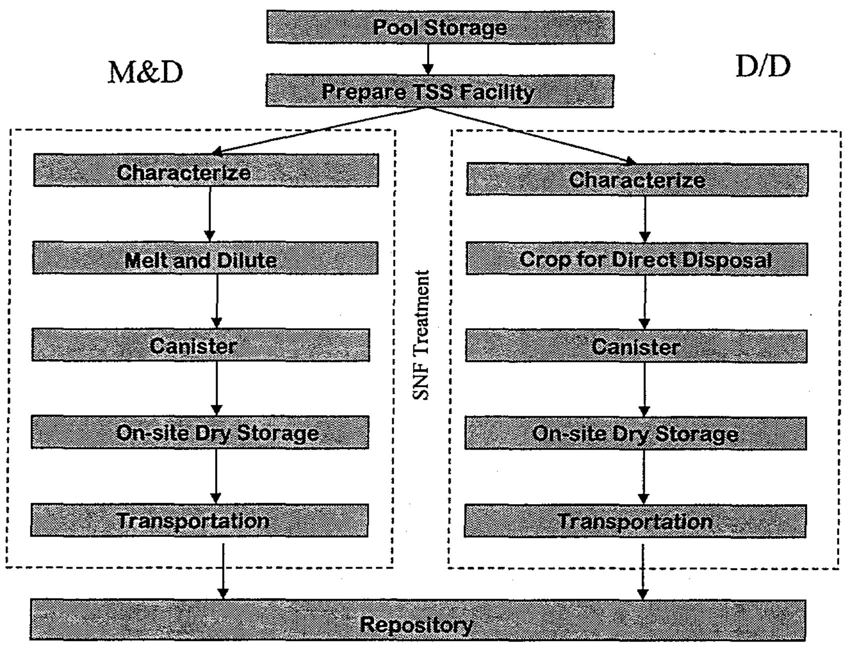

Figure 1. Process Steps for the Two Alternatives

The process steps identified for the two alternatives appear somewhat similar. However, the attribute data that is collected for each step varies markedly depending on the alternative path that is being evaluated. The treatment alternatives are distinguished by quantifiable attributes that will be discussed in the following section. Data for each attribute in each process step will be collected and then summed for each step in the process. This data collection includes uncertainties. Uncertain parameters that affect the decision are sampled using a Latin Hypercube Sampling technique in order to assure a statistically valid representation of the uncertainty that includes extreme values (tails) of the uncertainty distributions.

Identification of Attributes and Weights

Decisions like the one under consideration are made between *alternatives*. These alternatives have properties or *attributes* (e.g., cost, radiological risk, and schedule). For this analysis, the DOE-SR decision-makers identified the following six attributes as the key parameters that needed to be considered in the selection between the two alternatives. The six attributes are; 1) capital cost, 2) other costs (e.g. operational and maintenance), 3) public radiological health, 4) acceptability, 5) secondary waste, and 6) likelihood of proliferation.

After much discussion with the decision-makers, these six attributes were deemed to be key to properly discriminate the important aspects of the decision. In the analysis, each attribute has both a *value* and a *weight*. The *value* is the number or measurement of the attribute. The value can be measured by either or natural scale (e.g., dollars) or by a constructed scale to represent, for example, likelihood of proliferation. Data is then collected for each one of these attributes for each process steps. The data is collected in the form of a cumulative density function (CDF) in order to be able to account for uncertainty in the data. Figure 2 shows the CDF for the capital costs for each alternative.

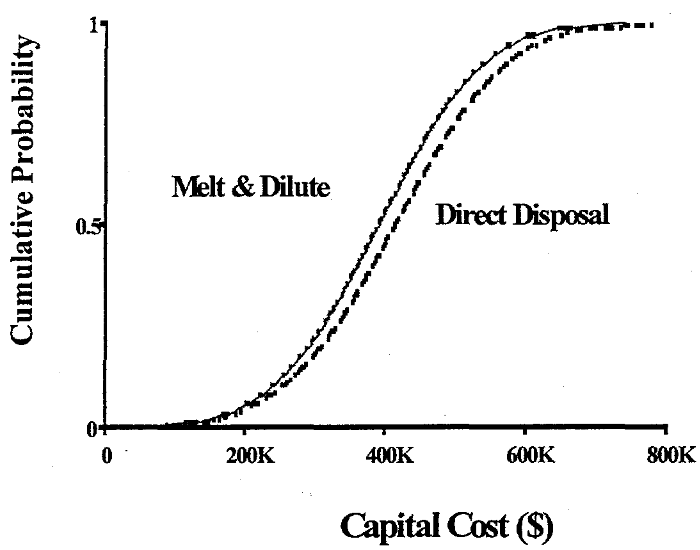

Figure 2. Capital Cost CDF

This CDF indicates that capital costs for the two alternatives will be fairly similar. In addition, the slope of the CDF indicates that there is a fair amount of uncertainty associated with the cost estimates. CDFs for the other five attributes were also developed.

The *weight* of an attribute is the value which that attribute has to the decision-maker relative to the other attributes; 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. The weights assigned to the six attributes are shown in Table 1 below.

Table 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**

Development of 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 translates each attribute value to a utility value. Each alternative will have unique attribute values and thus unique utility values. For this analysis, each attribute value was normalized to a utility value between 0 and 1.

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.

The utility functions for the six attributes are shown below in Figures 3 – 7.

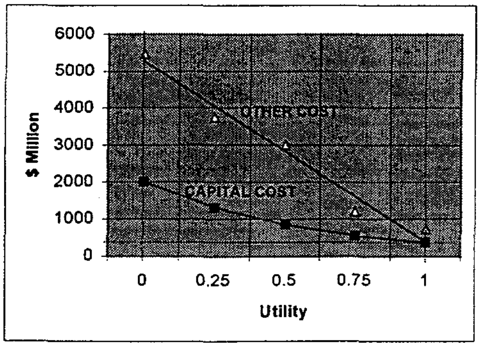

Figure 3. Capital & Other Cost Utility Function

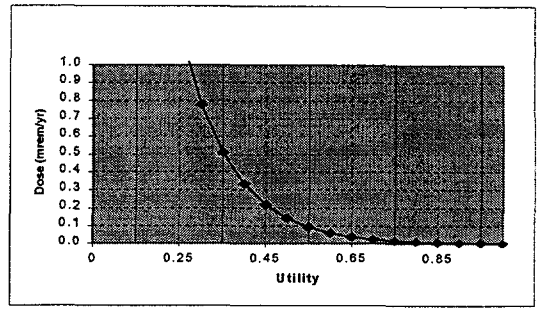

Figure 4. Public Radiological Health Utility Function

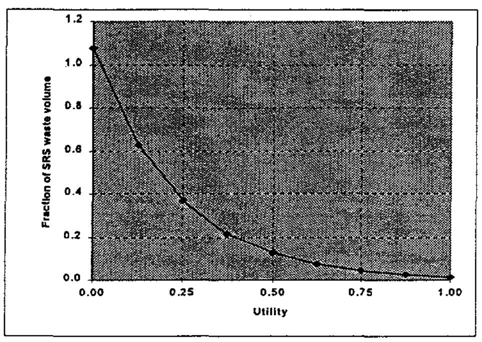

Figure 5. Secondary Waste Utility Function

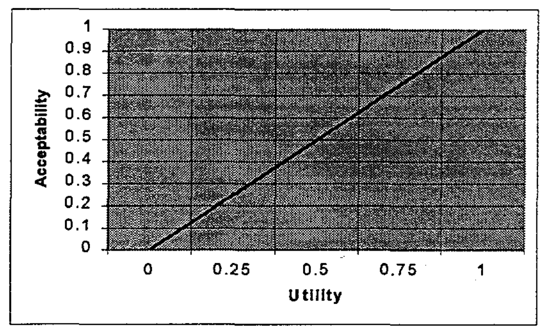

Figure 6. Acceptability Utility Function

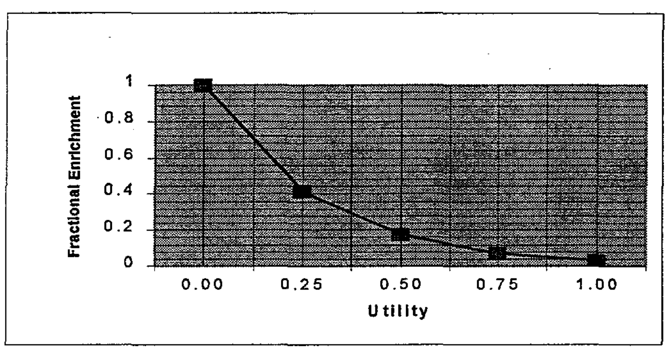

Figure 7. Likelihood of Proliferation Utility Function

Analysis

For each event defined in Figure 1, attribute data is collected with uncertainties included. This results in a cumulative distribution function (CDF) for each event for each attribute. TheCDFs in each event are then added to each other for each alternative. This results in six CDFs (i.e., one CDF for each attribute) for each alternative.

The CDFs are then mapped into the utility space using the utility functions shown above. For example, the Capital Cost CDF (Figure 2) is mapped into the Capital Cost Utility (Figure 3). Figure 8 illustrates the Capital Cost Utility for both the direct disposal and the melt and dilute treatment alternatives. This figure represents the capital cost (in terms of utility to the decision maker) with uncertainty for each treatment process as defined in the process steps illustrated in Figure 1.

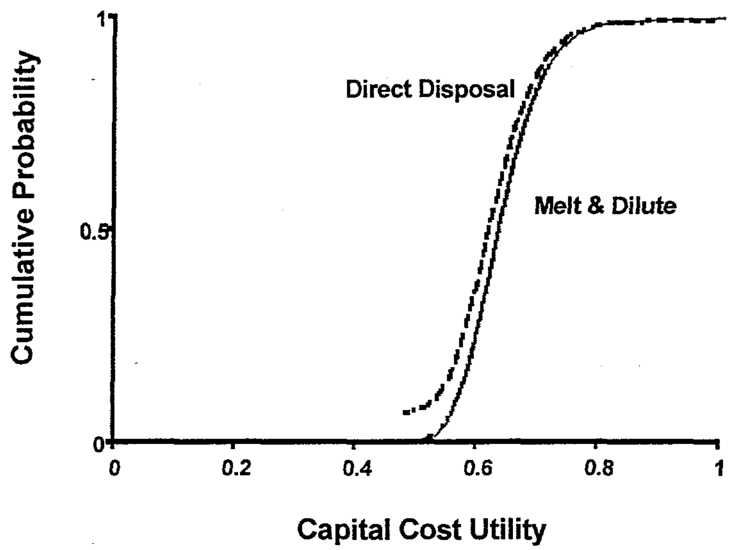

Figure 8. Capital Cost Utility

Consistent with Figure 2, the capital costs for the two alternatives are similar. Figure 8 is a representation of a single attribute utility. The other five utilities were generated in the same manner. By adding the six utilities together, a single decision metric is obtained that is termed the multi-attribute utility.

The software used to construct the model shown in Figure 1 is called Analytica. Analytica is a commercial product that is designed both as a visualization tool and a mathematical tool. Analytica is adept at performing all of the necessary mathematical calculations as well as providing the capability to maintain the proper quality assurance procedures to qualify the input data.

Results

Figure 8 represents the single attribute utility. All six attribute utilities are summed using a linear combination. The attribute weights are the coefficients of the utilities. The sum of the products of the weights and the single attribute utilities is a multi-attribute utility. This utility is generated using the following equation:

$$MUA = (0.23*U_{\text{Capital Cost}}) + (0.13*U_{\text{Other Cost}}) + (0.21*U_{\text{Public Dose}}) + (0.07*U_{\text{Secondary Waste}}) + (.28*U_{\text{Acceptability}}) + (0.08*U_{\text{Proliferation}})$$

The result of applying this equation is shown in Figure 9 for both the direct disposal and the melt and dilute treatment alternatives.

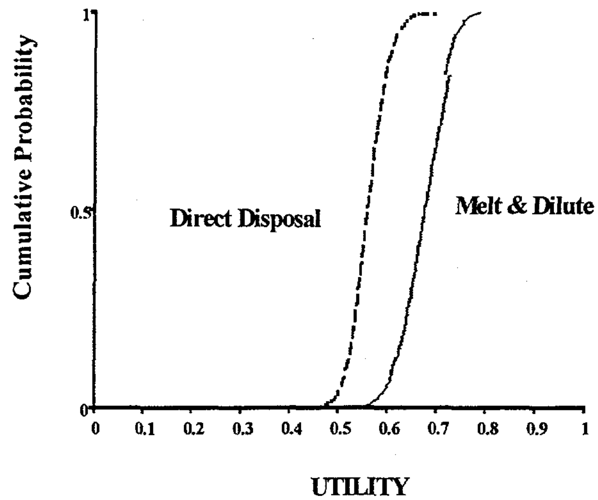

Figure 9. Multi-Attribute Utilities

Figure 9 shows a clear distinction of utilities between the two alternatives. Throughout the range of uncertainties, the melt and dilute option retains a higher utility that the directdisposal option. This can be represented by taking the ratio of the melt and dilute utility to the direct disposal utility as shown in Figure 10.

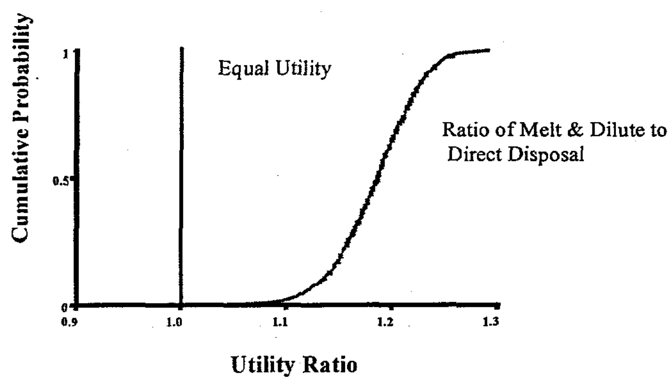

Figure 10. Utility Ratio

Conclusions

This MUA indicates that the melt and dilute option is the better treatment option for the Savannah River AL-SNF based on the defined attributes and weights that were assigned by the decision-makers. In addition, the ratio indicating that the melt and dilute has a higher utility over the range of uncertainties of the data provides added assurance that the melt and dilute alternative is most likely the better alternative.

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