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Multiattribute Analysis of Alternatives for Hanford Tanks Remediation System

by

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MULTIATTRIBUTE ANALYSIS OF ALTERNATIVES FOR
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Abstract

In the present work we created and used an integrated multiattribute decision analysis model of the Hanford Tank Waste Remediation System (TWRS). The model, named MAATWRS, allows decision makers to: evaluate existent TWRS strategies, analyze tradeoffs among multiple attributes, test strategies' robustness using sensitivity analysis methods and search for better alternatives for retrieval, pretreatment and immobilization of Hanford tank nuclear waste. The model would also allow a decision maker to simulate the behavior of other interested parties and identify the optimal decisions from their point of view.

The decision model can be broken conceptually into two parts. The first part, calculates for each of the available alternatives a set of consequences. The second part evaluates the desirability of various sets of consequences using a multiattribute utility function. The model incorporates modules for: cost, socioeconomic impact, land use, health effects on public and workers, extra-regional impact, single and multiattribute utility functions. MAATWRS is built using a combination of Excel, Visual Basic, @Risk and DPL.

The model is applied to evaluate three large scale retrieval strategies "Simple Separations", "No Separations" and "Extensive Separations". A mean-variance method for comparing alternatives is introduced. Results of the analysis of other scenarios are also presented. Particularly interesting are the alternatives in the "In Place" group. According to those scenarios most of the waste would remain on site. Those alternatives, although in contradiction with current inter-agency agreements and some regulations are less expensive and have a lower variance in cost.

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1. Introduction

The Department of Energy's Hanford site was the original plutonium-production complex and a source of plutonium used in the bomb detonated over Nagasaki. Today Hanford is an agglomeration of decrepit and contaminated facilities. High-activity radioactive waste has been stored in large underground storage tanks since 1944. In 1989 DOE began deactivating and cleaning up Hanford. DOE spends more than $1 billion at Hanford every year just for the mitigation of safety issues, maintenance and other programs.

1.1 Nuclear Waste Cleanup

1.1.1 A national problem

The Hanford cleanup project is just one piece of a DOE program to close down part of its nuclear weapons program[1] - about a fifth in size[2].

Starting with the Manhattan Project, United States assembled a huge industry for producing plutonium for nuclear weapons. Uranium processed at facilities in the states of Idaho, Kentucky, Ohio and Tennessee was irradiated and chemically treated to separate plutonium both at Hanford, WA and at Aiken, SC. plutonium was machined into weapons parts at Rocky Flats Colorado. Bombs were finally assembled at a plant called Pantex in Texas. Until the seventies plutonium production was emphasized above everything else and agencies that oversaw weapons complexes did not adopt the increasingly stricter rules to mitigate the environmental impact of their activity.

The attitude towards environmental impact started to change in the mid 1980s when DOE created the Office of Environmental Management. This year, this office alone will receive 37% of total DOE budget of $16.3 billion [Zorpette, 96].

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[1] The DOE complex currently has 332 underground storage tanks that have been used to process and store radioactive waste generated from production of weapons material. Together they contain close to 300 million gallons of waste material. Only 100 million gallons of radioactive waste has been treated and disposed of in final form [Zorpette, 96].

[2] This year $ 1.3 billion or 21% (the largest share) of the Environmental Budget will go to Hanford. DOE has spent $7.5 billion cleaning up Hanford over the past seven years [Zorpette, 96].

1.1.2 Hanford Remediation

The DOE Hanford Site in Washington State has the most diverse and largest volume of highly radioactive waste of any site in the United States. The current primary mission of the Hanford site is waste clean-up and site remediation. A major aspect of the remediation process is long term protection of the environment from hazardous wastes stored at Hanford.

There are several major problems associated with remediation of the Hanford site:

- Contaminated soil and water. Since 1944 it is believed that 1.3 billion cubic meters of liquid waste and contaminated effluents were pumped into the soil. In some places the damage is irreversible[3]. Remediation of soil and water is not considered however as urgent as disposition of the high level waste tanks contents.
- Safety problems associated with high level waste tanks have been the most difficult and costly to deal with so far. Approximately 227,000 cubic meters of caustic liquids, slurries, "salt cakes", and sludge are stored in 177 tanks. Some of the tanks have leaked while others build up flammable gases, produce excessive amounts of heat and/or contain potentially explosive chemicals.
- 2100 tons of irradiated fuel are stored in water filled basins that are 40 years old. Much of the fuel is corroded. A strong earthquake might release a huge amount of contaminated water from basins into the soil and finally into Columbia river.
- Contaminated buildings. For example: the large and heavily contaminated reprocessing plants called canyons, consume around $40 million per year each, just for maintenance and surveillance.

1.2 Background on Hanford Tank Waste Remediation

Tank waste remediation is probably one of the most important problem to be solved among other Hanford issues. Since 1944 approximately 227,000 m^3 (60 Mgal) of waste have been accumulated in 177 tanks. The wastes are stored in 28 double shell tanks (DST)[4] and 149 single shell tanks

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[3] It is extremely difficult to separate tritium from water. In order to obey to the Tri-Party Agreement stipulations DOE spends around $23 million a year on groundwater treatment. Unfortunately that could result in only a very limited improvement in existing plumes of contamination [Zorpette, 96].

[4] The double shell tanks consist of a carbon steel inner tank inside a steel lined concrete tank. Each tank has a nominal capacity of 1 Mgal. The use of the first DST began in 1970.

(SST)[5]. These wastes consist of many chemicals[6] dominated by various nitrate and nitrite salts. The wastes are in several physical forms: sludge, "salt cakes", slurries and liquids. The radionuclides are transuranic elements and fission products ^{90}Sr and ^{137}Cs. The single shell tank contents are highly diluted when compared with radioactive content of spent fuel from power plants. In some of the double shell tanks tank void space radiation fields can reach 10,000 rad/h [DOE, 94]. Around sixty-six of the older SST are suspected to have leaked a total of approximately 1 Mgal of waste into the ground. Interstitial liquids have been removed from leaky tanks. No waste has been added to SST tanks since 1980. None of the double shell tanks has leaked.

The Tank Waste Remediation System (TWRS) program is large and complex and has high priority within the DOE. Here are some of the elements that contribute to the complexity of the problem:

- Safety issues
- Diversity of waste types; uncertainty regarding tank content
- Multiple stakeholders
- Dynamic regulatory environment; policies change while being implemented.

These issues will be briefly discussed next.

1.2.1 Safety Issues

1.2.1.1 Safety concerns

Safe storage of the wastes is a factor influencing the pace of recovery and ultimate disposition of tank contents. A number of safety issues have been raised about tank wastes. Some of them are presented below:

- Flammable gas generation, accumulation and release. 23 tanks generate hydrogen and other flammable gases and release them episodically. A potential exists for ignition of hydrogen-air, hydrogen-nitrous oxide and air-organic mixtures.
- Potential explosive mixture of ferrocyanide in tanks. Eighteen tanks contain insoluble ferrocyanide salts in a sodium nitrate / sodium nitrite matrix. Ignition of organic-nitrate or

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[5] The single shell tanks are made of reinforced concrete with a steel liner. Their capacities range from 208 m^3 (55,000 gal) to 3800 m^3 (1 Mgal).

ferrocyanide-nitrate mixtures of the right ratios might be initiated by radioactive or chemical heating. Recent studies have tended to cast a doubt as to whether the tank ferrocyanide has concentrated and thus ignition of the ferrocyanide-nitrate mixtures is unlikely [Grigsby, 96]

- Potential organic-nitrate reactions in tanks. Eight tanks[7] contain organic chemicals at potentially dangerous concentrations. Secondary ignition of organic-air or organic-nitrate mixtures initiated by burning of flammable gases is possible.
- Poor condition of tank farm equipment and instrumentation; corrosion, as described in paragraph 1.2.1.2

Immobilizing waste (should and acceptable treatment be available today) might be the best way to resolve the safety issues.

1.2.1.2 Past incidents at Hanford

1.2.1.2.1 Steam explosion in 1965

A powerful steam release (lasting about 30 minutes) occurred at the single shell tank 105A in 1965. There are no available records of the amount of radioactivity, if any, released to the atmosphere. Investigations showed that the steel liner of the tank was strongly deformed (the bulge on the bottom of the liner had a height of about 8.5 feet). A possible explanation for the event is the following: water may have leaked through the thermally stressed liner into the narrow space between the concrete shell and the steel liner; the material at the bottom of the tank became hot from radioactive decay; as a consequence, the interstitial water was transformed into high pressure steam which bulged the liner and finally produced a rupture.

1.2.1.2.2 Tank temperatures above limits

Tank 105A was not the only one where temperatures higher than normal have been encountered. The safe temperature limits were not defined with sufficient precision until recently. Also the temperature modeling capabilities at single shell tanks are limited. For example natural convection of water in the tanks is usually ignored [Van Der Helm, 96]. Temperature is measured using "thermocouple trees", many of which had not functioned properly until they were replaced within the last few years. It is questionable whether the results of the measurements of a single tree

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[6] The folowing components are present: nitrate and nitrite salts (about a half of the total waste), ferrocyanides, phosphate precitpitates and hydrated netal oxides. Most of the waste is alkaline.

[7] Three hydrogen and ferrocyanide tanks also appear on the "organic" list.

present in each tank, even if correct, are representative for the temperature distribution inside the tanks[8].

1.2.1.2.3 Tank Corrosion and Leakage

The estimated lifetime for the double shell tanks (at .001 inches/year uniform corrosion) is considered to be 50 years. The conditions in the tanks may be more favorable to corrosion than laboratory test conditions. Many single shell tanks are known to have leaked. For example in 1973 a single shell tank leaked about 115,000 gallons of liquid into the ground. The 1973 leakage is the largest in a series of 65 leaks (750,000 gallons in total) due to single shell tanks.

1.2.1.3 Nuclear Waste Accidents in USSR

The weapons material production plant at Kyshtym in the Ural mountains was roughly the USSR equivalent of the Hanford Nuclear Reservation in the US. The explosion of a high level nuclear waste dump at Kyshtym released about 20 million curies of radioactivity into the atmosphere[9]. The fallout contaminated, primarily with ^{90}Sr, a total area of 23,000 square kilometers. About 10,000 inhabitants of the region had to be evacuated ([Wodrich, 1991], [Medvedev, 79]). The explosion, with an estimated force of 5-10 tones TNT was due to the reaction of dried sodium nitrate and sodium acetate in an underground concrete vault[10].

Process chemistry in the early Soviet technology differs from that used in USA. Hanford tanks contain however large amounts of $NaNo_3$ and oxidizable organic materials; therefore accidents favored by high temperatures and the absence of sufficient water accidents similar to the Kyshtym accident should be considered when studying Hanford tanks safety issues.

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[8] For example, the results of these measurement do not exclude the possibility of existence of so called "hot spots" which may be initiators for explosion.

[9] For comparison: fifty million curies were released at Chernobyl.

[10] Kyshtym turned out to be only the second in a series of three major radiological disasters in the Cheliabinsk area (which have so far been acknowledged by Russian authorities). The first of these disasters is the result of dumping of high level waste into the nearby Techa river between 1949 and 1951. Residents in towns downstream were exposed to high levels of radioactivity. The third disaster occurred when lake Karachy, which has had been used as a dump for high level radioactive waste dried up partially. The wind then blew contaminated dust from the exposed lake bed.

1.2.2 Uncertainty regarding tank contents and applicable technology

Very few things are certain about the Hanford tanks. Cleanup plans and decisions usually do not last more than a few years. A possible case, although a highly improbable one, is that the project will be abandoned[11]. Activities take place on a time span of tens of years, some new (untested yet) technologies may be used and the attitude of various stakeholders is highly unpredictable. Some major sources of uncertainty are the following:

- The composition of waste inside tanks is not known precisely. Nuclear waste from several reprocessing technologies were accumulated throughout the years. Waste was moved from a tank to another when some of the vessels leaked. Various processes were used to extract from the tanks troublesome isotopes[12]. Two independent reviews of historical records have been conducted to estimate the content of single shell and double shell tanks[13]. The tank waste characterization program, advances slowly due to the waste complexity, radioactivity and toxicity.
- Cost and schedule estimates have been notoriously inexact.
- Technical feasibility of some of the proposed alternatives rely on "first of a kind engineering" solutions or on uncertain extrapolations of current technologies. DOE faces the risk that some of the proposed technological processes will not work in practice.

1.2.3 Multiple Stakeholders

There are many parties that have an interest in TWRS decisions. Those groups might have different sets of values or contradictory interests. A list of major stakeholder groups is given below:

- The States of Washington and Oregon
- Local communities around Hanford site
- US Environmental Protection Agency
- Westinghouse Hanford Company and Pacific Northwest Laboratory (site contractors to DOE)

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[11] The Supercollider project (the construction of a large particle accelerator in Texas) was shut down after having consumed more than $3 billion [NYT, 93]. The Tri-Part Agreement, wich has the power of law, makes it very unlikely that Congres will stop cleanup at Hanford site, at least for a couple of decades.

[12] For example up to 140 metric tons of ferrocyanide were added to several single shell tanks in 1950 in order to scavenge radioactive cesium from the supernatant liquid stored in tanks. As mentioned in 1.2.1.1 the so called "ferrocyanide tanks" have been a safety concern.

[13] These inventory databases are TWRS Process Flowsheet [Orme, 95] and Los Alamos National Laboratory Inventory [Agnew, 96].

- US Department of Energy.

1.2.4 Lack of a long-term vision

Hanford cleanup started about 6 years ago but little progress has been made up to date. It seems that DOE has not sustained a long-term vision seriously enough to make significant progress. Proposed remediation programs usually do not last more than 2-3 years since priorities shift continuously. On the other hand, such long term vision is very hard to achieve given the complexity of the project.

1.2.5 Regulatory Issues

1.2.5.1 Tri-Party Agreement (TPA)

In 1989 Department of Energy, Environmental Protection Agency and the state of Washington signed the Hanford Federal Facility Agreement and Consent Order also known as the Tri-Party Agreement (TPA). This legally enforceable document governs hazardous and radioactive waste cleanup at the Hanford site over a 30 year period. In January 1994, the Tri-Party Agreement was modified to incorporate changes in the TWRS program. According to TPA the separations process for Hanford tank wastes would produce two types of waste: high level waste (HLW) and low level waste (LLW) streams[14]. The high level waste stream will require disposal of vitrified waste in a geologic repository while the low level waste stream, also in a vitrified form may be subject to less stringent requirements.

Although it allowed DOE, EPA and the state of Washington to start collaborating despite a degree of distrust, the TPA contains serious contradictions and flaws. For example:

- TPA subjects Hanford to the jurisdiction of both Resource Conservation and Recovery Act (RECRA) and Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). Dealing with the final waste forms without final Nuclear Regulatory Commission rules on what might be acceptable at the geologic repository (or even at a LLW waste repository) may prove difficult for DOE.
- Some of the cleanup projects that TPA mandates are not cost effective. For example DOE was forced to spend $5 million and is expected to spend more in order to prevent an annual amount

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[14] The current assumption is that no more than 10% of the total radioactivity content will be in the low level stream.

of 0.25 Ci of Sr from reaching the Columbia river which actually caries 6,000 Ci each year from natural sources upstream.

- Congress might consider that the vitrification of *entire* amount of waste, as TPA requires, is much too expensive.
- TPA casts into law Washington State's wish to have the HLW and the TRU waste disposed of in permanent repositories in other states. Opposition from various stakeholders has so far blocked the opening of a TRU repository in New Mexico and may delay for decades (if not for ever) the completion of Yucca mountain repository in Nevada.

1.2.5.2 Regulatory relief

Although DOE is currently legally and politically committed to the Tri-Party Agreement and other rules and orders it may worthwhile to consider options that do not necessarily comply with all regulations and covenants. Sooner or later nuclear waste clean-up will compete for financial resources with other important national programs like plutonium disposition, social programs, etc. and the Congress might be put in the situation to make certain tradeoffs. A good example in this sense is the idea to contain in place part of the tank waste. The contents of about half of the tanks is low enough in radioactivity and organics that it may be left in place. This would achieve a serious reduction ($10-15 billion) in TWRS program cost while also posing fewer health costs to Hanford workers. If the perceived advantages of this alternative will stand to a closer scrutiny one might consider the possibility of relaxing certain regulatory requirements and maybe renegotiating TPA. Another alternative is to vitrify the waste for storage on site. Again this will save $10-15 billion [Curtis, 95].

1.3 Tank Waste Remediation System (TWRS)

The Tank Waste Remediation System Program (TWRS) has been established in 1991 by DOE to manage and immobilize nuclear and other hazardous wastes currently located in tanks, in anticipation of permanent disposal of the high-level radioactive waste fraction in a geologic repository. The milestones for this program are established by the Tri-Parti Agreement in 1989 and its modification in 1994.

TWRS's declared mission is to "*store, treat, and immobilize highly radioactive Hanford waste in an environmentally sound, safe and cost effective manner*". Implementing this program will require resolving several waste tank safety issues to maintain safe storage, and then retrieving, treating, and immobilizing the waste for disposal. This is a complex, massive, costly program that will take decades to carry out. Acquiring the financial commitment to conduct this program will require a national consensus; therefore it is very important to use optimized solutions in planning and conducting the TWRS program.

1.4 Previous Studies

This section contains a short description of previous work that addressed TWRS issues in a comprehensive manner or is otherwise relevant to the present thesis. It is not by any means an exhaustive review, but highlights work that was similar in scope to the present thesis.

Tank Waste Technical Options Report [Boomer, 93] is a massive document that analyzes technology options for disposal of tank wastes at the Hanford site. It provides detailed descriptions of the elements of the tanks waste disposal system (waste characterization, safety issues resolution, waste retrieval, separation into LLW and HLW stream, treatment of HLW and LLW). It also examines closure options for tanks. The document does not quantify the uncertainties and does not provide a methodology for evaluation of various alternatives based on the combination of attributes in a single measure.

The *Preliminary Draft Environmental Impact Statement* (DEIS) [DOE, 95] analyzes potential environmental consequences related to the Hanford Site Tank Waste Remediation System alternatives for retrieval, pretreatment, treatment, immobilization and disposal of wastes[15] stored in the 177 underground storage tanks and other 40 miscellaneous tanks. DEIS also analyzes the management of the strontium and cesium capsules stored at the Hanford site. The document evaluates in great detail seven major alternatives and sub-alternatives for the tank waste and four alternatives for the Cs/Sr capsules. Those alternatives and sub-alternatives are: no action, minimal retrieval (In Situ Vitrification) with sub-alternative "Fill and Cap", selective retrieval and extensive retrieval (Ex Situ Vitrification) with sub-alternatives "No separations vitrification or calcination" and "Extensive separations".

The *Tank Waste Disposal Program Redefinition* [Grygiel, 91] presents the results of a systematic evaluation of technical issues and regulatory requirements associated with Hanford waste program

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[15] Classified as radioactive, hazardous and mixed wastes

as those issues were perceived in 1991. The document proposes a time-phased implementation of waste pretreatment. In the time-phased approach existent mature technologies should be used in the near term for certain types of waste; an intermediate phase can be started after demonstration of more aggressive in-tank pretreatment processes; in the long term pretreatment would be accomplished using advanced separation technologies. The document identifies the values and concerns of various stakeholders involved in the choice of waste disposal alternatives and presents an elaborate set of objectives and attributes. The method used is a simplified form of multiattribute utility analysis where scores are associated with various attributes and then an MAU is derived as a weighted average of those scores (additive approach). It is not however a probabilistic analysis. The scores associated with various attributes can not be interpreted as utilities since they fail to take into account stakeholder's attitude towards risk. The range of alternatives considered is narrower compared to Tank Waste Technical Options Report [Boomer, 93].

Decision Analysis Model for Assessment of Tank Waste Remediation System Waste Treatment Strategies [McConville, 95] describes the capabilities of a TWRS decision analysis model known as the Insight model. The first version of this model was created in early 1992 [Johnson, 93]. Insight model relies on data available from several sources including the Tank Waste Technical Options Report [Boomer, 93]. It calculates TWRS performance measures (cost, duration, volumes of waste, radionuclide inventory) that may be used to compare various Hanford tank waste treatment strategies. If used in combination with a software called Supertree[16] the model can perform probabilistic evaluations as well. It does not combine the performance measures in any way and does not use any weights or other method of scoring of alternatives. The model does not contain health-safety data and at least for this stage it cannot analyze several valid alternatives like no-action and minimal retrieval. Some of the results of this model were benchmarked against more detailed analyses like the *TWRS Process Flowsheet* [Orme, 95]. The model developed for the present thesis incorporates Insight as a module.

Transporting Spent Nuclear Fuel: A framework for decision Making, a MIT PhD thesis by Katherine Yuracko [Yuracko, 90] explores whether a consensual decision-making approach could be capable of resolving controversies involving the transportation of spent nuclear fuel. Interviews with various stakeholder groups were conducted in order to identify objectives and specific issues

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[16] Supertree is a decision analysis software owned by Strategic Decisons Group

in dispute. The objectives of each of the parties were combined in a composite objectives hierarchy. Multiattribute value functions were assessed for nine stakeholder groups and a computer model was developed to estimates of safety and economic impacts of the alternatives. Results suggest that it may be possible to make agreements that are to the advantage of all parties. While this document is not used directly in the present thesis, it is however an illustration of how multiattribute analysis can be used to resolve policy issues involving multiple interested parties.

Policy Analysis of Hanford Tank Farm Operations With System Dynamics Approach, a MIT PhD thesis by Sangman Kwack [Kwack, 95] presents a system dynamics model that can analyze the effect of various factors on policy options. Results suggest that external factors represent a major source of the current system inefficiency. Other sources of inefficiency identified are budget constraints and delays in material procurement.

1.5 Decision Maker's Challenge

Designers of waste management strategies must determine the best course of action regarding a huge number of interdependent activities. These activities have to be performed taking into account many constraints: financial, safety, time, personnel, hardware, public opinion, technical, etc. To make things even worse the working environment is dynamic (i.e. new problems might be diagnosed) and large uncertainties are associated with parameters involved. Therefore, the need arises for development of decision methods based on limited knowledge about the system and the surrounding world, which can produce optimal or at least satisfactory solutions.

It is essential that the TWRS plans be evolutionary in approach with ability to change when waste properties are better understood, essential decisions are better negotiated, and lessons learned are available from initial efforts. In consequence the need arises for planing tools which can help explore all the available options.

Anyone trying to create a model that provides a coherent picture of TWRS issues would face several major challenges:

- Solving a real world problem. Theoretical Operations Research offers a wide panoply of tools and methods that work only if certain conditions are satisfied. This is however a complex, real world problem that would not necessarily satisfy all those conditions. The solution to the problem is not purely technical. There will be difficult political, social and technical tradeoffs to be made as Hanford cleanup progresses. Furthermore a large amount of time will be spent in not so "glorious" jobs like collecting and sorting data, separating important issues from less important ones, before reaching the stage of performing sophisticated mathematical analyses.

- Creating a simplified yet comprehensive picture of the system. The modeler would most certainly have to face the tree versus forest dilemma. How deep can he go into detail without losing the general picture from sight? If the model is too detailed one can loose the perspective on the whole system and run into computational problems as well. One would also have to run to Monte Carlo simulations on too many variables (some of them insignificant). On the other hand, if the model is too simplistic it is worthless. The challenge is to keep the right balance between these two tendencies.
- Optimizing with respect to several attributes (cost, risk, duration). In a sense this is similar to finding a reasonable method to add apples and oranges. Decision Theory offers several solutions to this type of problem. Use of multiattribute utility functions is a possible approach. Unfortunately this method assumes that certain conditions like the utility independence of various attributes holds. This may or may not be true in practice.
- Unavailability of reliable data. Data may be hard to find or simply does not exist. "Engineering judgment" then comes into play.

1.5.1 What an ideal decision tool should look like?

An ideal planning tool would have the following features:

- given the fact that the TWRS environment is very changeable this tool should help examine how "robust" the plans are with respect to modifications in the elements of this environment
- it will be modular; local models generated for a restrained domain of interest have to be easily inter-connectable with other local models created using the same methodology
- will contain a formal structure of incorporating probabilistic data
- it will allow optimization with respect to different utility functions based on data we already have
- will create a concise yet correct picture of the system
- it will be able to easily incorporate new information, refined data
- will help the decision makers play scenario games and explore the space of future options
- will be usable as a way of codifying debate with the public and a base for discussions with the regulators.

1.6 Characteristics of the present model

This work presents an integrated multiattribute decision analysis model for the Hanford Tank Waste Remediation System intended to help decision makers evaluate several clean-up alternatives. The model is named MAATWRS (from **M**ultiattribute **A**nalysis of **T**ank **W**aste **R**emediation System). By contrast with [Grygiel, 91] that uses a deterministic approach, this model is probabilistic. Compared with [Grygiel, 91] MAATWRS uses a narrower set of attributes. This is partially due to the fact that interviewing stakeholders in order to identify issues of interest was beyond the purpose of the present work. By contrast with Insight ([Johnson, 93] and [McConville,95]) this model introduces the multiattribute utility as a measure of the desirability of an alternative and considers additional issues like health effects on workers and public and socioeconomic impact of various alternatives. Insight is incorporated as a module in MAATWRS. In this work we also introduced a mean variance method of comparing alternatives that relies on the capabilities of MAATWRS.

MAATWRS is not yet the ideal tool presented in paragraph 1.5.1. It would take much more work to create such a tool. The characteristics of the present model are presented in the following paragraphs.

1.6.1.1 Comprehensive but simple approach

The essence of this work is to perform an integrated, general analysis that remains simple enough to be manageable. This allows a more rigorous and disciplined process of decision making with respect to TWRS strategies. The right trade-off has to be made between complexity and the integral view.

It is a good engineering practice to try to tackle problems by starting with "back of the envelope" calculations that would be subsequently refined into more complex models. It seems that the problem at hand is so complex that one would have to adopt from the beginning a "back of the laptop" approach rather than a "back of the envelope" one. Of course, final decisions are taken after running more sophisticated and detailed analyses. However running extremely detailed analyses may be computationally expensive or even wasteful in the early stages of the decision making process. A simplified model is portable, runs on readily available machines and, in consequence, can be reviewed by and is able to collect input from a broader array of people. Such a simplified model will also help identify early in the project which areas really need a detailed treatment and which not.

1.6.1.2 Capability to perform sensitivity analyses and test strategies' robustness

The first application of the model is in performing sensitivity analysis of proposed strategies in order to evaluate their robustness. Given that no TWRS model will ever represent the system exactly, sensitivity analysis is as important as the optimization process itself. In this application we investigate whether the optimal TWRS strategy changes when parameters or probability distributions change. The proposed solutions should be acceptable even under extreme circumstances.

There are uncertainties associated with the parameters involved in risk, cost and duration calculations. The optimal plans should be "robust" with respect to these uncertainties; by "robust," we mean plans that given the uncertainty and indeterminism existent in real world minimize the impact of "unforeseen" circumstances. A good example, although an extreme one, of unforeseen circumstance is a severe limitation on funds at an advanced stage of the TWRS project.

1.6.1.3 Capability to simulate the behavior of various stakeholders

The utility functions for each attribute are combined to create a multiattribute utility function (MAU). Coefficients used in weighting the single attribute utility have a high impact on the choice of the best strategy; this is one of the reasons for decoupling of the sensitivity study of "physical parameters" from the sensitivity analysis on weight coefficients. Different stakeholders might have different sets of weight coefficients. By changing the nominal values of those coefficients the decision maker might play the role of various stakeholders and find the optimal decision from their point of view. An interesting use of the model might be the one presented below.

1.6.1.3.1 Simulating “unexpressed” preferences.

Consider the following situation: the mayor of a certain town might have an “unexpressed” set of preferences. For example his tacit interest might be to attract as much government spending as possible in his community while the utility function for cost that an analyst would build using his answers to a formal questionnaire would decrease monotonically with cost (i.e. would indicate preference for less spending). However despite his expressed preferences the mayor will act during negotiations according to his real, unarticulated utility function. It would be very helpful for DOE to be able to simulate in advance the behavior of different stakeholders in order to identify the strategies that might have a better chance of being accepted by each of the interested parties.

1.6.1.4 Tool to identify new alternatives

Another purpose of the model is to help in identifying new strategies with an increased value of the multiattribute utility function. Given that the functions to be optimized—e.g. the total program cost or the multiattribute utility as functions of the parameters defining a strategy – are far from being "smooth," the use of nonlinear programming techniques is not effective. We considered other Operations Research techniques and chose an approach based on genetic algorithms (GA).

1.6.1.5 Starting point for a larger scale integrated model

The model incorporates several modules: cost, socioeconomic impact, lad use, health effects on public and workers, extra-regional impact, single and multiattribute utility functions. The model can be extended and refined as shown in section 5.2.3. The same methodology may be used to analyze other clean-up activities.

2. Review of Alternatives

The purpose of this chapter is to present a brief review of major alternatives considered up to date by DOE, Westinghouse Hanford and others. Some of these alternatives were studied in more detail ([Boomer, 93], [DOE, 95]) while others are only in their conceptual phase.

2.1 Introduction

The spectrum of solutions to the Hanford tank waste problem is very wide. It ranges from the "wait and see" (no action) option to alternatives that involve very sophisticated chemical procedures (extensive separations) or even further to the restoration of the Hanford site to its pristine condition.

2.1.1 Major questions

There are some of the major dilemmas associated with Hanford tank waste problem:

- Should DOE proceed now (or in the near future) with clean-up or adopt a "wait and see" policy for several decades?
- If they decide to act now should they immobilize the tanks content in place, retrieve the entire amount of waste from all tanks and immobilize it in some other form or proceed selectively (i.e. retrieve the waste only from a few tanks). What retrieval methods should be used?
- The more extensive the separations the lesser the volume of HLW to be sent to an off-site repository. Which is the right degree of separation into high and low level waste streams? Which would be the best pretreatment process?
- Which high level waste and low level waste forms would be appropriate?
- There are stakeholders who believe that Hanford site should be brought as close as possible to a pristine condition. How clean would be clean enough ?

Figure 1 is a schematic representation of some major issues a decision maker should address when designing a TWRS alternative. Table 1 and Table 2 contain lists of possible high level and low level waste forms. A list of pretreatment processes and facilities is given in Appendix A, Table 14.

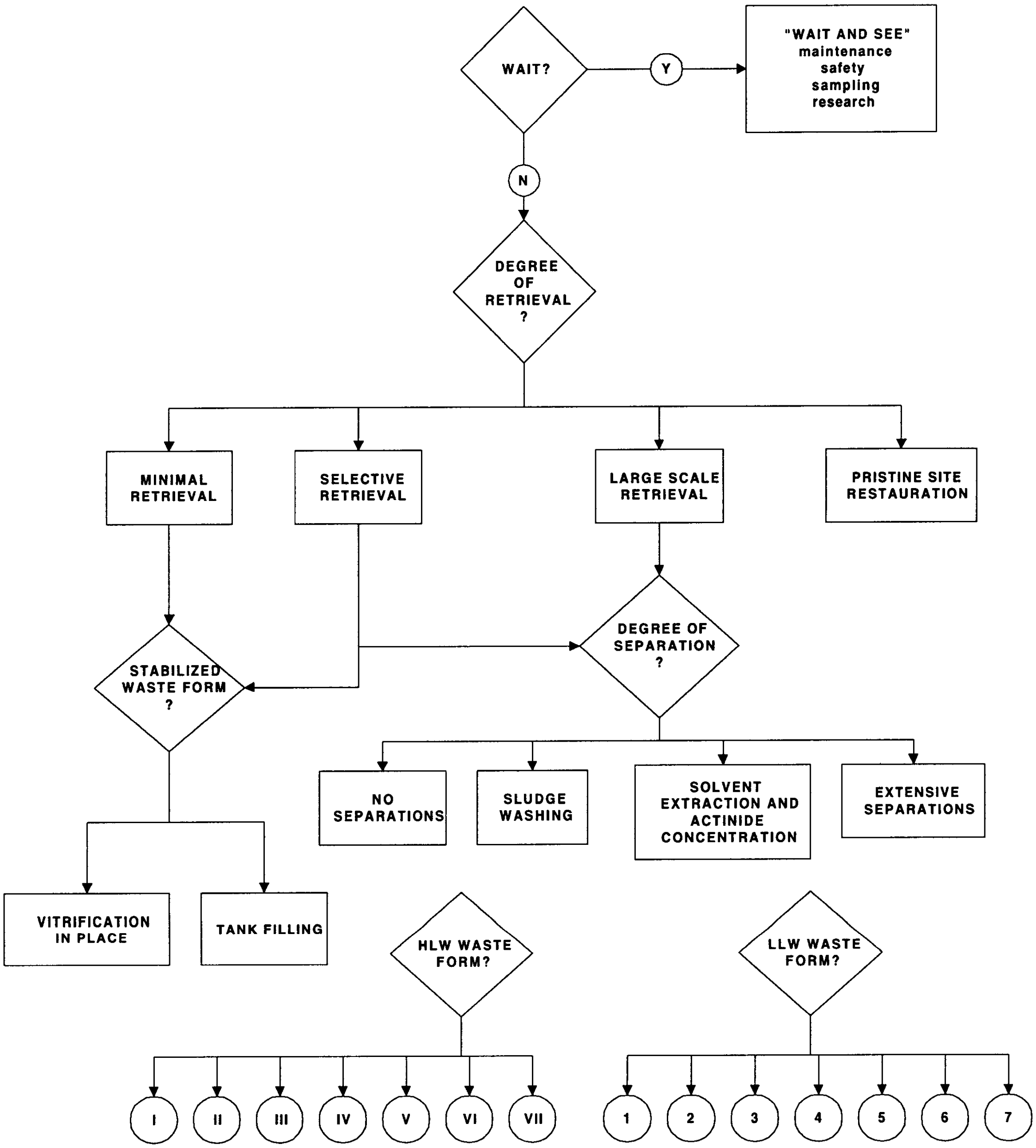

Figure 1 Major questions regarding tank waste remediation
Codes for possible high level waste forms (I through VII) and low level waste forms (1 through 8) are explained in Table 1 and Table 2. A list of pretreatment processes is given in Appendix A, Table 14.

Table 1 High level waste forms

Code in Figure 1	High level waste form
I	Low temperature, non-crystalline glass
II	High temperature, non-crystalline glass
III	High temperature, non-crystalline glass cullet
IV	Low temperature, non-crystalline glass
V	HIP Ceramic (2500 kg per container)
VI	Calcined in casks (10 m^3 per container)
VII	Ceramic pellets (1500 kg per container)

Table 2 Low level waste forms

Code in Figure 1	Low level waste form
1	Salt grout (5300 m^3 per vault)
2	Glass in sulfur cement (5300 m^3 per vault)
3	Glass (15 m^3 container)
4	Mineral grout (5300 m^3 per vault)
5	Ceramic grout (5300 m^3 per vault)
6	Salt polyethylene (1.14 m^3 per container)
7	In situ vitrification (7300 m^3 per melt)
8	No low level waste form

2.1.2 TPA stipulations

The Hanford Federal Facility Agreement and Consent Order (the Tri-Party Agreement) is an agreement to clean-up hazardous and radioactive waste at Hanford. This agreement contains specific requirements for tank waste management, treatment, storage and disposal. According to the Tri-Party agreement plans, all tank waste will be retrieved, separated through pretreatment into high-level and low-level waste streams, and immobilized. The immobilized low-level waste stream will be disposed of on site. High level waste will finally be sent for disposal into an off-site geological repository. A schematic representation of TWRS activities as envisioned by Tri-Party Agreement is given in Figure 2.

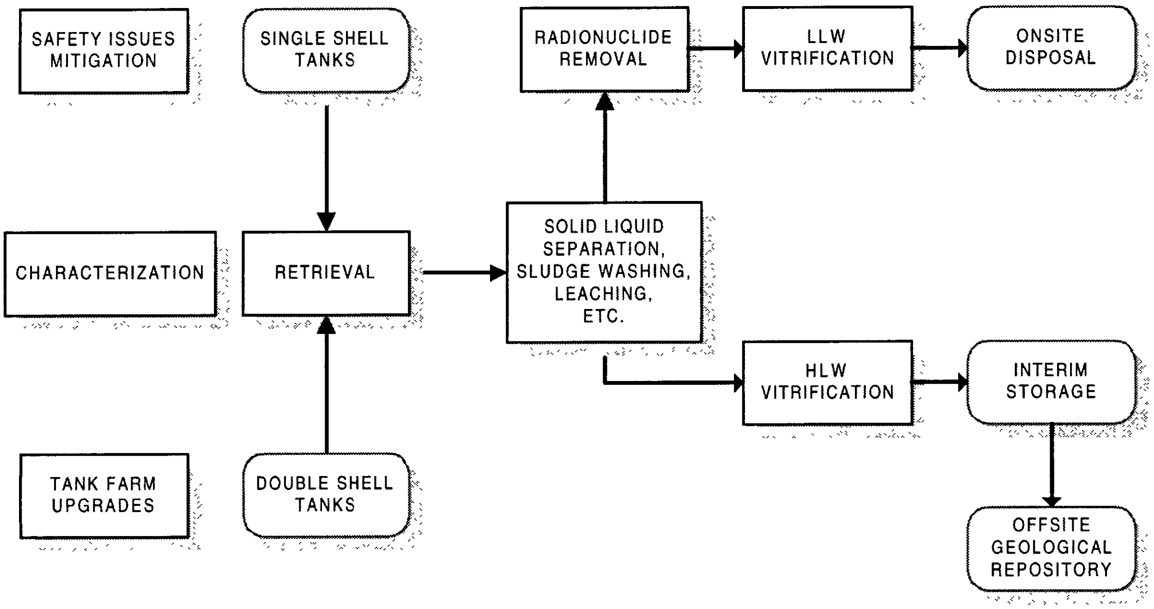

Figure 2 Tank Waste Remediation System

2.2 Alternatives

This is a review of the most representative alternatives. Many more can be imagined. The options considered in this paragraph cover fairly well the range of possible solutions to the Hanford problem.

2.2.1 “Wait and see” option

According to this scenario wastes would be continuously stored in tanks. The tanks would not be treated nor immobilized. Monitoring and institutional control would continue for 100 years. During these 100 years data will be collected in order to assess potential health and environmental impacts. Single shell tanks and miscellaneous underground storage tanks will remain in place. Current operations to remove supernatant liquids in single shell tanks will be completed. Safety issues will be mitigated and tanks will be monitored. Double shell tanks will be retrieved and placed into new double shell tanks at 50-year[17] intervals. Since this alternative will consist in the continuation of current operations, it does not present major uncertainties regarding technological process. Implementing this alternative will be contrary to some RECRA and Tri-Party Agreement stipulations and would not meet Nuclear Regulatory Commission, DOE and state requirements for disposing of high level waste.

2.2.2 Large Scale Retrieval

According to the plans for this alternative, as much of the tank waste as possible[18] would be retrieved from each of the 177 tanks. The recovered waste would be separated into high-level and low level streams that would undergo the processing and disposal methods appropriate for each type of waste. The high level waste would be vitrified and temporarily stored on place before being sent off-site to a national geologic repository. The low level waste would be vitrified, mixed with cement and stored on site in near-surface vaults. Figure 3, based on the *Tank Waste Technical Options Report* [Boomer, 93] presents in more detail the extensive retrieval alternative. Several processing scenarios are presented. The vertical arrow on the right side of Figure 3 indicates that the higher the degree of chemical separations the smaller the amount of vitrified high level waste that would have to be sent off-site.

The large scale retrieval alternatives comply with the Tri-Party Agreement, the Atomic Energy Act and DOE requirements for disposal of high level and low level waste respectively.

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[17] The design life of a DST is 50 years. There is some uncertainty in estimating the actual functional life.

[18] Between 95 and 99% of the waste volume in each tank.

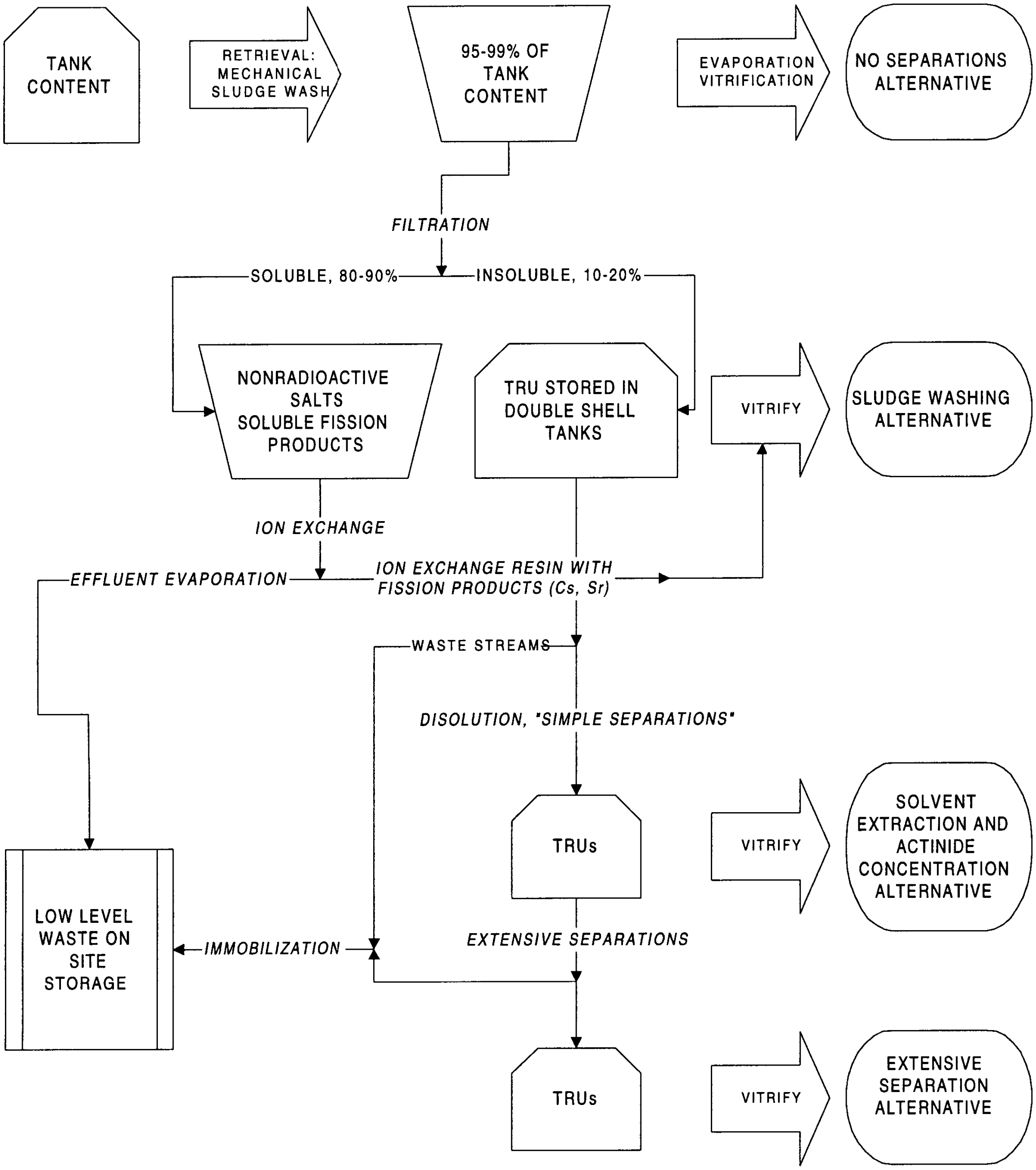

Figure 3 Processing scenarios for Hanford tank wastes
Adapted from [Boomer, 93]. Note: The vertical arrow on the right side points in the direction of an increase in the complexity of the separation process. The more advanced the separation process the lower the volume of waste shipped off-site.

2.2.2.1 No separations alternative

This alternative differs from the large scale retrieval alternative presented above by the fact that wastes will not be separated into high-level and low-level waste streams. Tank content would be submitted to the following procedures: sludge washing, mechanical removal, water evaporation, calcination, recovery of nitric oxides and vitrification of the residue. All waste would be processed in one vitrification plant. A calcination process may be substituted for the vitrification process.

The process would result in a very large number of canisters of glass. Transportation of a larger number of canisters to the repository would almost surely encounter increased opposition from "corridor" states. Additional problems might appear due to the limited physical capacity of the repository. Wastes are very diverse; controlled blending of selected wastes will be needed in order to avoid problems in the vitrification plant.

2.2.2.2 Sludge washing alternative

In this case the supernatant liquid is pumped out of the tanks and the residue is washed with an alkaline solution[19]. Insoluble residues would be removed with remotely operated robotic systems. It is expected that around 5% of the tank content would remain inside as an insoluble solid. The insoluble fraction should contain alkaline-insoluble fission products, strontium and all the actinide elements. The sludge washing process could reduce volume of wastes requiring vitrification by an order of magnitude compared with the "no separations" option. The required capacity of the vitrification plant would be smaller than that needed for the "no separations" option.

2.2.2.3 Solvent extraction

The insoluble material that remains after the sludge washing procedure may be treated further with acids in order to solubilize the actinides. The solution might be further undergo TRUEX type processes for extraction of actinides thus reducing the volume of HLW to a quarter compared with "sludge washing" option.

2.2.2.4 Extensive separations

Further treatment of the radioactive material discharged by the TRUEX process would result in an order of magnitude reduction in the volume of HLW compared with the "solvent extraction"

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[19] Liquids and the fraction of suspended solids pumped out of the tank would contain more than 90% of the Na and Cs, 20% - 40% of the Sr and approximately half of the Tc.

alternative. None of the separation processes required by this alternative has been tested outside the laboratory. In addition, under this option large secondary waste streams would be produced. Those wastes would put additional disposal problems.

2.2.3 "In-place" Option (Minimal Retrieval)

The in-place scenario involves minimal retrieval of material from tanks. Several alternatives are considered. In each case waste would remain in place. Tank content would be either vitrified (In Situ Vitrification) or stabilized by removing the liquids and filling the tanks with gravel and other materials. This option would be very probably unacceptable to stakeholders like Washington State, although the low cost might make it more attractive. This alternative involves disposal of high level waste in near-surface as opposed to deep geological repository. Implementation of the "in-place" option would require some form of regulatory relief (e.g. amendments to the Nuclear Waste Policy Act and Atomic Energy Act).

2.2.3.1 Vitrification in place

According to this scenario all tank waste would be immobilized in place by vitrifying the tanks and their contents. The stable glass form would be obtained by solidification of a high temperature mixture of molten soil and wastes created through electrical resistance heating. A confinement facility would collect the off-gases generated during the vitrification process. Vitrified waste would remain in place covered by a multi-layered surface barrier that isolates the waste by limiting water migration and intrusion by plants, animals or people. In place (in situ) vitrification may comply with Tri-Party agreement requirements.

2.2.3.2 Tank Filling

The tank waste would be stabilized by removing the liquids from tanks, filling the tanks with gravel and engineering a multi-layered barrier over tank farms ("fill and cap"). The barrier limits water infiltration from above. Liquid removal would be achieved through pumping and using an evaporator. Additional drying would be achieved using radio-frequency heating. Filling the tanks with gravel would prevent tank dome collapse and destruction of the multi-layered barrier. Implementing this alternative would not meet RCRA requirements for disposal of hazardous wastes. Tri-Party agreement would have to be renegotiated in order to include "fill and cap" as a valid disposal method for certain wastes.

2.2.4 Moderate Retrieval

The moderate (selective) alternative represent a combination of the minimal retrieval and large scale retrieval alternatives. Decisions regarding waste retrieval will be made on a tank by tank basis. Some of the tanks will be treated using minimal retrieval procedures (vitrification in place or tank filling). The contents of the tanks not selected for "in situ" treatment will be retrieved, separated into low level and high level waste streams and vitrified in a vitrification plant. High level waste would be stored in canisters in interim storage before being sent to an a geological repository. The empty tanks will be filled with gravel and multi-layered barriers will be constructed over all tank farms. The *Preliminary Draft Environmental Impact Statement* [DOE, 95] estimates that, by selectively retrieving tanks, approximately 90 percent of the components that contribute to the long term risk will be disposed of ex-situ.

2.2.5 Pristine site restoration

An extreme alternative is the restoration of the site to its pristine condition. Such a goal is at least highly impractical from a technical point of view if not simply impossible to achieve. This alternative would involve the removal of all added radioactivity from the entire site. It would be necessary to remove steel structures, significant quantities of soil in addition to the tank waste and other types of waste. Under this scenario underground water should be pumped and treated to bring its radioactivity back to natural levels. The cost of this option was estimated to be anywhere between 300 and 600 billion dollars [National Academy, 96]. In addition, this is not necessarily the best alternative from the health effects point of view. It would "export" the risk from Hanford to somewhere else. Transporting the waste would be an increased risk (likely small) to populations along the routes and it would arouse political opposition from the corridor states (thereby increasing the total program cost).

3. Method

3.1 General Presentation

The purpose of the present work is to create and use an integrated multiattribute decision analysis model of the Hanford Tank Waste Remediation System (TWRS). This model is meant to help identify better solutions by providing insight into the desirability of each of the possible strategies. Specifically this model allows decision makers to:

- evaluate existent TWRS strategies
- analyze tradeoffs among multiple attributes (like duration, costs, environmental impact, etc.)
- test a strategy's robustness using sensitivity analysis methods
- identify better alternatives through a systematic search.

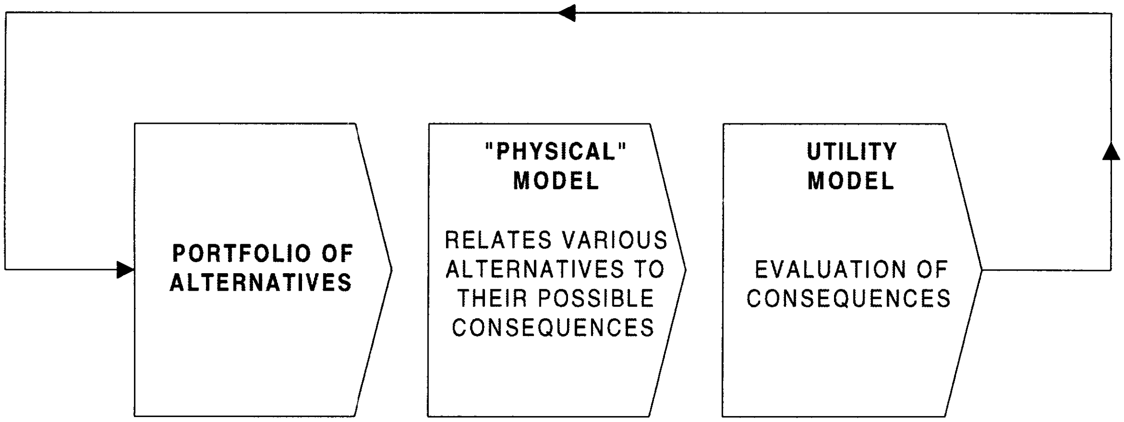

Figure 4 Main blocks of the decision model

As one can see in Figure 4 the decision model can be broken conceptually into two parts. The first part, “Physical Model”, evaluates for each of the available alternatives the corresponding set of consequences (that might happen with a certain likelihood). The second part evaluates the relative desirability of various sets of consequences. The two parts, in combination, determine the relative merit of alternatives. The evaluation is based on likelihood of the consequences and the value (utility) associated with those consequences.

Let $S = \{S^j | j = 1, J\}$ be the set of alternative solutions and let $O = \{O_m | m = 1, M\}$ be the set of objectives identified for the problem. The model determines how well the alternatives measure up in terms of objectives using a set of measures, called attributes. Attributes indicate the degree to which objectives are met. We will designate the set of attributes by $A = \{A_i | i = 1, I\}$ and use the notation x_i to designate a specific quantity of A_i. Under this notation the consequence of an alternative S^j can be written as a vector $(x_1^j, \ldots, x_I^j)$ in the deterministic case (Equation 1) or as a set of probability distribution functions $\{f_{X_1}^j(x_1), \ldots., f_{X_I}^j(x_I)\}$ in the probabilistic case (Equation 2).

$$S^j \to (x_1^j, \ldots, x_I^j) \qquad \textbf{Equation 1}$$

$$S^j \to \{f_{X_1}^j(x_1), \ldots., f_{X_I}^j(x_I)\} \qquad \textbf{Equation 2}$$

Equation 3 presents a concise description of the method. In the first step, for each alternative a set of consequences is calculated in the form of probability distributions functions for various attributes. In the second step, utility functions are assigned to each attribute. Finally the utilities are combined into a multiattribute utility function that represents the overall desirability of the alternative.

$$S^j \to \{f_{X_1}^j(x_1), \ldots., f_{X_I}^j(x_I)\} \to \{U_1, \ldots, U_n\} \to MAU^j \qquad \textbf{Equation 3}$$

↑ Portfolio of alternatives

↑ "Physical" Model

↑ Utility Model

Figure 5 presents the structure of the model. The model incorporates several modules: cost, socioeconomic impact, lad use, health effects on public and workers, extra-regional impact, single and multiattribute utility functions, etc. One of the modules, "Ins" is based on the "Insight" model from Westinghouse Hanford [Johnson, 93], [McConville, 95]. Data used for building other modules comes from various DOE documents like [DOE, 94], [DOE, 95], [Boomer, 93]. The model is implemented using a combination of Excel, Visual Basic, @Risk and DPL[20]. The appendices contain specific details. Appendix B presents more information regarding the Visual Basic functions used throughout the model. Appendix C contains descriptions of the types of software used and a list of the components of the present model (Table 16).

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[20] Appendix C contains descriptions of @Risk and DPL; Excel and Visual Basic are widely known products of Microsoft Corporation.

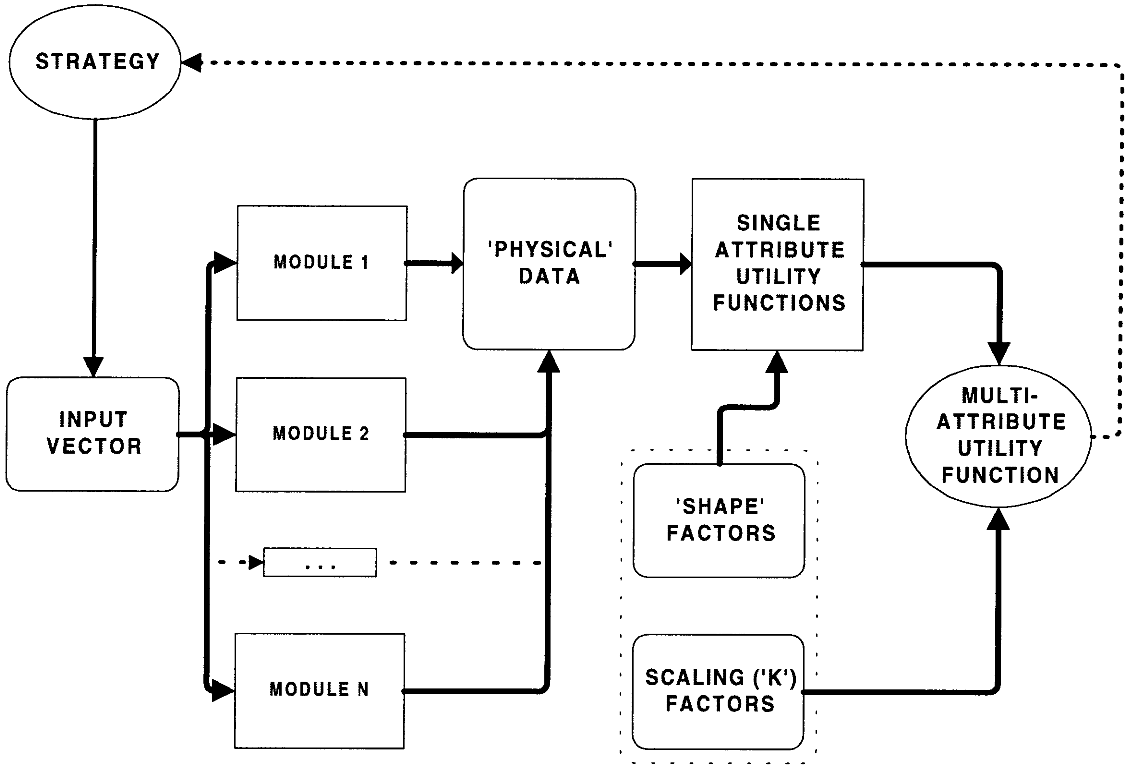

Figure 5 The Model
Each strategy is represented by an input vector. The first part, “Physical Model”, evaluates for each of the available alternatives the corresponding set of consequences. The second part (“Single attribute utility functions”) evaluates the desirability of various sets of consequences. The two parts in combination determine the relative merit of consequences using a multiattribute utility function. The complete list of modules is presented in Appendix C.

3.2 Utility model

3.2.1 An overview of the method

We consider for the beginning a one dimension (single attribute case). In general any decision model assigns a value to each consequence of an alternative and uses the set of values obtained to reflect preferences over alternatives. Each type of decision problem commands a specific type of objective function. In deterministic cases where no uncertainty is apparent in associating consequences with alternatives, a model that would simply assign higher values to better alternatives would be sufficient[21]. In most situations, like the present problem, alternatives have uncertain consequences. In this case an utility function is more appropriate. It has been demonstrated ([von Neumann, 47], [Pratt, 65], [Fishburn, 70]) that if certain reasonable axioms are accepted, the expected (average) utility associated with each alternative (via the uncertain consequences of that alternative) is an appropriate criterion for decision making. An alternative with a higher expected utility will be preferred to one with a lower expected utility.

Let us suppose that we have to decide among several tank clean-up operations and the only attribute that really matters is the health impact on workers, expressed as the number of latent cancer fatalities (LCF) in the worker group. We denote the set of alternatives with $S = \{S^j | j = 1, N\}$. The consequence of each alternative, i.e. the number of LCF, is uncertain. We will assume that dose calculations and expert opinion elicitation led us to the conclusion that the LCF number for a strategy say j (denoted LCF^j) is a variable distributed lognormally with the probability distribution function f_{μ^j,σ^j} defined by Equation 32. Suppose we do the same thing for each of the alternatives S^j , $j = 1, N$. Up to now we have completed the "physical" part of the model in Figure 4 and linked it to the portfolio of alternatives.

$$S^j \to f_{\mu^j,\sigma^j}(x) \quad \text{for } j = 1, N \qquad \textbf{Equation 4}$$

---

[21] The objective function in this case is called an ordinal objective function. If however the decision maker is interested in more than simply ranking the alternatives (i.e. the differences in the values of the objective function should be relevant) it is approriate to use what decision literature calls a measurable value function.

The second part of the model will evaluate the relative desirability of each consequence. Let assume that the decision maker's utility function can be approximated by the "triangular" utility function $U_{c,r,a,b}(x)$ in Figure 8 where x is the latent cancer fatalities variable. The determination of the shape of the utility function is normally accomplished by interviewing the decision maker. According to utility theory the decision maker will choose the alternative that maximizes the expected utility, i.e. will choose that j for which the expected utility e^j is maximum, where e^J is given by Equation 5.

$$e^J = E(U) = \int f_{\mu^J,\sigma^J}(x) \cdot U_{c,r,a,b}(x)\, dx \qquad \textbf{Equation 5}$$

In general one cannot calculate an analytical expression for e^j. The expected utility can be evaluated through numerical integration. Another approach is to bypass the calculation of distribution functions using Monte Carlo simulation.

In conclusion, for a one-dimension decision problem, one can evaluate the relative desirability of alternatives by the method suggested in Equation 6.

$$S^j \rightarrow f_{\mu^J,\sigma^J}(x) \rightarrow e^j \quad \text{for} \quad j = 1, N \qquad \textbf{Equation 6}$$

The appropriate model for TWRS should definitely be multidimensional (or multi-attribute). We can generalize the method presented above. The list of relevant attributes chosen for our model is: 1) cost, 2) duration, 3) socioeconomic impact, 4) land use, 5) health effects on public, 6) health effects on workers, 7) extra-regional impact. These are described in more detail in section 3.2.4.3 Using notations similar to those in Figure 12 the set of attributes can be written as follows:

$$(A_C, A_D, A_S, A_L, A_P, A_W, A_E) \qquad \textbf{Equation 7}$$

The elements that define an alternative are presented in section 3.4. The "physical" part of the decision model presented in Figure 4 and Figure 5 evaluates for each alternative a set of probability distribution functions for each dimension involved.

$$S^j \rightarrow \{f_{X_C}(x_C), f_{X_D}(x_D), f_{X_S}(x_S), f_{X_L}(x_L), f_{X_P}(x_P), f_{X_W}(x_W)\}$$ **Equation 8**

The second step is to determine (or postulate for the beginning) utility functions for each attribute. Throughout this model we consider "triangular" utility functions of the type in section 3.2.3 and represented in Figure 8. To each attribute A_i we associate a single attribute utility function $U_i(x_i|c_i, r_i, a_i, b_i)$ where c_i, r_i, a_i and b_i are parameters given in Figure 8 and explained in section 3.2.3.

$$A_i \rightarrow U_i(x_i|c_i, r_i, a_i, b_i) \text{ where } i \in \{C, D, S, L, P, W, E\}$$ **Equation 9**

The next step is combining the single attribute utilities into a multiattribute utility function.

$$\{U_i(x_i|c_i, r_i, a_i, b_i)\} \rightarrow U(x_C, x_D, x_S, x_L, x_P, x_W|\{k_i\}, \{c_i\}, \{r_i\}, \{a_i\}, \{b_i\})$$ **Equation 10**

where $\{k_i\}$ represents the set of scaling coefficients and $\{c_i\}$ and $\{r_i\}$ are parameters that control the shape of the utility function and $i \in \{C, D, S, L, P, W\}$. Under certain independence conditions (described in section 3.2.2.3) the multiattribute utility function can be calculated as will be shown later in Equation 19.

The optimal strategy S^j will be the one that maximizes the expected multiattribute utility e^j:

$$e^j = E(U) = \int f^j_{X_C}(x_C) \ldots f^j_{X_W}(x_W) \cdot U(x_C, \ldots.., x_W) \, dx_C \ldots dx_W$$ **Equation 11**

The value of e^j depends on the scaling, "shape" and other parameters described above. One of the purposes of this work is to study the sensitivity of e^j, and implicitly of the optimal strategy to these parameters.

$$e^j = e^j(\{k_i\}, \{c_i\}, \{r_i\}, \{a_i\}, \{b_i\})$$ **Equation 12**

The expected utility can be evaluated through numerical integration. In the computer implementation of this model the calculation of distribution functions for the consequences is bypassed entirely since we use Monte Carlo simulation to calculate the expected utility. The actual model works as follows:

- probability distribution functions for input parameters are sampled
- the consequences are calculated
- the values of the utility function are calculated and merged to form a multiattribute utility function (MAU)

The process above is repeated thousands of times in order to create a MAU histogram. Using data in this histogram the code calculates e^j, the expected multiattribute utility for alternative j. The process is repeated for all the alternatives available.

3.2.2 Multiattribute Utility Theory

In this section we give a brief description of the concept of multiattribute utility. A comprehensive treatment of the subject can be found in [Keeney, 75]. Multiattribute utility theory provides a method for making the multiple dimensions of a problem commensurable. This theory recommends the following approach to a decision problem:

- identify the multidimensional consequences and present them to the decision maker
- vary one dimension at a time to obtain a decomposed judgment from the decision maker (i.e. measure decision makers single attribute von-Neumann-Morgenstern utility function[22])
- compare full range changes on several dimensions at a time to obtain the scaling coefficients (weights)
- combine the one dimensional utilities by an additive model if the scaling constants sum to 1.0 or by a multiplicative model otherwise.

3.2.2.1 von-Neumann-Morgenstern utility

A value function $v(x_1,...,x_n)$ is defined on the space of consequences and gives the order of preference of various consequences. In another formulation:

$$v(x_1,...,x_n) \geq v(y_1,...,y_n) \Leftrightarrow (x_1,...,x_n) \text{ is preffered to } (y_1,...,y_n) \qquad \textbf{Equation 13}$$

---

[22] To be presented in the next subsection

The utility function (in the von-Neumann-Morgenstern sense) is a value function that can be used to evaluate alternatives with uncertain consequences. Unlike value functions which are ordinal objective functions, utility exists on a cardinal scale.

von-Neumann-Morgenstern utility [von Neumann, 53] represents a scaling of objective values in terms of probabilities. The attitude of a decision maker towards risk is captured through lotteries on the lowest C_* versus the highest C^* objective value as shown onward. As shown in Figure 6 a lottery is characterized by a set of possible outcomes y_i that occur with probabilities p_i. A short notation for the lottery represented in is $(y_1, p_1; y_2, p_2; ...; y_n, p_n)$ where $(y_1, y_2, ..., y_n)$ is the set of possible outcomes which we assume are ranked in the order of increasing preference:

$$(C_* = y_1 \prec y_2 ... \prec y_{n-1} \prec y_n = C^*) \qquad \textbf{Equation 14}$$

If $n = 2$ the lottery is called binary and can be represented by the triplet (y_1, p_1, y_2).

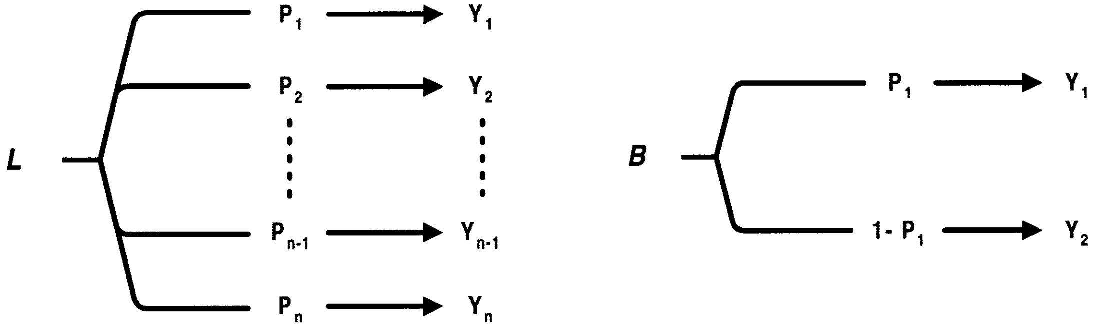

Figure 6 Lotteries
A lottery represents a set of n possible outcomes y_i that occur with probabilities p_i. If $n = 2$ the lottery is called binary

Utility theory is based on a set of assumptions in addition to the axioms required for value functions. The assumptions are:

- Probabilities for a spectrum of consequences exist and can be quantified
- Monotonicity (i.e. "the higher the probability of a benefit the better"). Given two uncertain outcomes y_1 and y_2 where y_1 is preferred to y_2 the decision maker will choose the lottery

that has the higher probability p_1 of getting y_1. If y_1 is preferred to y_2 and $p_1 > p_1^{/}$ then lottery $L = (y_1, p_1, y_2)$ is preferred to $L^{/} = (y_1, p_1^{/}, y_2)$.

- Substitution or independence axiom. A decision maker's preference for an outcome varies linearly with the probability of occurrence i.e. each outcome y_i can be replaced with a lottery $L_i = (y_n, p_i, y_1) = (C^*, p_i, C_*)$ and the utility for y_i is a positive linear transformation of p_i:

$$U(y_i) = \alpha + \beta \cdot p_i \text{ where } \beta > 0 \qquad \textbf{Equation 15}$$

3.2.2.2 Attitude toward risk

Let us consider the binary lottery $B = (y_1, p_1, y_2)$ again. The expected (average) outcome of this lottery is:

$$\bar{y} = p_1 \cdot y_1 + (1 - p_1) \cdot y_2 \qquad \textbf{Equation 16}$$

Faced with the choice between a lottery and its expected (average) outcome the decision maker might prefer to take the lottery and risk getting the worse outcome, say y_1 (which may happen with a probability p_1) or accept the average $\bar{y}$ for sure. A decision maker is risk averse if he prefers the expected consequence of a lottery to that lottery, i.e. his utility for the average outcome is higher than the average of the utilities for the two possible consequences:

$$U(\bar{y}) = U[p_1 \cdot y_1 + (1 - p_1) \cdot y_2] > p_1 \cdot U(y_1) + p_2 \cdot U(y_2) = E(U) \qquad \textbf{Equation 17}$$

Similarly a decision maker is risk prone when he prefers the lottery to the expected outcome of that lottery. One can prove that a decision maker is risk averse (prone) if and only if his utility function is concave (convex). A linear utility function indicates a risk neutral decision maker (i.e. someone who would be indifferent between a lottery and its expected outcome). Figure 7 presents a risk averse utility function and an example for this section.

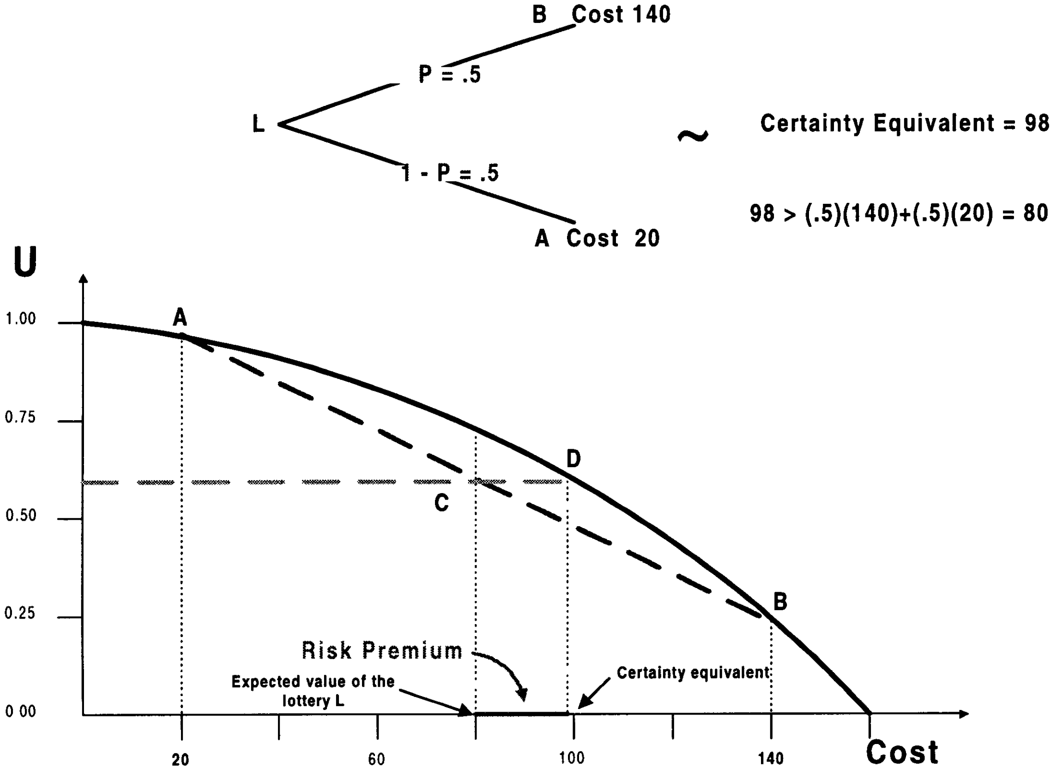

Figure 7 Example of decreasing utility function presenting risk aversion

Figure 7 presents an utility function. The shape of the utility function is concave. As shown in Section 3.2.2.2 a concave utility function indicates a risk averse attitude. Faced with a lottery like *L*, presented in the upper right corner of the figure, i.e. with a project that costs either 120 billion to complete, with a probability $p = 0.5$, or 20 billion with a probability of $1 - p$, (an expected cost of $\bar{c} = (.5) \cdot (140) + (1 - .5) \cdot (20) = 80$) the decision maker will prefer to subcontract this project to a company that guaranties a total cost of, for example, 98 billion. This price of 98 billion is named decision maker's "certain equivalent" for lottery *L*. For a risk averse decision maker the certain equivalent is higher than the expected value of the lottery, the difference between them representing the "risk premium". The risk premium can be interpreted as a fee that a risk averse decision maker faced with an uncertain project will be willing to pay to avoid the risk. Numeric values are given for illustration purposes only.

3.2.2.3 Concepts of Independence

It has been demonstrated that if certain assumptions can be made about the attributes, one can draw specific conclusions regarding the shape of the utility functions. A book by Keeney and Raiffa [Keeney, 76] contains a detailed treatment of these issues in particular and also of the multi-attribute utility theory in general. Informal presentations of two important independence concepts follow. These assumptions simplify the utility measurement process because they allow decomposing of n-dimensional utility functions in n one-dimensional portions.

3.2.2.3.1 Additive Independence.

Attributes are additive independent if decision maker's preference for the consequences depends only on the individual level of the separate attributes and not on the manner in which the levels of different attributes are combined.

Fishburn [Fishburn, 65] proved that if additive independence holds for all combinations of attributes then the utility function must have the following form:

$$U(x_1, x_2, \ldots, x_n) = \sum k_i \cdot U_i(x_i)$$ **Equation 18**

Defining multi-attribute utility $U(x_1, x_2, \ldots, x_n)$ as the weighted sum of the utilities for individual attributes $U_i(x_i)$ has a fundamental disadvantage: it can not take into account the interaction among various dimensions.

3.2.2.3.2 Preferential Independence

A pair of attributes is preferentially independent of other attributes if preferences over the pair of attributes do not depend on the levels of any of the other attributes.

3.2.2.3.3 Utility Independence

An attribute is utility independent of the other attributes if the indifference between a lottery and a certainty equivalent for that attribute does not depend on the levels of other attributes. This allows measuring the way utility changes for one attribute independently of other dimensions.

3.2.2.4 Multiplicative and additive form of multiattribute utility

When the preference and utility independence assumptions hold, it can be proven [Keeney, 76] that the multiattribute utility function $U(x_1, x_2, \ldots, x_n)$ is defined by Equation 19:

$$K \cdot U(x_1, \ldots, x_n) + 1 = \prod (K \cdot k_i \cdot U_i(x_i) + 1)$$

Equation 19

where:

$U(x_1, x_2, \ldots, x_n)$	is the multi-attribute utility function (MAU)
$U_i(x_i)$	are one dimensional utility functions for each X_i
k_i	are individual scaling factors for each attribute
K	is an additional scaling factor (normalizing parameter). K insures consistency between the definitions of $U(x_1, x_2, \ldots, x_n)$ and $U_i(x_i)$.

Figure 37 in Appendix B presents the Visual Basic module associated with Equation 19 and Equation 23.

Using Equation 25 and Equation 26 in Equation 19 one can prove that factor K is determined by Equation 20 (except for the case when Equation 22 is valid):

$$K + 1 = \prod (K \cdot k_i + 1)$$

Equation 20

Equation 20 is usually solved numerically. Figure 35 and Figure 36 in Appendix B present the Visual Basic module used to calculate the normalizing parameter K. In the case of only two dimensions, an explicit expression for K is available:

$$K + 1 = \left(1 - k_1 - k_2\right) / k_1 k_2$$

Equation 21

Another special case appears when the following relation holds:

$$\sum k_i = 1$$

Equation 22

When Equation 22 is true, the multiattribute utility function is calculated as a weighted sum of the single attribute utility functions:

$$U(x_1, x_2, \dots, x_n) = \sum k_i \cdot U_i(x_i)$$ **Equation 23**

3.2.2.5 Scale for Utility

Utilities are defined up to a linear transformation of the form:

$$U_i'(x_i) = \alpha \cdot U_i(x_i) + \beta \qquad \alpha > 0$$ **Equation 24**

We will say that utilities $U_i'(x_i)$ and $U_i(x_i)$ have the same "shape". Although the vertical scale may differ considerably for the two utility functions they are identical in terms of expressing a decision maker's preferences. This also means that we can scale the utilities such that

$$U_i(x_i^*) = 1 \quad \text{and} \quad U_i(x_{i*}) = 0$$ **Equation 25**

where x_{i*} and x_i^* are the worst and best levels of x_i. Similar relations hold for the multi-attribute utility:

$$U(x_1^*, \dots, x_n^*) = 1 \quad \text{and} \quad U(x_{1*}, \dots, x_{n*}) = 0$$ **Equation 26**

3.2.3 "Triangular" utility function

Interviewing stakeholders in order to determine one-dimensional utilities is beyond the scope of the present work. However in order to perform the analysis we had to make certain assumptions regarding utility functions. For the purpose of this analysis we "designed" the generic utility function presented in Figure 8. Although simple, this function can still capture the decision maker's attitude towards risk. The utility function is obtained from the superposition of a linear (risk neutral utility) function (fine continuous line) with a "triangular" function (dashed line). The shape of the utility function is governed by two parameters ("shape factors") : *c* and *r*. The position of the maximum of the triangle, i.e. the position of the "elbow" is given by *r*. This parameter that can take values in the interval (0,1).

$$0 \le r \le 1$$ **Equation 27**

Another parameter involved in the calculation is parameter c . This parameter is allowed to vary in the [-1,1] range.

$$-1 \le c \le 1$$ **Equation 28**

The "shape factor" c is a rough measure of a decision maker's attitude towards risk, as explained in Table 3.

Table 3 "Shape factor" c is a rough measure of decision maker's attitude towards risk

As mentioned in section 3.2.2.2 the decision maker is risk averse (prone) if and only if his utility function is concave (convex). Factor c governs the shape of the utility function, hence is a rough measure of a decision maker's attitude towards risk.

If ...	then the decision maker is ...
$0 < c \le 1$	risk averse (utility function as in Figure 8)
$c = 0$	risk neutral (Figure 9)
$-1 \le c < 0$	risk prone (Figure 10)

Parameter c connected to the height of the triangle ***a C b*** in Figure 8. Equation 29 gives the vertical coordinate y_C of triangle's top (point ***C***).

$$y_C = \begin{cases} c \cdot r & \text{if } c \ge 0 \\ -|c| \cdot (1 - r) & \text{if } c < 0 \end{cases}$$ **Equation 29**

Table 4 presents two extreme cases ($c = -1$ and $c = 1$) and the risk neutral case as well (c=0).

Table 4 Vertical coordinates of points A, B and C for different values of shape factor c.

The position of points A, B and C first introduced in Figure 8 depend on the value of shape factor c. Figures corresponding to the various cases are presented in the first row of this table, under the values of c

Point	$-1 \leq c \leq 1$ (Figure 8, Figure 10)	$c = -1$ (Figure 11B)	$c = 0$ (Figure 9)	$c = 1$ (Figure 11A)
A	$(1-r)+y_C$ [23]	0	$1-r$	1
B	$1-r$	$1-r$	$1-r$	$1-r$
C	y_C	$-(1-r)$	0	r

The use of a triangular utility function allows us to characterize a stakeholder s, by the vector in Equation 30

$$H^s = (\{k_1^s,\ldots,k_n^s\},\{c_1^s,\ldots,c_n^s\},\{r_1^s,\ldots,r_n^s\}) \quad \textbf{Equation 30}$$

where:

k_i^s Scaling coefficient of stakeholder s for attribute i

c_i^s c "shape factor" for the utility function of stakeholder s with respect to attribute i

r_i^s r "shape factor" for the utility function of stakeholder s with respect to attribute i.

The "attitude" stakeholder s would have regarding a particular attribute, cost for example (indexed with number 1), would be represented by the following triplet:

$$H_1^s = (k_1^s, c_1^s, r_1^s) \quad \textbf{Equation 31}$$

We chose the "triangular" utility function represented in Figure 8 due to several reasons:

- It is simple enough and therefore "economical" from a computational point of view
- Although simple it can capture stakeholders' attitude towards risk (risk averse, risk prone) via c and r factors. If c is positive the function is concave, reflecting risk aversion. If c equals zero we are in the risk neutral case.

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[23] Parameter y_C is given by Equation 29

- It is flexible. One can easily perform sensitivity analysis on "shape factors" c and r as well on the limits a and b. One can also easily transform it into a monotonically decreasing utility function.

We claim that at least for this stage of the analysis the use of this type of utility function is appropriate.

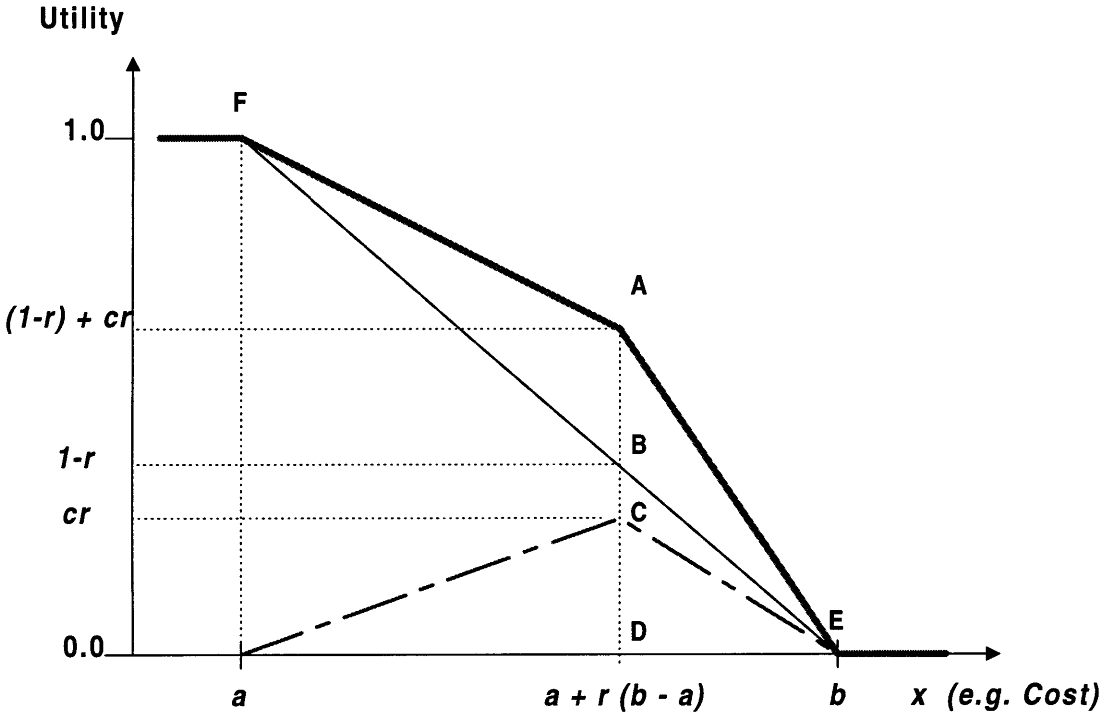

Figure 8 Triangular utility function $U_{c,r,a,b}(x)$ risk averse case ($c > 0$)

The "triangular utility function (thick continuous line) is obtained as a superposition of a linear function (continuous line) with a "triangular" function (dashed line). The positive value of c results in a concave shape of the function. A concave utility function indicates a risk averse attitude of the decision maker. Figure 34 in Appendix B presents the Visual Basic module used to calculate the utility function in Figure 8.

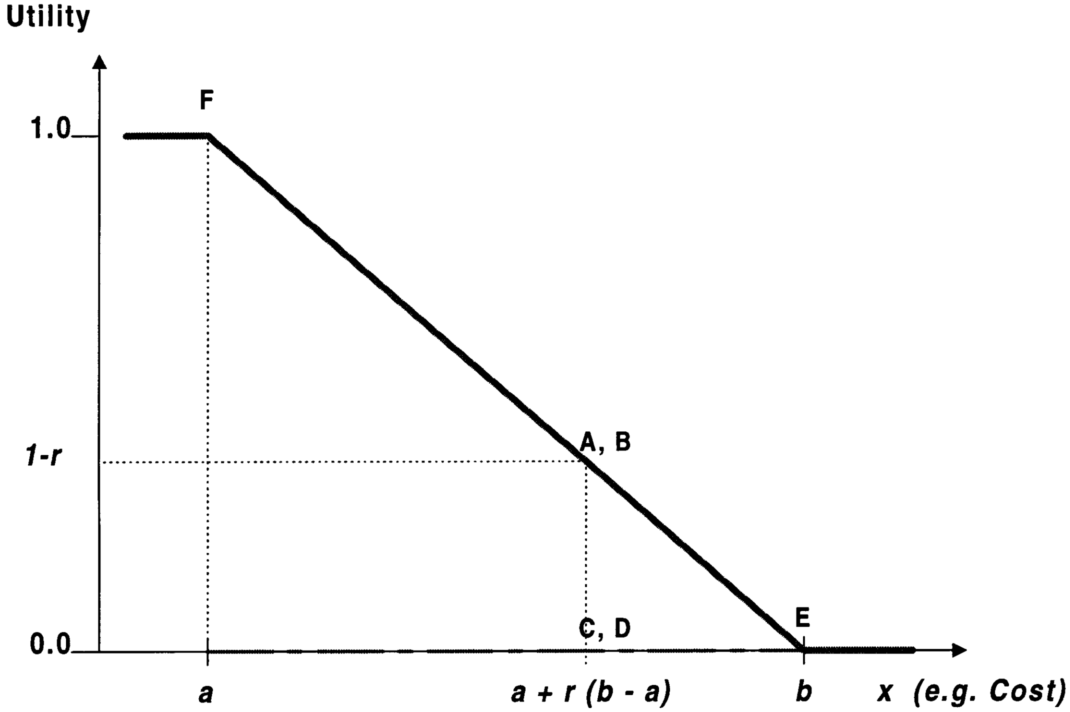

Figure 9 Triangular utility function $U_{c,r,a,b}(x)$ in the risk neutral ($c = 0$) case

A linear utility function indicates a risk neutral decision maker. A risk neutral decision maker would be indifferent between a lottery and its expected outcome.

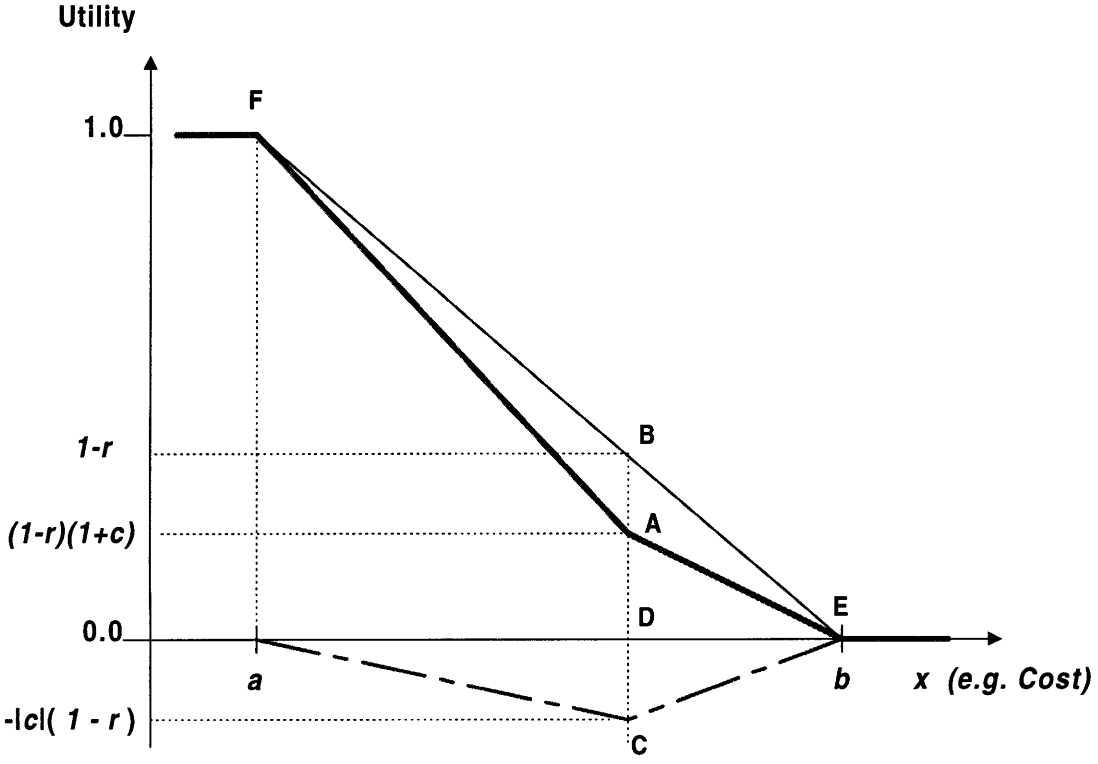

Figure 10 Triangular utility function $U_{c,r,a,b}(x)$ in the risk prone ($c < 0$) case

The "triangular utility function (thick continuous line) is obtained as a superposition of a linear function (continuous line) with a "triangular" function (dashed line). The negative value of c results in the convex shape of the function. A convex utility function indicates a risk prone attitude of the decision maker.

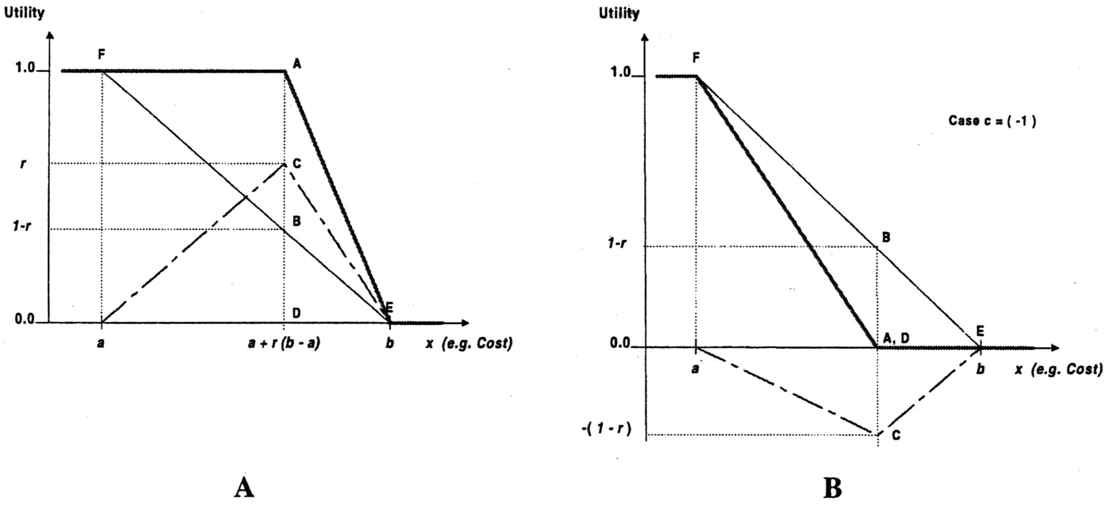

Figure 11 Triangular utility function $U_{c,r,a,b}(x)$ **for the extreme cases** $c=1$ **(A) and** $c=-1$ **(B) presented in Table 4.**

3.2.4 Attributes

The set of objectives and corresponding attributes are key to designing a decision model. The attributes are specific descriptive variables while objectives are more abstract notions that define goals to be achieved. Attributes indicate the degree to which alternatives meet the objectives.

3.2.4.1 What is an attribute?

There are no universally accepted definitions of the term attribute. In this work we use a more informal definition synonymous with: dimension, variable, factor. We limited the scope of the present analysis to quantifiable dimensions. For the purpose of this work an attribute is defined as a quantifiable dimension[24] that indicates the degree to which an objective is met.

3.2.4.2 Attribute Selection

The attributes were selected according to the following criteria:

- Is the attribute important enough to be a primary concern to DOE and the public?
- Do we have enough physical data to quantify the attribute?. This rule limited severely the number of attributes we could consider in the model. We felt however that it is better to have a model with a reduced set of attributes rather than having one with incomplete data.
- Are the attributes independent? We tried to avoid double counting. This is a problem frequently encountered in Multiattribute Decision Making. An attribute may appear in more than one place in a "disguised" form.

3.2.4.3 Attributes presentation

This section provides a short description of the attributes considered in the present model. The attributes are presented in Figure 12.

3.2.4.3.1 Cost

This attribute refers to the life-cycle cost in 1995 dollars. It includes the retrieval, pretreatment and disposal elements of the TWRS program.

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[24] The only exception to this approach is the attribute "regulatory compliance" (Figure 12). This attribute, however, is not used to evaluate strategies in the same manner as other attributes (i.e. assessing a single attribute utility function and then combining with other utility functions to obtain MAU).

3.2.4.3.2 Schedule

The two components of this attribute are:

- Duration - This performance measure is determined as the number of years necessary to finish the immobilization of tank wastes once tank waste retrieval has commenced.
- Project Completion - Represents the year when project will be completed.

Using both project duration and project completion as attributes might appear as a redundancy. In reality they complement each other: one positions the project on the time line while the other show the duration of the project.

3.2.4.3.3 Socioeconomic Regional Impact

An exhaustive treatment of the socioeconomic regional impacts of the TWRS program is beyond the purpose of this thesis. We limited the analysis to two elements that we found representative:

- Average size of the TWRS labor force
- Relative fluctuation in the size of the labor force.

Estimates of the elements above do not exist for each strategy. We rely on labor force estimates given in [DOE, 95] for several representative alternatives and assume that data are similar for other scenarios in the same category. The same comment is valid for the public and worker health effects data.

3.2.4.3.4 Land Use

We considered the following two components to be most relevant to the land use dimension:

- Volume of waste remaining on site
- Radioactivity of the waste remaining on site; the radioisotopes remaining on site fall in two categories:
    1. long lived isotopes (^{99}Tc, TRU)
    2. short lived (^{90}Sr and ^{137}Cs).

3.2.4.3.5 Health Effects – Public

This group of attributes deal with the health effects to public, off-site. We included the following attributes:

- Post-remediation - Probability that a recreational user of the Hanford area would develop cancer from post-remediation conditions,

- Accidents - Cancer fatalities among general public due to accidents resulting in release of radioactivity,
- Normal Conditions - Cancer fatalities among general public due to radioactive releases under normal conditions,
- MEI normal. - Probability that the maximally exposed individual (MEI) to normal (routine) radionuclide releases in the general public will die of cancer,
- MEI accidents - Probability that the maximally exposed individual to accidental radionuclide releases in the general public will die of cancer,
- Non-radioactive toxic releases that affect the general population.

3.2.4.3.6 Health Effects – Workers

This group of attributes addresses the health effects on workers onsite. The list of attributes includes:

- Accidents Occupational - Number of fatalities due to occupational and transportation accidents,
- Injuries occupational - Injuries and illnesses due to occupational and transportation accidents,
- Accidents - Cancer fatalities among onsite workers due to accidental radioactive releases,
- MEI normal release - Probability that the maximally exposed individual among workers onsite, to accidental or normal radionuclide releases will die of cancer,
- Normal releases - Cancer fatalities among onsite workers due to routine radioactive releases,
- Non-radioactive toxic releases that affect workers.

3.2.4.3.7 Extra regional impact

Transporting the high level waste for disposal in a permanent geological repository will affect regions outside the Hanford area. A good measure of the extra-regional impact of various strategies is the volume of high level waste shipped off-site.

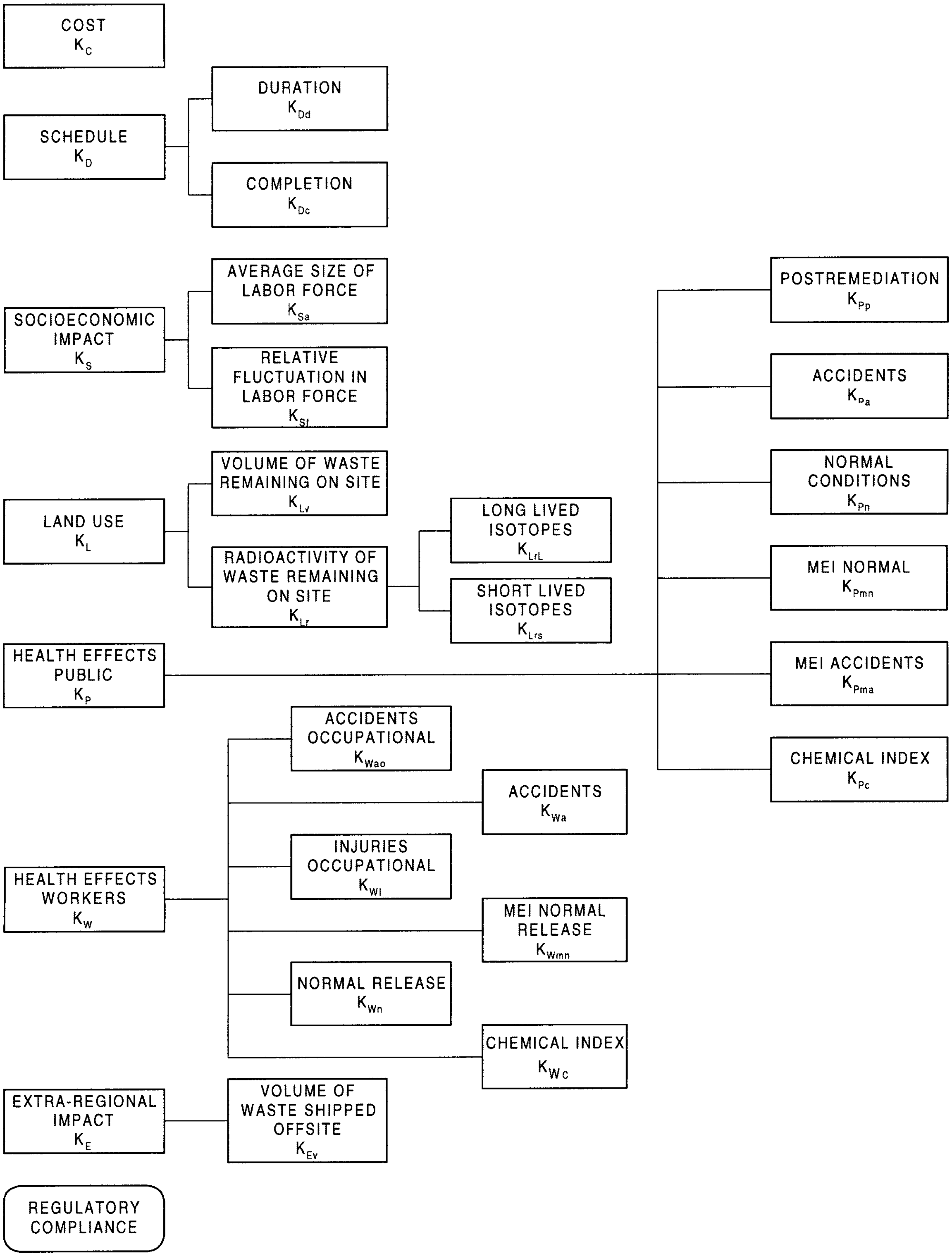

Figure 12 Attributes

See also text in section 3.2.4.3 Symbols of the form K_C in Figure 12 denote the scaling ("k") factors (Equation 19) associated with each attribute.

3.3 *Physical model*

3.3.1 General presentation

The "physical" model relates various alternatives to their possible consequences. The elements that define a strategy are shown in section 3.4. A presentation of the major groups of options was given in a previous chapter. Figure 5 presents the structure of the MAATWRS model which has a modular approach and is implemented using a combination of Excel, Visual Basic, @Risk and DPL[25]. The function of the physical model is to calculate the values associated with the attributes presented in Figure 12. Data for cost, schedule, land use and extra-regional impact are calculated using a Westinghouse Hanford spreadsheet model named Insight [McConville, 95] which is incorporated as a module in the present code. Other modules calculate data associated with the rest of the attributes. More specific information about the model is given in appendices B and C.

Table 5. Typical Draft Environmental Impact Statement [DOE, 1995] results.
Excerpted from Table E.52 "Latent Cancer Fatality Risk from Tank Dome Collapse" in [DOE, 1995]

Receptor	Case	Dose (person-rem)	Annual Frequency	LCF[26]/rem	Time (year)	LCF risk
Workers	Nominal-case	8.7E+01	7.5E-05	4.0E-04	24	6.3E-05 (3.5E-02)[27]
	Worst-case	6.2E+04	7.5E-05	4.0E-04	24	4.5E-02 (2.5E+01)[28]

3.3.2 Using lognormal distributions to represent radiological and chemical hazards

The Draft Environmental Impact Statement (DEIS) [DOE, August 1995] usually presents consequences of accidents and routine operations for two scenarios: a nominal case and a worst

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[25] Appendix C contains brief descriptions of the software used.

[26] LCF stands for Latent Cancer Fatality

[27] Total number of fatal cancers in the population if the accident occurs

case. An example is presented in Table 5 . As Table 5 indicates, the value of the dose is used to calculate the latent cancer fatality risk (LCF) by multiplication with a constant (number of latent cancer fatalities per rem). We use the LCF to calculate the utility function associated with the health effect attribute.

In order to perform a sensitivity analysis we need to make certain assumptions regarding the probability distribution functions associated with the dose and other parameters. We chose to use a lognormal probability distribution function for the reasons explained in section 3.3.2.5. Equation 32 defines the lognormal probability density function. More information on $f_{\mu\sigma}$ is given in Table 6.

$$f_{\mu,\sigma}(x) = \begin{cases} \frac{1}{x\sqrt{2\pi\sigma}}\exp(\frac{-(\ln x-\mu)^2}{2\sigma^2}) & \text{if } x>0 \\ 0 & \text{otherwise} \end{cases} \qquad \textbf{Equation 32}$$

The lognormal distribution depends on two parameters: σ and μ . Let us denote the values for the dose in nominal and worst cases by N and W respectively. We also denote the mean of the lognormal distribution by m, the mode by M and the standard deviation by s. We use N and W to calculate σ and μ . We considered two ways of doing this calculation. The first way is to assume that the mean m of the lognormal distribution is equal to nominal value N . In the second approach we assumed that the nominal value N is actually the mode M (i.e. the most probable value) of the distribution.

3.3.2.1 Method 1. The nominal value is the mean.

In this method the following assumptions are made:

1. The mean m equals nominal value N

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[28] Total number of fatal cancers in the population if the accident occurs

$$m = N$$ **Equation 33**

2. The maximum dose value *W* equals the mean value *m* plus 3 standard deviations

$$W = m + 3 \cdot s.$$ **Equation 34**

Table 6 gives the following relations among *σ*, *μ*, *m* and *s*:

$$m = e^{\left(\mu + \frac{\sigma^2}{2}\right)}$$ **Equation 35**

$$s^2 = e^{(2\mu + \sigma^2)}\left(e^{\sigma^2} - 1\right).$$ **Equation 36**

From Equation 35 and Equation 36 we obtain:

$$s^2 = m^2 \cdot \left(e^{\sigma^2} - 1\right).$$ **Equation 37**

After solving Equation 37 for σ^2 we get:

$$\sigma^2 = \ln\left[1 + (s/m)^2\right].$$ **Equation 38**

From Equation 38 and Equation 35 one can derive *μ*

$$\mu = \ln\left[\frac{m}{\sqrt{m^2 + s^2}}\right].$$ **Equation 39**

Table 6. Lognormal distribution function

Cumulative distribution function (CDF)	No closed form
Parameters	Shape parameter $\sigma > 0$ and scale parameter $\mu \in (-\infty, \infty)$
Mean (m)	$e^{\left(\mu+\frac{\sigma^2}{2}\right)}$
Variance (s^2)	$e^{(2\mu+\sigma^2)}\left(e^{\sigma^2}-1\right)$
Mode	$e^{\mu-\sigma^2}$
Range	$[0,\infty)$

3.3.2.2 Method 2. The mode equals the nominal value

In this method the following assumptions are made:

1. The mode M equals the nominal value N

$$M = N \qquad \textbf{Equation 40}$$

2. The maximum dose value W equals the mean value m plus 3 standard deviations

$$W = m + 3 \cdot s. \qquad \textbf{Equation 41}$$

Using relations in Table 6 in Equation 40 and Equation 41 we obtain the following system of equations:

$$e^{\mu-\sigma^2} = N \qquad \textbf{Equation 42}$$

$$e^{\mu+\frac{\sigma^2}{2}} + 3 \cdot e^{\mu+\frac{\sigma^2}{2}} \cdot \left(e^{\sigma^2}-1\right)^{1/2} = W \qquad \textbf{Equation 43}$$

We make the following notations:

$$e^{\mu} = x$$ **Equation 44**

$$e^{\sigma^2} = y$$ **Equation 45**

Equation 44 and Equation 45 imply that $x > 0$ and $y \geq 1$.

With the notations in Equation 44 and Equation 45, Equation 42 and Equation 43 become:

$$x \cdot y^{-1} = N$$ **Equation 46**

$$x \cdot \sqrt{y} + 3 \cdot x \cdot \sqrt{y} \cdot \sqrt{y-1} = W$$ **Equation 47**

We solve for x in Equation 46 and make and substitute the result in Equation 47 to obtain

$$x = N \cdot y$$ **Equation 48**

$$y \cdot \sqrt{y} \cdot \left(1 + 3 \cdot \sqrt{y-1}\right) = W / N$$ **Equation 49**

The fact that the function $f(y) = y \cdot \sqrt{y} \cdot \left(1 + 3 \cdot \sqrt{y-1}\right)$ is an increasing function of y in the range $[1, \infty)$ implies that Equation 49 has a unique solution in this range. Let's denote this solution by y^*. One can find y^* numerically and than calculate σ and μ using equations Equation 45, Equation 44 and Equation 48.

$$\mu = \ln(N \cdot y^*)$$ **Equation 50**

$$\sigma = \sqrt{\ln(y^*)}$$ **Equation 51**

3.3.2.3 *Example*

Table 7 summarizes the results obtained using data in Table 5. It is noted that the values obtained for the pairs σ and μ are very different. The two distributions obtained are so different that it is difficult to represent them on the same graph. Figure 13 presents instead the results of calculations with a smaller value for W ($6.22 \cdot 10^2$ instead of $6.22 \cdot 10^4$).

Table 7. Results obtained using data in Table 5.

Method	N	W	M	m	s	σ	μ
1. The nominal value is the mean	86	$6.22 \cdot 10^4$	$6.22 \cdot 10^{-6}$	86	20638	3.31075	-1.0262
2. The nominal value is the mode	86	$6.22 \cdot 10^4$	86	$6.05 \cdot 10^3$	18980	1.648	7.17

3.3.2.4 *Conclusion*

The two methods result in very different results. The 'mode' method (method 2) is more conservative since it generates higher values for the dose. Therefore we chose to use this method in the MAATWRS model.

3.3.2.5 *Why lognormal ?*

There are several reasons for choosing a lognormal distribution in this case:

- Convenience. The lognormal distribution depends on two parameters μ and σ that can be derived from "nominal"-"worst case" pairs of data.
- Long tail. The lognormal distribution has a "tail" long enough to allow for representation of events with small probability and high consequences.
- No negative values. The lognormal distribution, as opposed to the normal distribution does not take negative values in any situation. Variables distributed according to a lognormal distribution cannot be negative.
- Extensive use in other cases. (For example WASH-1400, [Rasmussen, 75]).

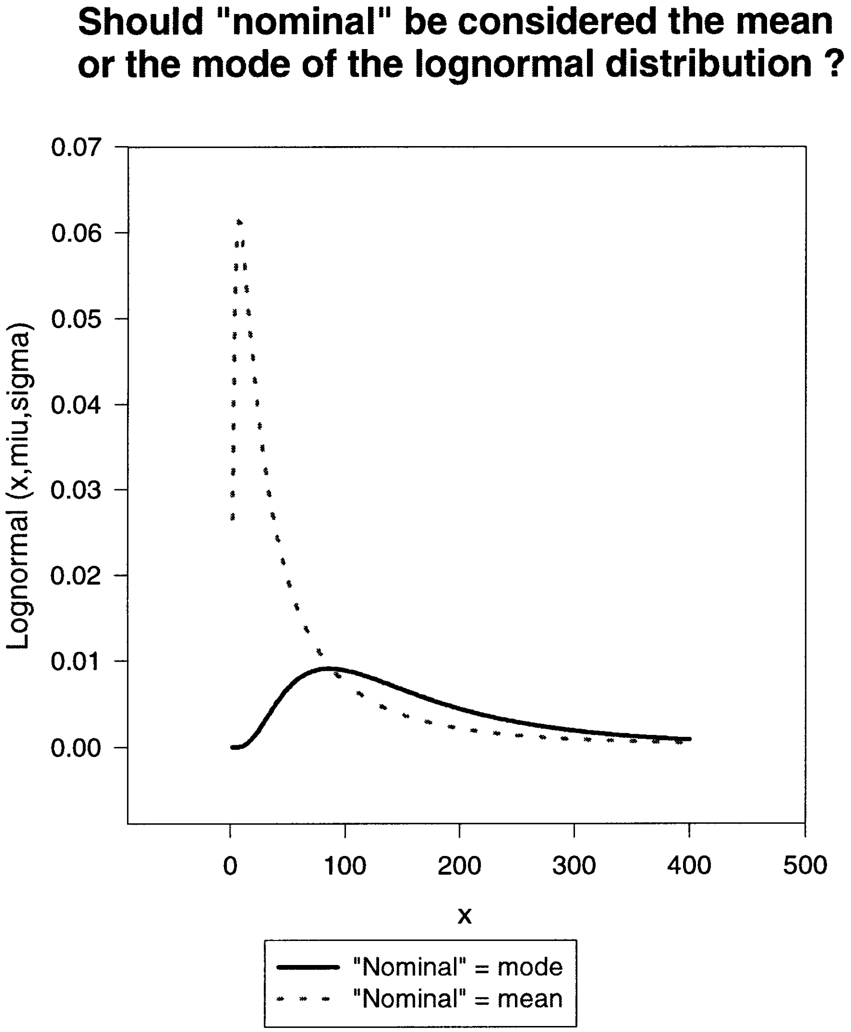

Figure 13 Mode versus mean

This figure presents the graphs of lognormal distributions obtained for $W = 6.22 \cdot 10^2$ and N=86 using the 'mode' (continuous line) and the 'mean' (dotted line) approach. One can see that the former approach is more conservative. For $W=6.22 \cdot 10^4$ the distributions were so different that they could not be plotted clearly on the same graph.

3.4 What defines a strategy?

In the present model a strategy (alternative) is defined by a strategy vector. A strategy vector is a sequence of variables (switches) associated with retrieval sequence and methods, pretreatment process and facility, treatment and disposal of low level and high level waste. The strategy vector associated with an alternative, say j is presented in Equation 52.

$$S^j = \{R_S, R_M, P_T, P_F, H_T, H_F, L_T, L_F\} \qquad \textbf{Equation 52}$$

The symbols in Equation 52 are defined below:

R_S	Retrieval Sequence
R_M	Retrieval Method
P_T	Pretreatment Technology (options available are presented in Table 14 in Appendix A)
P_F	Pretreatment Facility (Table 14)
H_T	High Level Waste Technology (a list of HLW technologies and forms is presented in Table 15)
H_F	High Level Waste Form (presented in Table 15)
L_F	Low Level Waste Form (a list of LLW forms is presented in Table 13)

3.5 Optimization

Another purpose of the model is to help in identifying new strategies with optimal values for certain attributes (e.g. cost). Given that the function to be minimized – cost as a function of the parameters defining a strategy -- is far from being "smooth," the use of nonlinear programming techniques is not effective. We considered various Operations Research techniques and chose an approach based on genetic algorithms (GA). The first genetic algorithms were developed in the early 1970's by John Holland [Holland, 75]. These algorithms, just like evolution in nature, make the strategy vectors mutate, cross over and evolve towards optimal solutions. Although one cannot prove that the strategies found using GA's have the absolute minimum cost or maximum utility value within the space of possible solutions they may still be very interesting from a pragmatic point of view.

In Appendix A we present the use of genetic algorithms to identify alternatives with a reduced cost.

4. Evaluation of Selected Alternatives and Sensitivity Analysis

4.1 Introduction

Throughout this chapter we illustrate the general method described in the previous sections by presenting several applications. We also introduce a mean-variance (MV) for multiattribute utility method to compare alternatives. Mainly, we consider for illustration three classes of large scale retrieval alternatives: “Simple Separations”, “No Separations” and “Extensive Separations”. Information about these alternatives is presented in Table 8, Figure 3 and in section 2.2.2. We also present results of the analysis of other scenarios. A particularly interesting option is the “In Place” alternative. According to this option all or most of the tank waste should be left or treated in place. This alternative is clearly in contradiction with the Tri Party Agreement and other regulations but has the advantage of a lower cost. One can also argue that it has less severe health effects on Hanford workers given that it involves minimal retrieval of waste from tanks. We do not consider the results presented as the ultimate evaluation of Hanford tank waste strategies and are aware of the many uncertainties in the data and imperfections in the model; we performed these evaluations in order to illustrate the capabilities of the model.

An application of the model is in performing sensitivity analysis of proposed strategies in order to evaluate their robustness. Given that no TWRS model will ever represent the system exactly, sensitivity analysis is as important as the optimization process itself. In this application we investigate whether the optimal TWRS strategy changes when parameters of the model change. The proposed solutions should be acceptable even under extreme circumstances.

The utility functions for each attribute are combined to create a multiattribute utility function (MAU). Scaling coefficients associated with single attribute utility functions have a high impact on the choice of the optimal strategy; this is one of the reasons for decoupling of the sensitivity study of "physical parameters" from the sensitivity analysis of the scaling coefficients. Different stakeholders might have different sets of scaling coefficients. By changing the nominal values of those coefficients the decision maker might play the role of various stakeholders and find the optimal decision from their point of view.

There are uncertainties associated with the parameters in the risk, cost and duration calculations. The optimal plans should be "robust" with respect to those uncertainties; by "robust," we mean plans that given the uncertainty existent in the real world, minimize the impact of "unforeseen" circumstances. A good example, although an extreme one, of unforeseen circumstance is a severe limitation on funds at an advanced stage of the TWRS project.

Another purpose of the model is to help in identifying new strategies with an increased value of the multiattribute utility function. Given that the function to be maximized -- the nominal multiattribute utility as a function of the parameters defining a strategy -- is far from being “smooth,” the use of nonlinear programming techniques is not effective. We use an approach based on genetic algorithms to identify alternatives with a reduced total program cost.

Using Monte Carlo simulation we generated probability distribution functions for single attribute and the multiattribute utility as measures of interest for some strategies. First we perform a mean variance analysis of TWRS program cost.

4.2 Mean-variance analysis of TWRS program cost

Cost uncertainty is one of the major factors that have to be taken into account when analyzing various alternatives. In this section we perform mean-variance analyses of TWRS program cost.

Figure 14 is a mean-standard deviation[29] diagram for the total program cost of several alternatives. The vertical axis represents the mean cost of the project while the horizontal axis represents the standard deviation, a measure of the risk associated with the cost of an alternative. Costs for various alternatives were calculated using the “Insight” model available from Westinghouse Hanford ([Johnson, 93], [McConville, 95]) and data from [DOE, 95]. The symbols used for various alternatives are based on the type of pretreatment process involved. Symbols of the form “E1” refer to advanced separations alternatives, those of the form “S1” denote sludge wash alternatives while labels containing only numbers (e.g. “`1”) refer to enhanced sludge wash alternatives. The symbol “== IP ==” denotes a group of alternatives that would leave most of the

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[29] This type of analysis is inspired by the Markowitz mean-standard deviation model widely used in modern portfolio theory [Markowitz, 52, 59]. The representation of risk by means of standard deviation (or variance) of a distribution proved very useful in finance theory leading to the capital asset pricing model (CAPM) in the early 1960s.

waste in place. The double line in the symbol "=== IP ===" is used to illustrate the fact that we only have a point estimate for the cost associated with the in place alternatives. The symbols used in this diagram are explained in Table 8, Table 9, Table 10 and Table 11.

Alternatives with smaller expected cost and reduced variance should be preferred. Representative points for better alternatives lie closer to the lower left corner of the diagram. For example alternative "3" in Figure 14 is to be preferred to alternative "SS" (Simple Separations) if cost is the only element to be considered. One can note however (as shown in Figure 21) that alternative "Simple Separation" has a higher expected multiattribute utility than "3". Because the technologies involved by the "In Place" options (symbol ===IP===) are relatively simple, it is reasonable to assume that the standard deviation of the cost for the "in place" alternatives should be lower compared to other options. The "in place" alternatives are discussed in section 4.7.

A difference from the mean variance representation in the Markowitz model is that there is no Hanford equivalent of a risk free investment (treasury bonds have zero risk for all practical purposes). In the Hanford case uncertainties are so large that basically one cannot think about any alternative that would have zero variance in the total cost. The closest equivalent might be the "No Action" alternative with an estimated cost of 22.5 billion dollars [DOE, 95]. There is little variance in cost estimates for the "No Action" alternative since most of the activities associated with this option are current, routine operations.

The standard deviation $\sigma = [E(x_C - \bar{x}_C)]^{1/2}$ (or equivalently variance σ^2) is the best known and earliest measure of the degree of risk of a random variable x_C but it is not the only one. Beside the standard deviation of a distribution, other univariate measures of risk can be imagined: the mean absolute deviation $E(|x_C - \bar{x}_C|)$, the range between extreme values of the cost $[\max(x_C) - \min(x_C)]$, interquartile range $[F_C^{-1}(.75) - F_C^{-1}(.25)]$, the difference between the 95th and the 5th percentiles $[F_C^{-1}(.95) - F_C^{-1}(.05)]$ or the entropy $\int f_C(x) \cdot \ln(f_C(x))\, dx$.

Each of the measures above are convenient univariate representations of uncertainty but are subject to various problems. For example: standard deviation reflects the change of cost in both directions. While an increase in cost is undesirable, a decrease of the cost can hardly be considered a risk. Another drawback of the mean-variance method is the following: one can prove that a decision maker that relies on maximization of the expected utility would generate the same ranking of alternatives as another decision maker who would use the mean-variance method if and only if his utility function is of the form $U(x) = ax + bx^2$. The assumption of a quadratic utility function contradicts practical observations.

Figure 15 represents a "mean - range between extreme values" diagram for total program cost. The "range" represents the difference between the maximum and the minimum cost associated with a particular scenario.

Not all the possible alternatives are represented in Figure 14 and Figure 15. The lists of possible pretreatment alternatives, high level and low level waste forms are given in Appendix A (Table 13, Table 14, Table 15).

One can note that in general, enhanced sludge wash alternatives are less costly than alternatives that involve simple sludge wash as a pretreatment process. Advanced separations alternatives also have a low cost but they rely on technologies not yet tested on an industrial scale.

A particular interesting alternative is "3". In this scenario nuclear waste would undergo a pretreatment process consisting of enhanced sludge wash, Cs ions exchange, selective Sr and TRU precipitation in a new enhanced sludge wash pretreatment facility. Single shell tanks would be retrieved using 40 sluicing systems and 2 mechanical arms. Nuclear waste will be retrieved from double shell tanks using a mixer pump. A gas fired melter would be used to stabilize high level waste into high temperature, non-crystalline glass cullet. Low level waste will be disposed of in 5300 m^3 underground vaults in the form of glass cullet in sulfur polymer cement.

4.2.1 Searching for low cost alternatives using genetic algorithms

Alternative "E1" was identified using a search technique based on genetic algorithms as described in Appendix A. The fundamental difference between "E1" and "3" is in the pretreatment part. Alternative "E1" involves an advanced separations pretreatment process. Single shell tanks would be retrieved using 20 sluicing systems and 4 mechanical arms. A mixer pump will be used to retrieve double shell tanks. Similarly to "3" the "E1" high level waste would be stabilized into high temperature, non-crystalline glass cullet produced in a gas fired melter and low level waste will be disposed of in 5300 m^3 underground vaults in the form of glass cullet in sulfur polymer cement. As one can see in Figure 14 “E1” is slightly less costly than alternative “3” but the standard deviation of “E1” total cost is higher than the standard deviation of the cost for “3”. If a decision maker had to choose between “3” and “E1” based solely on results presented in Figure 14 and Figure 15, the better choice would be “3” since its cost is lower and less uncertain. It would be a lot more difficult to choose between “E1” and another advanced separations alternative, “ES”, since the latter, although costs more (a disadvantage) is also more predictable, given its lower standard deviation in cost (an advantage).

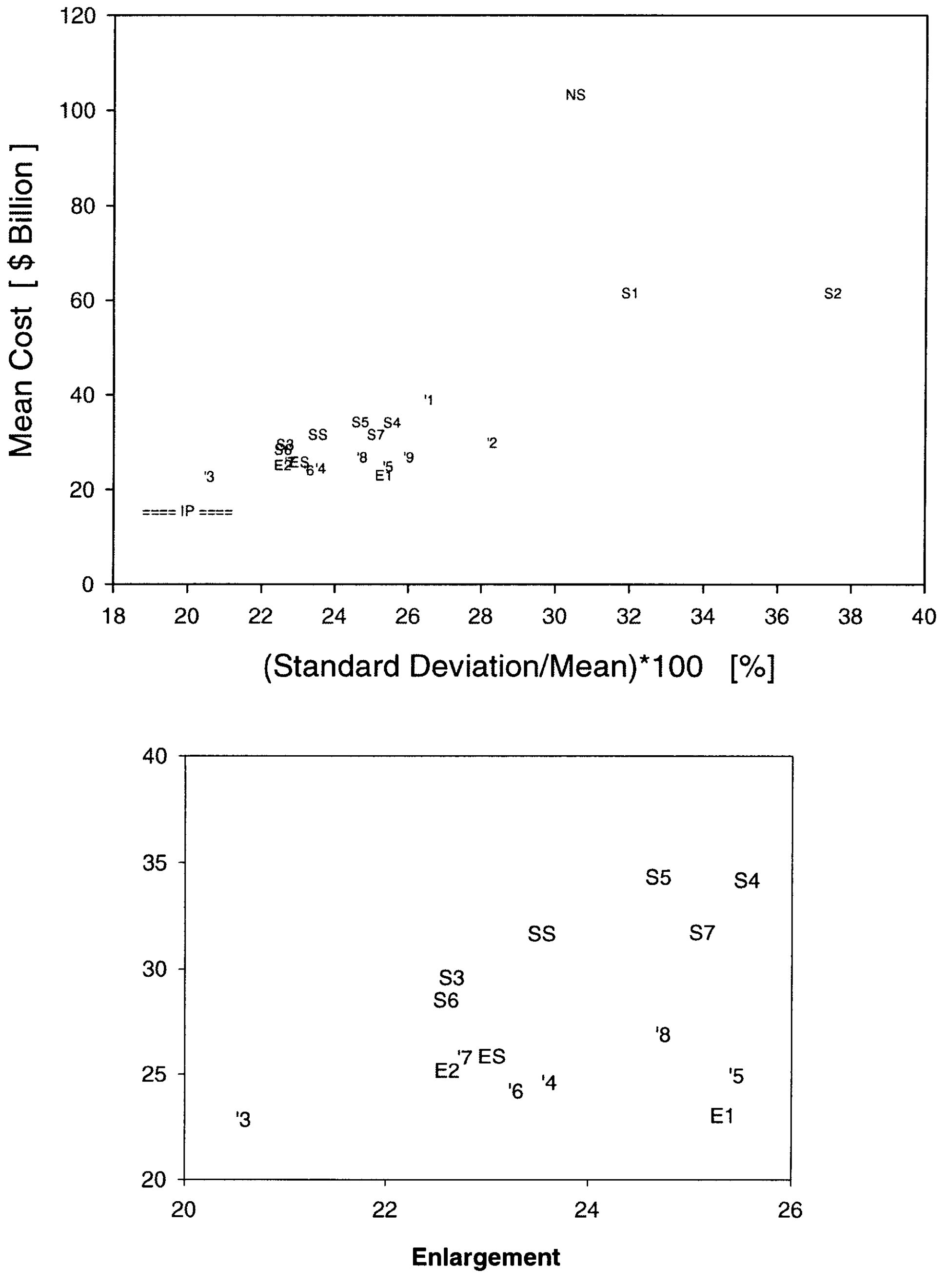

Figure 14 Mean vs. standard deviation for total program cost

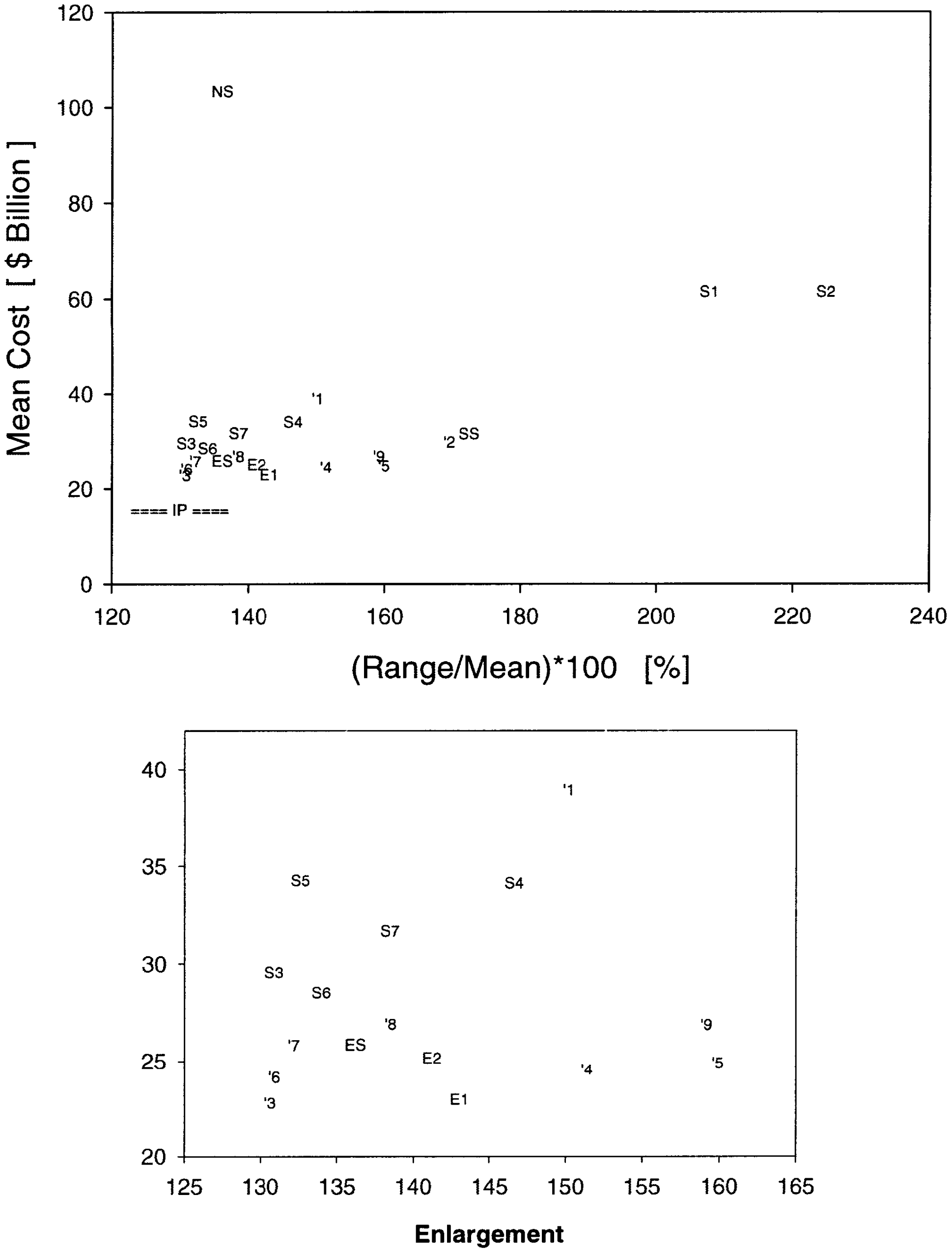

Figure 15 Mean vs. range between extreme values for total program cost

Table 8 Description of selected alternatives

Alternative	Pretreatment process and facility	Retrieval Systems for SST and DST	HLW Form and Technology	LLW Form
SS	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Sludge Wash Pretreatment Facility	24 Sluicing Systems / 12 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass (15 m^3 containers)
ES	CLEAN Advanced Separations / New Solvent Extraction Pretreatment Facility	24 Sluicing Systems / 12 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass (15 m^3 containers)
NS	No Pretreatment / Off-site Disposal	24 Sluicing Systems / 12 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Combustion Melter	No LLW form
=== IP ===	No Pretreatment / On-site Disposal	Vitrification in place		
`1	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	10 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / Joule Heated Melter	Salt Grout (5300 m^3 vaults)
`2	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	10 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m^3 vaults)
`3	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	40 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m^3 vaults)

Table 9 Description of selected enhanced sludge wash alternatives

Alternative	Pretreatment process and facility	Retrieval Systems for SST and DST	HLW Form and Technology	LLW Form
`1	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	10 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / Joule Heated Melter	Salt Grout (5300 m^3 vaults)
`2	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	10 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m^3 vaults)
`3	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	40 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m^3 vaults)
`4	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Salt Grout (5300 m^3 vaults)
`5	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m^3 vaults)
`6	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature Non-crystalline Glass / 10 MT per day Joule heated melter	Glass in Sulfur Cement (5300 m^3 vaults)

Continued on next page

Continuation of Table 9

Alternative	Pretreatment process and facility	Retrieval Systems for SST and DST	HLW Form and Technology	LLW Form
`7	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / 10 MT per day Joule heated melter	Glass in Sulfur cement (5300 m^3 vaults)
`8	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass (15 m^3 per container)
`9	Enhanced Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Enhanced Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / 10 MT per day Joule heated melter	Glass (15 m^3 per container)

Table 10 Description of advanced separations alternatives

Alternative	Pretreatment process and facility	Retrieval Systems for SST and DST	HLW Form and Technology	LLW Form
ES	CLEAN Advanced Separations / New Solvent Extraction Pretreatment Facility	24 Sluicing Systems / 12 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass (15 m^3 containers)
E1	CLEAN Advanced Separations / New Solvent Extraction Pretreatment Facility	20 Sluicing Systems / 4 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m^3 vaults)
E2	CLEAN Advanced Separations / New Solvent Extraction Pretreatment Facility	20 Sluicing Systems / 4 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass (15 m^3 containers)

Table 11 Description of selected sludge wash alternatives

Alternative	Pretreatment process and facility	Retrieval Systems for SST and DST	HLW Form and Technology	LLW Form
SS	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Sludge Wash Pretreatment Facility	24 Sluicing Systems / 12 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass (15 m^3 containers)
S1	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / Joule Heated Melter	Glass in Sulfur Cement (5300 m3 vaults)
S2	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Sludge Wash Pretreatment Facility	30 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / Joule Heated Melter	Glass in Sulfur Cement (5300 m3 vaults)
S3	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	High Temperature, Non-crystalline Glass Cullet / Gas Fired Melter	Glass in Sulfur Cement (5300 m3 vaults)
S5	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / New Sludge Wash Pretreatment Facility	20 Sluicing Systems / 2 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / 10 MT per day Joule heated melter	Glass in Sulfur Cement (5300 m3 vaults)
S6	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / Distributed Compact Process Unit	20 Sluicing Systems / 4 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / 10 MT per day Joule heated melter	Glass in Sulfur Cement (5300 m3 vaults)
S7	Sludge Wash, Cs Ion Exchange, Selective Sr & TRU Precipitation / In tank, large scale	20 Sluicing Systems / 4 Mechanical Arms / Mixer Pump	Low Temperature, Non-crystalline Glass / 10 MT per day Joule heated melter	Glass in Sulfur Cement (5300 m3 vaults)

4.3 Mean-variance evaluation of TWRS alternatives

Decision theory, [Ramsey, 34], [von Neuman, 44], indicates that ranking of alternatives should be done solely on the basis of the expected multiattribute utility (the expected utility hypothesis). The average (expectation) is taken on the physical parameters. The risk attitude of the decision maker is accounted for by the shape of the single attribute utility functions. This implies that information other than the average, contained in the probability distribution for the multiattribute utility is not relevant. A question arises as to whether a cumulative distribution function can be used for more than calculating the expected values. In this section we propose an approach that expands the use of the mean-variance method (MV) from cost to the multiattribute utility analysis.

Using the MV method for the multiattribute analysis, although it departs from classical theory, makes sense because:

- it creates a pictures easier to understand and communicate to the public,
- it takes into account uncertainty from other factors like variation of scaling and shape factors inside a given stakeholder group and
- can be used as a substitute when one does not have complete utility data.

Figure 16 presents the cumulative distribution of the multiattribute utility for three major alternatives. This cumulative distribution function was obtained by sampling distributions for a number of relevant physical parameters in the model. The multiattribute utility function was obtained by combining single dimension utility functions associated with each attribute. As we shown in a previous section, decision maker's attitude towards risk is given by the shape of the utility function. For example a concave utility function like the one presented in Figure 8 "penalizes" extreme values of the attribute. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 16 were set to the following values $\{.4,.2,.4,.4,.4,.4,.2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ were set to (0.5). Figure 17 presents the cumulative distribution function of the multiattribute utility for the risk neutral case (all $\{c_i\}$ shape factors set to zero).

Figure 18 is a mean - standard deviation representation of the multiattribute utility for three strategies. The vertical axis presents the mean of the multiattribute utility while the horizontal axis shows its standard deviation. According to the expected utility hypothesis, that recommends the ranking of alternatives based solely expected utility, the order of preference should be:

Extensive Separations $\succ$ Simple Separations $\succ$ No Separations

since

$$E(U_{ES}) > E(U_{SS}) > E(U_{NS})$$

where $E(U_{ES})$, $E(U_{SS})$ and $E(U_{NS})$ are the expected (average) utilities for three large scale retrieval alternatives. One can also note that in this case the standard deviation for "ES" is smaller than the standard deviation for "EE" which is another reason to prefer "ES" to "EE". This is not however, always the case, as we show in the next paragraph.

We will consider now two of the alternatives represented in Figure 21 : "No Separations" and "2". Alternatives "No Separations" and "2" are described in Table 8. According to expected utility hypothesis, since:

$$E(U_{NS}) > E(U_2)$$

the former alternative is to be preferred to the latter. One can note however, that although the expected value for "No Separations" is higher than the one for "2", the "No Separations" alternative is, loosely speaking, more uncertain than the other. As one can see in Figure 21 and Figure 22 both the range (difference between the extreme values) and the standard deviation for "No Separation" are larger than their "2" counterparts. Could one use a criterion that takes into account both the uncertainty (measured by the standard deviation for example) and the expected value in the same way we did for cost calculations in the previous section? This would be equivalent to imposing an extra "super"-utility on top of the multiattribute utility already in place, since one-dimensional utilities, through their shape, already discount uncertainty. This approach would depart from classical theory but may have some merit. In a previous sub-section we presented mean-variance diagrams for a single attribute: cost. The mean variance approach for the multiattribute utility that we propose in this section has the advantage of discounting risk on an overall basis.

At this stage the shapes of the single attribute utility functions for various stakeholders are not known (their evaluation is beyond the scope of this thesis). There may also be variations of the "shape factors" among members of the same stakeholder group. We performed preliminary evaluations and comparisons of several alternatives using a method illustrated in Figure 17, Figure 18 and Figure 19. In order to avoid discounting for risk twice, all single dimension utilities were made risk neutral (all $\{c\}$ shape factors were set equal to zero). The probability distributions for multiattribute utility (MAU) were derived through Monte Carlo simulation. Figure 18 is a plot a the mean, $E(MAU)$, versus standard deviation of the multiattribute utility. Figure 19 represents the expected multiattribute utility versus the range between extreme values.

The mean - variance for multiattribute utility method presented above does not necessarily represent a better procedure of ranking alternatives than the method implied by the expected utility hypothesis, but creates however a picture easier to understand and communicate to the public similar to the mean-variance representation used in finance. This method also takes into account uncertainty from other factors like variation of scaling and shape factors inside stakeholder groups.

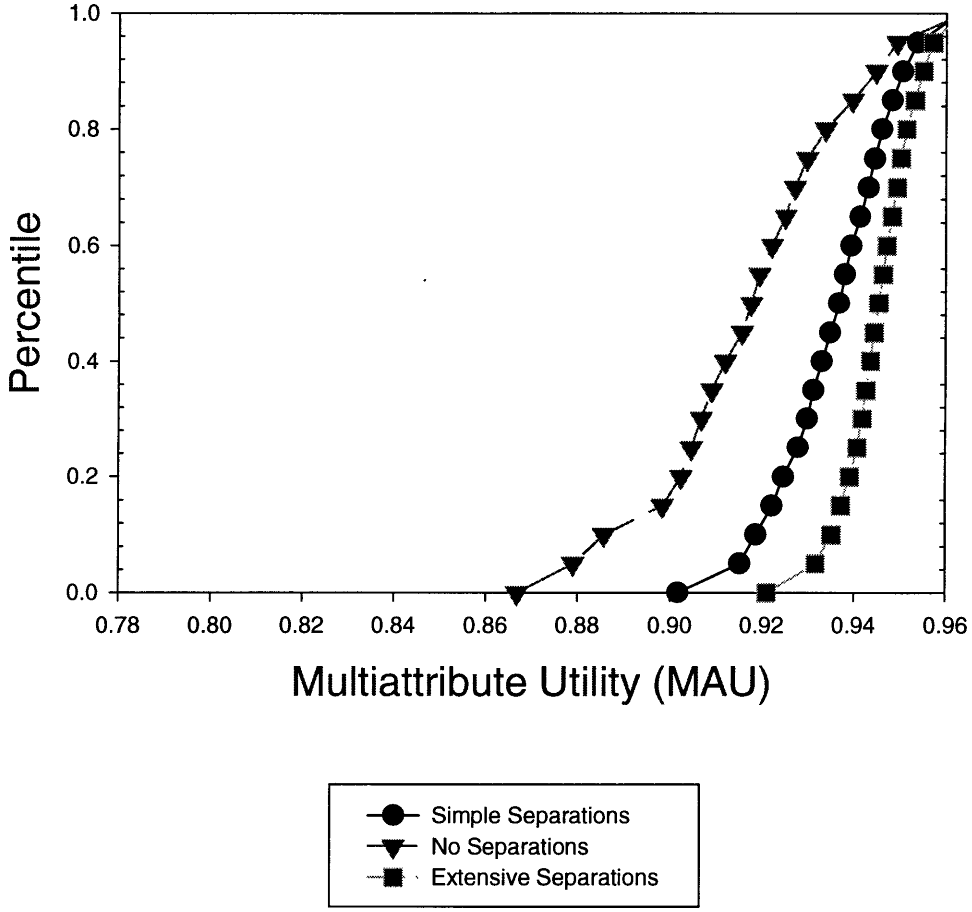

Figure 16 MAU cumulative distribution functions for three large scale retrieval alternatives

Probability distributions for multiattribute utility functions in Figure 16 were calculated using Equation 19 for the set of attributes presented in Figure 12 and section 3.2.4.3. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 16 take the following values $\{.4,.2,.4,.4,.4,.4,.2\}$. Determination of authentic utility functions (or shape factors) for various stakeholders is beyond the scope of this work; we assumed that all "shape" factors $\{c_i\}$ and $\{r_i\}$ took values of (0.5). It is noted that the "extensive separations" alternative dominates the other two options (the extensive separations procedures were not however tested under industrial conditions). As one can see on Figure 16 the "no separations" alternative is dominated by other options because of the large cost of disposing of the entire amount of waste off-site.

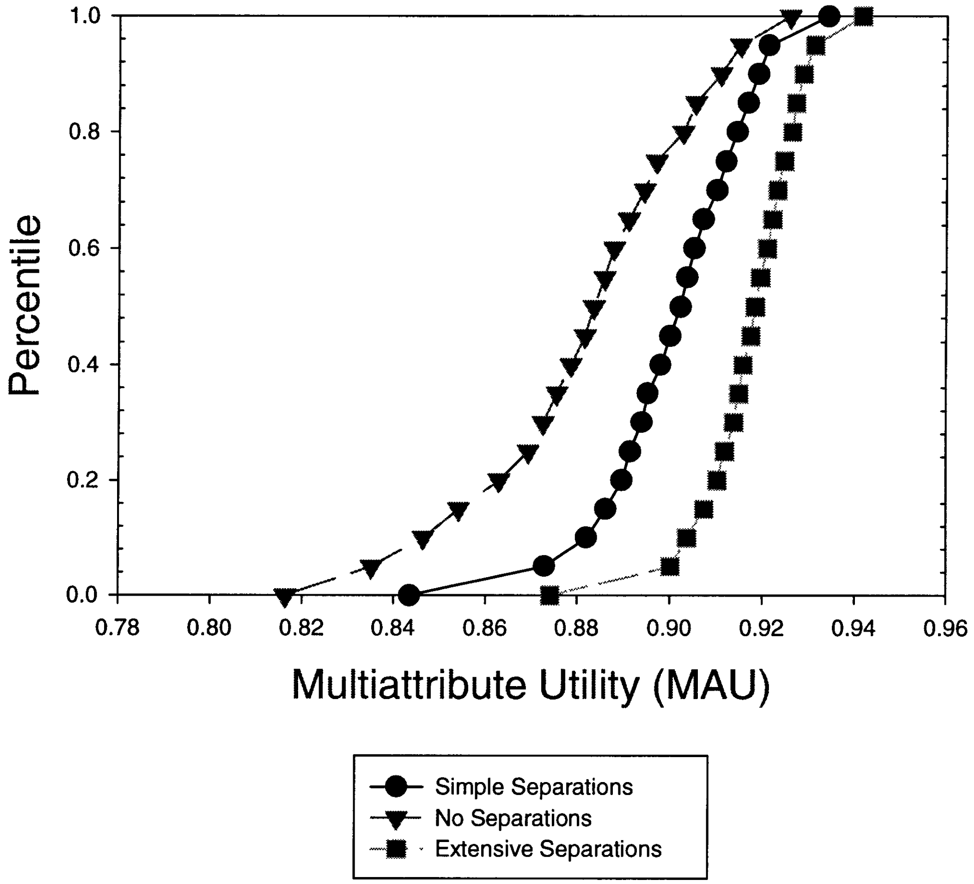

Figure 17 Cumulative distribution function for the multiattribute utility in the risk neutral case

Figure 17 is similar to Figure 16 but all the shape factors are set to zero. In this case all single attribute utility functions are considered risk neutral. One can note that probability distribution curves shifted to the left but the ranking of alternatives remained unchanged.

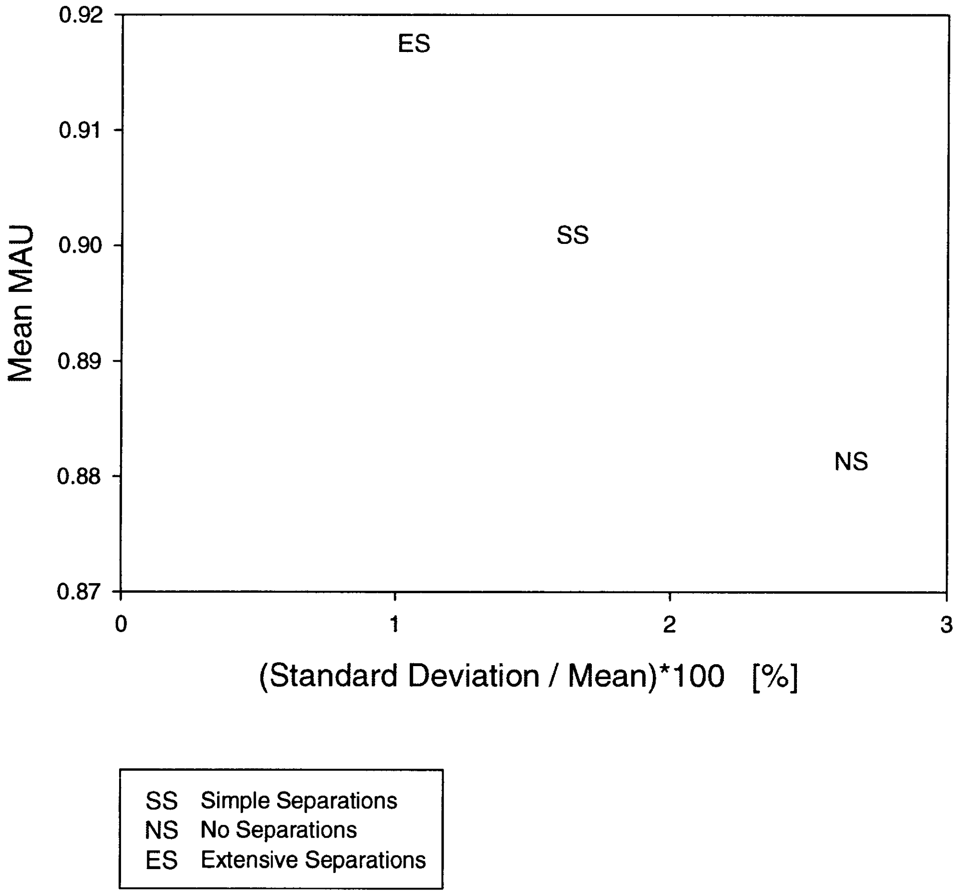

Figure 18 Mean vs. standard deviation for multiattribute utility for three major alternatives in the risk neutral case

The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 18 take the following values $\{.4, .2, .4, .4, .4, .4, .2\}$. All “shape” factors $\{c_i\}$ were set to zero.

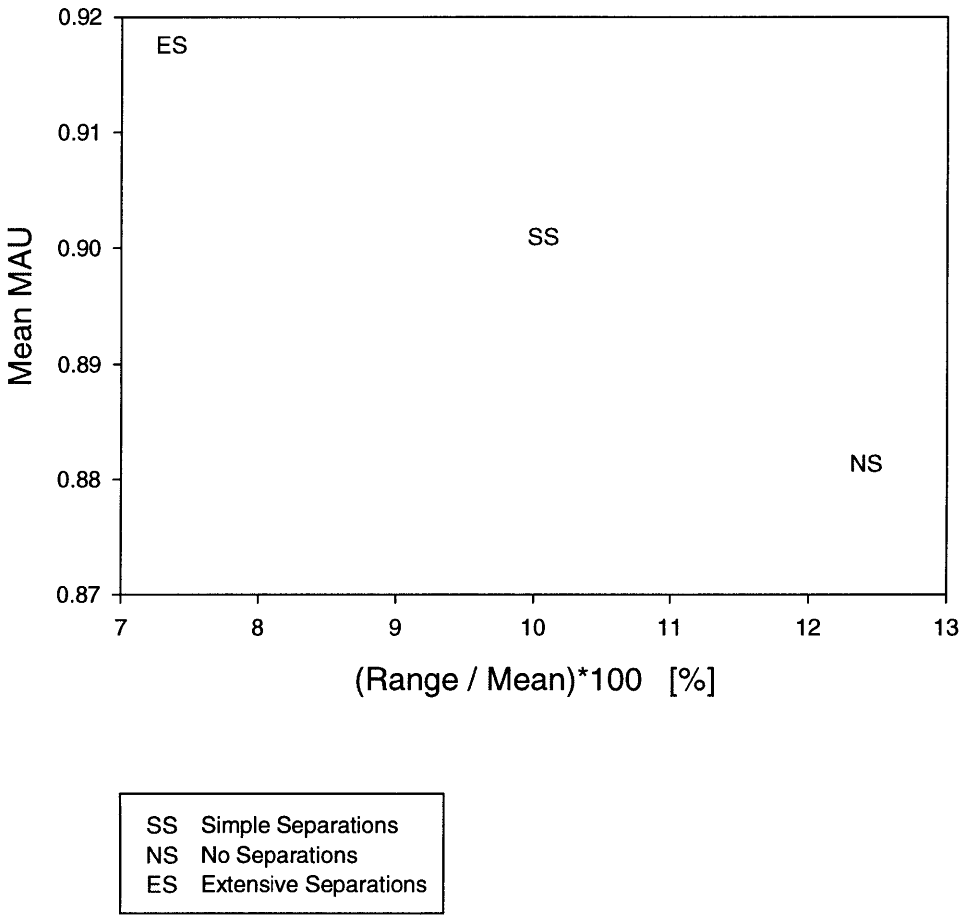

Figure 19 Mean vs. range between extreme values for multiattribute utility of three major strategies. Risk neutral case

Range is defined as the difference between extreme values of the MAU: $range = \max(MAU) - \min(MAU)$. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 19 take the following values $\{.4, .2, .4, .4, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ were set to zero.

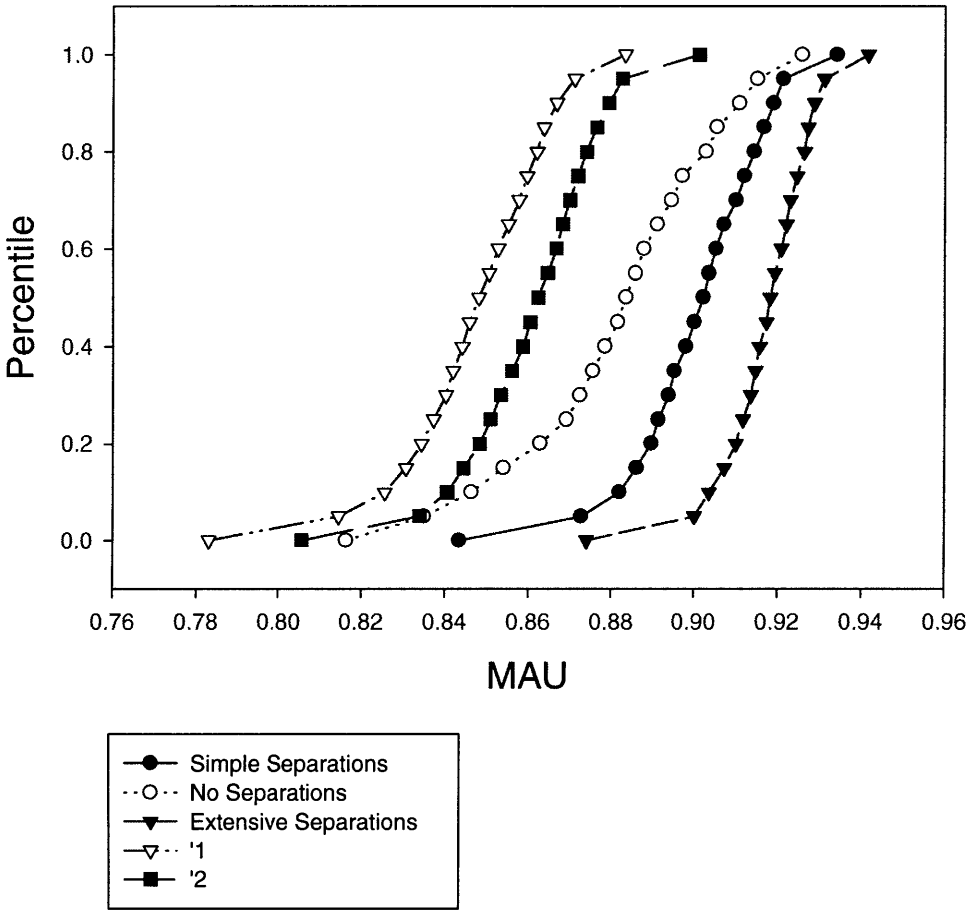

Figure 20 Cumulative distribution functions of the multiattribute utility for five alternatives

The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 20 take the following values $\{.4, .2, .4, .4, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ were set to zero. Alternatives are described in Table 8.

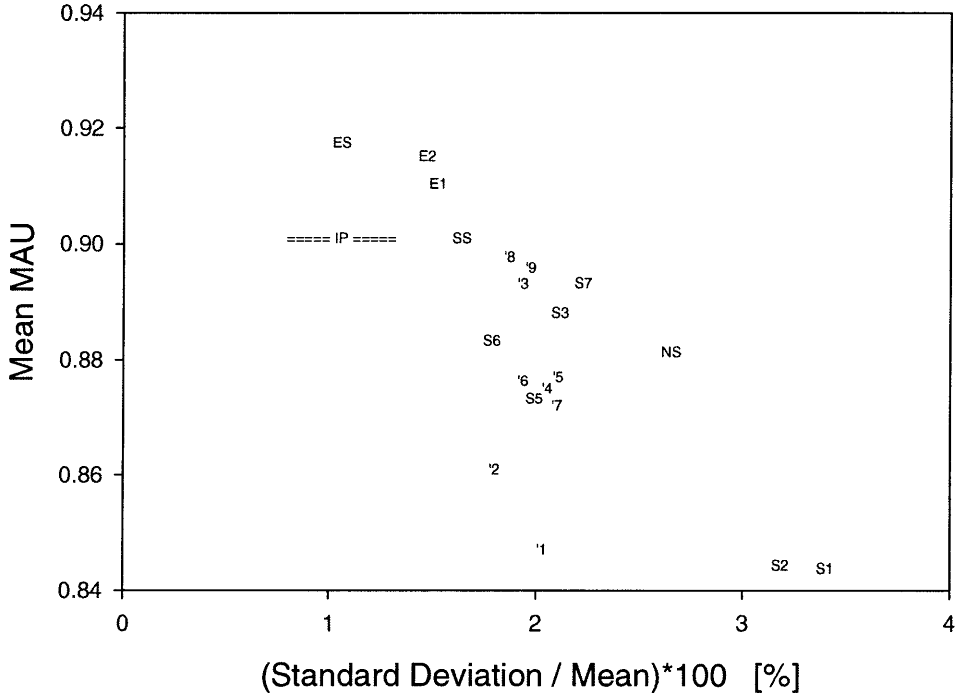

Figure 21 Mean - standard deviation diagram for multiattribute utility function in the risk neutral case, for several alternatives

The symbols used in Figure 21 are explained in Table 8, Table 9, Table 11 and Table 10. Symbols of the form “E1” refer to advanced separations alternatives, those of the form “S1” denote sludge wash alternatives while labels of the form “‘1” refer to enhanced sludge wash alternatives. The symbol “==IP==” denotes a group of alternatives that would leave most of the waste in place. The double line in the symbol === IP === is used to illustrate the fact that we only have a point estimate for the cost associated with the in place alternatives. Because the technologies involved by these options are relatively simple, it is reasonable to assume that the standard deviation of the cost for the “in place” alternatives should be lower compared with other options. The “in place” alternatives are discussed in section 4.7. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 21 take the following values $\{.4, .2, .4, .4, .4, .4, .2\}$. All “shape” factors $\{c_i\}$ were set to zero.

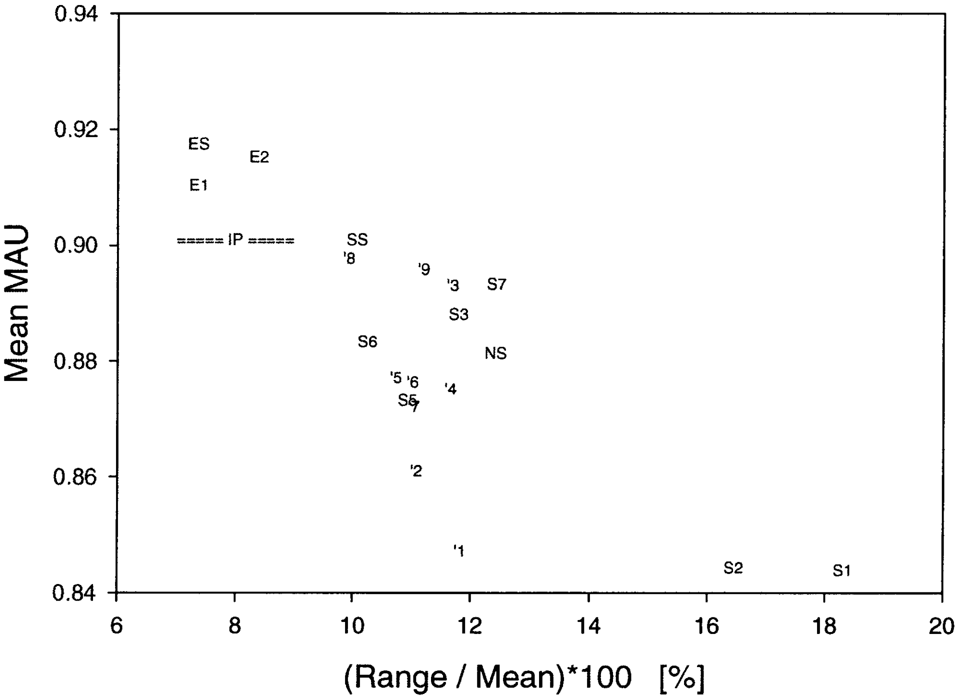

Figure 22 Mean vs. range between extreme values of multiattribute utility function for several alternatives (risk neutral case)

Range is defined as the difference between extreme values of the MAU: $range = \max(MAU) - \min(MAU)$. The symbols used in Figure 22 are explained in Table 8, Table 9, Table 11 and Table 10. Symbols of the form "E1" refer to advanced separations alternatives, those of the form "S1" denote sludge wash alternatives while labels of the form "'1" refer to enhanced sludge wash alternatives. The symbol "== IP ==" denotes a group of alternatives that would leave most of the waste in place. The "in place" alternatives are discussed in section 4.7. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 22 take the following values $\{.4, .2, .4, .4, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ were set to zero.

One can note in Figure 21 and Figure 22 that advanced separations alternatives ("ES", "E1", "E2") dominate other options in terms of expected multiattribute utility and predictability. The calculations assume however that the technologies involved by those alternatives will be successful on an industrial scale. Alternative "E2" is similar to alternative "E1" already presented in a previous with the exception of the low level waste. According to "E2" low level waste will be immobilized in glass in 15 m^3 containers; "E1" assumes that the LLW disposal form is glass in sulfur cement in 5300 m^3 vaults.

Another group of interesting alternatives is the triplet of enhanced sludge was alternatives "3", "9" and "8". All three alternatives assume the same type of pretreatment process (enhanced sludge wash in a new enhanced sludge wash pretreatment facility) but they differ in other aspects. High level waste would be immobilized in a high temperature non-crystalline glass cullet in alternatives "3" and "8" while in alternative "9" a Joule heated melter will be used to produce low temperature non-crystalline glass. The alternatives also differ in terms of the low level waste form which would be glass in the case of "8" and "9" and glass in sulfur for "3". Alternative "3" also differs from the other two by the fact that it uses 40 sluicing systems as a primary single shell tank retrieval system while the other two rely on only 20. Figure 21 and Figure 22 show that alternatives "8" and "9" dominate "3" in terms of multiattribute utility despite the fact that, as one can note in Figure 14 and Figure 15, their cost is higher and less certain than for alternative "3".

4.4 Performance profiles

Performance profiles, as used in this work, are diagrams presenting the performance of various alternatives in terms of single attribute utility functions. These diagrams are particularly useful in comparing alternatives on an attribute by attribute basis and in understanding the reasons for the differences in the multiattribute values of different alternatives. Figure 23 presents a "performance profile" for the three alternatives considered throughout this chapter: "Simple Separations", "No Separations" and "Extensive Separations".

The seven attributes of interest in Figure 23 are **C** - cost, **D** - schedule, **S** - regional socioeconomic impact, **L** - land use (dominated by the volume and radioactivity of the waste stored on site), **P** - health effects on public, **W** - health effects on workers, **E** - extra-regional impact (dominated by the volume of waste shipped off-site). These attributes are presented in more detail in Figure 12 and section 3.2.4.3.

As shown in Figure 23, the “No Separations” alternative costs more (attribute **C**), will take a shorter time to complete (**D**), leaves the minimum amount of waste on site (**L**) and is less hazardous for workers on site (**W**). It fares however poorer on the external impact attribute (**E**) because of the large amount of waste that will have to be shipped off-site. Alternative “Simple Separations” has a performance profile similar to “Extensive Separations” alternative with the exception of the land use attribute (**L**).

By examining Figure 23 one can also realize that the reasons for the “No Separations” (NS) alternative’s relative poor performance in terms of multiattribute utility (as shown in Figure 21 and Figure 22) are the cost (**C**) and external impact (**E**) attributes. “No separations” alternative would imply sending the entire amount of vitrified waste to an external repository. The repository disposal fee represents a major fraction of the total program cost. A new no-separations alternative that would leave all the vitrified waste on site would be less costly and would fare better in terms of the external impact attribute.

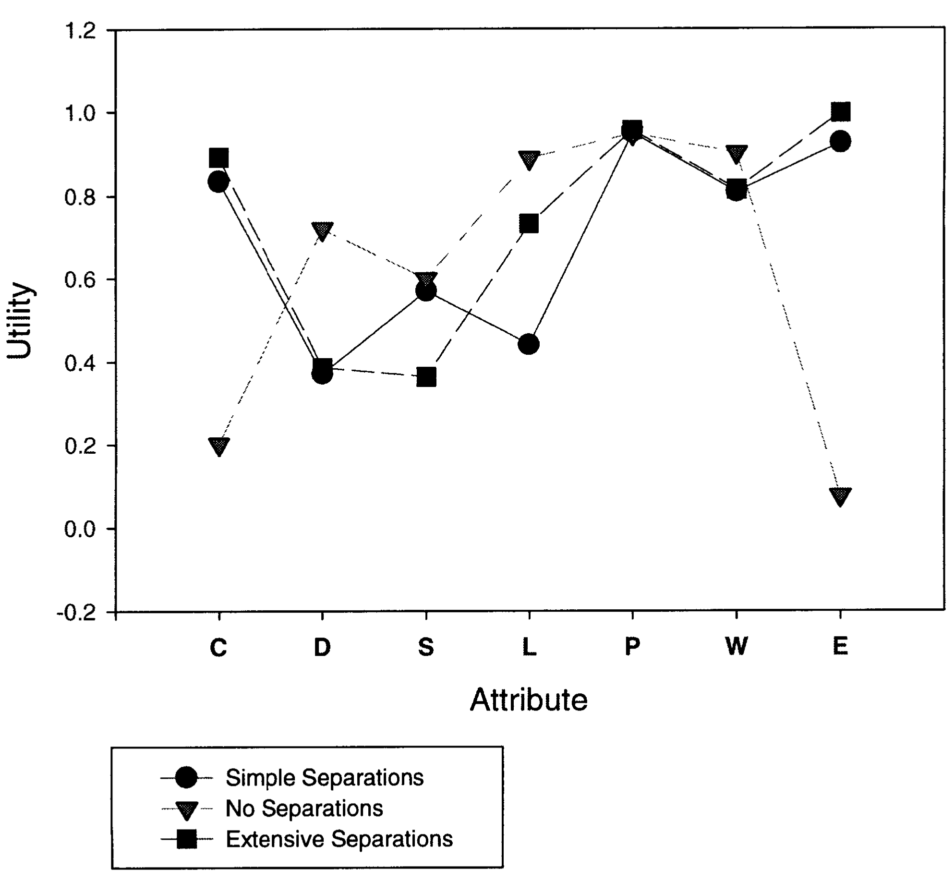

Figure 23 Performance profile for three large scale retrieval alternatives. Single attribute utilities for seven attributes

The symbols used for attribute are: **C** - cost, **D** - schedule, **S** - regional socioeconomic impact, **L** - land use, **P** - health effects on public, **W** - health effects on workers, **E** - extra-regional impact. The attributes are presented in more detail in Figure 12 and in section 3.2.4.3.

4.5 Sensitivity to attribute scaling factors and to "shape factors"

Another issue to be considered is the sensitivity of the mean MAU (the average being taken on physical parameters) to non-"physical" factors like scaling parameters and shape factors. Multiattribute utility of a certain stakeholder s, as calculated by Equation 19 or Equation 23 is a function of the set of "physical" parameters $\{x_i\}$ and depends on other items like scaling factors $\{k_i\}$ and shape factors $\{r_i\}$ and $\{c_i\}$, that appear in the calculation:

$$U^s = U(\{x_i\},\{k_i^s\},\{c_i^s\},\{r_i^s\},\{a_i\},\{b_i\}) \qquad \textbf{Equation 53}$$

For the purpose of the present model each stakeholder is identified by the following vector:

$$H^s = (\{k_1^s,\ldots,k_n^s\},\{c_1^s,\ldots,c_n^s\},\{r_1^s,\ldots,r_n^s\}) \qquad \textbf{Equation 54}$$

The study of the sensitivity of multiattribute utility MAU to scaling $\{k_i\}$ and shape factors $\{r_i\}$ and $\{c_i\}$ is important because of the following reasons:

- It allows the decision maker to simulate the behavior of various stakeholders and identify the optimal decisions from his point of view. This would allow DOE to better negotiate with other stakeholders by using methods derived from Game Theory[30].
- Identifies attributes and parameters that are important enough to warrant elicitation.
- Given that stakeholder preferences might change over time, sensitivity analysis shows how the change of their preferences will change their ranking of alternatives.
- There may be variations of preferences inside each stakeholder group. The use of this method will allow the study of the impact that certain factions in the group might have on the final group position.

4.5.1 Sensitivity to shape factors *r* and *c*

Figure 24 presents the variation of the expected MAU (expectation taken on physical parameters) to shape factors $\{r_i\}$ and $\{c_i\}$. What would be the use of such an approach? Shape factors are

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[30] A "natural" extension of the model would be to introduce elements of Game Theory

different for different groups of stakeholders but can also vary within the same group. In addition, decision maker preferences may change over time. If for example DOE had to choose between two strategies "A" and "B" with about the same expected utility (calculated through Monte Carlo sampling of physical parameters), and the expected utility $E(MAU)$ for "A" is more sensitive to shape factors than $E(MAU)$ for "B", the choice should probably be the latter option: "B".

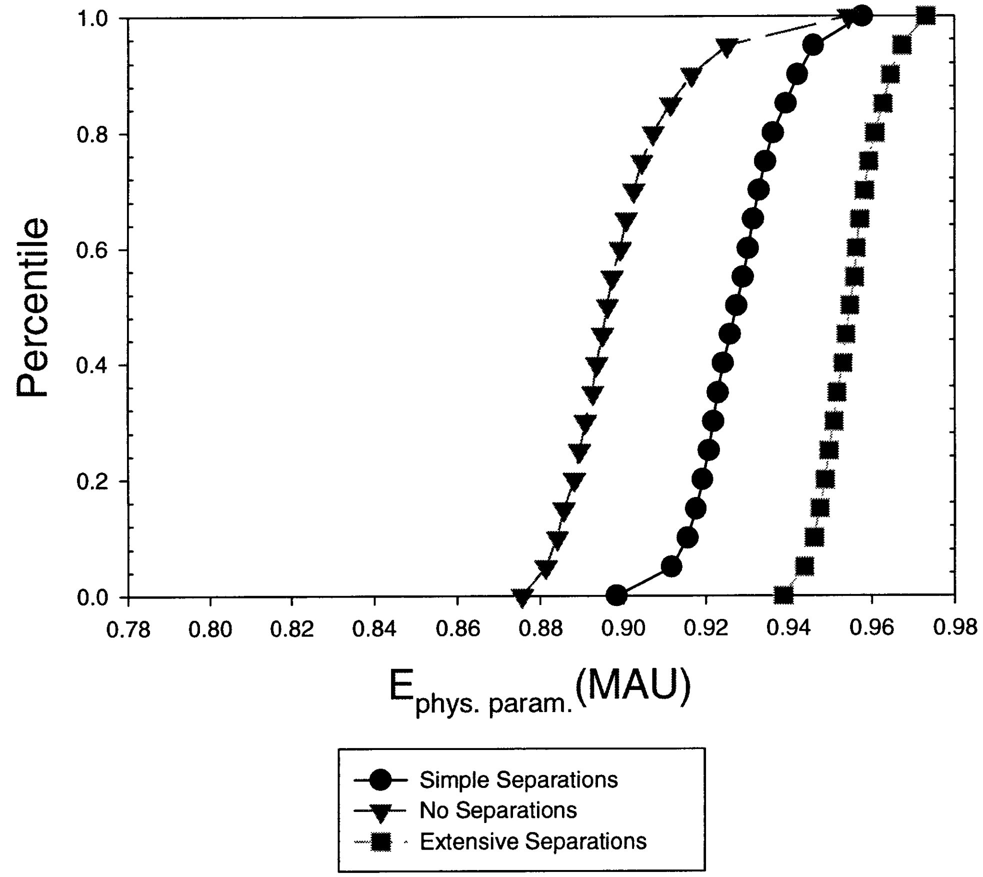

Figure 24 Sensitivity of MAU to "shape factors" {r} and {c}

Variation of expected multiattribute utility $E(MAU)$ with shape factors $\{r\}$ and $\{c\}$. The average is taken on "physical parameters". The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 24 take the following values $\{.4, .2, .4, .4, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ took values distributed uniformly in the range (.05,.95).

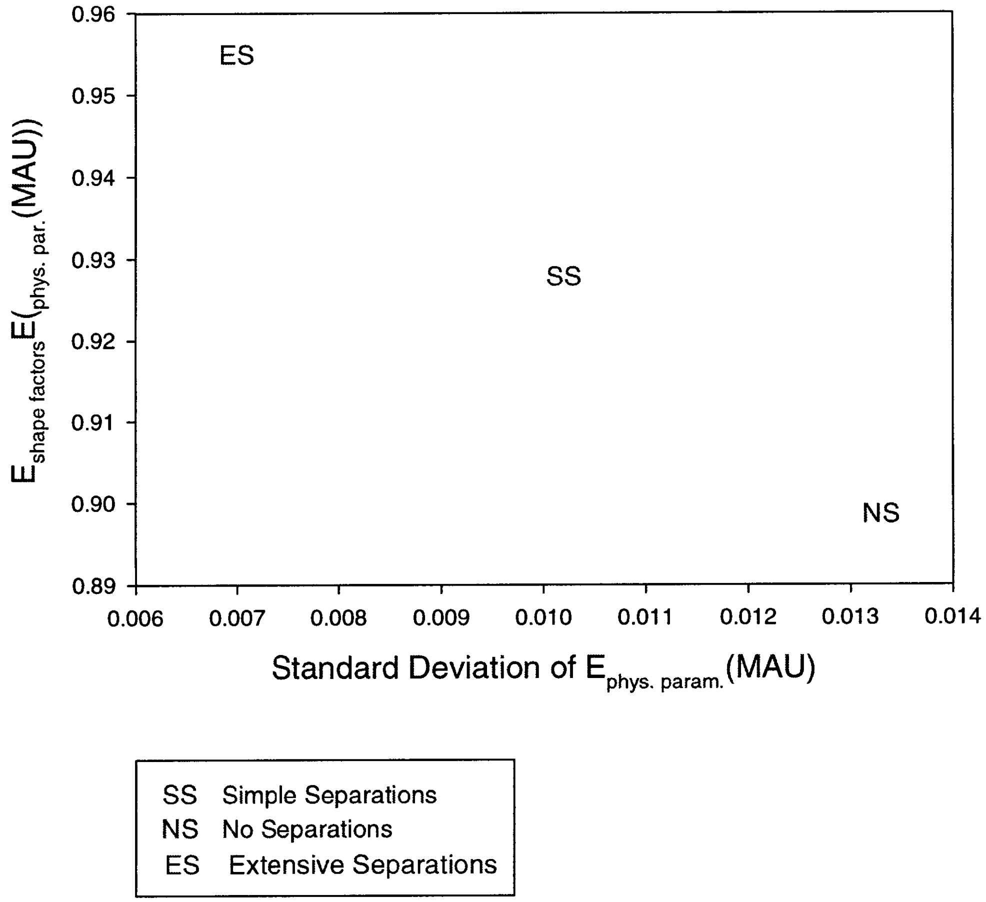

Figure 25 Average on shape factors versus standard deviation of expected* utility

* Average on "physical parameters". The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 25 take the following values $\{.4,.2,.4,.4,.4,.4,.2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ took values distributed uniformly in the range (.05,.95).

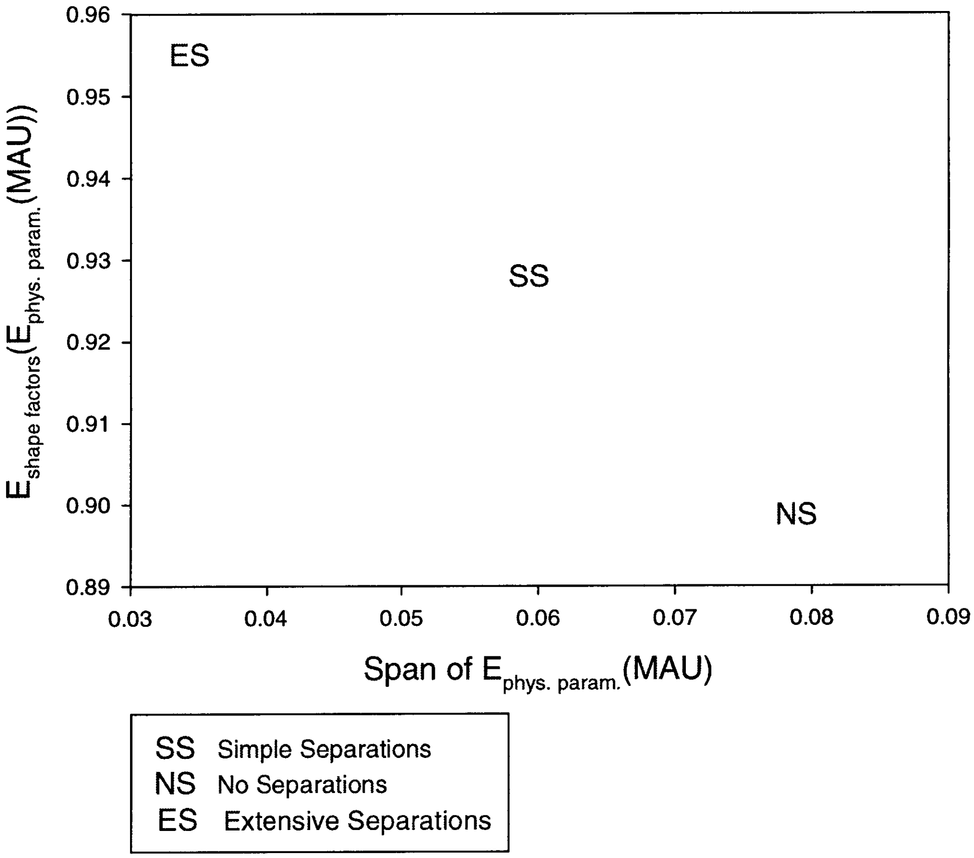

Figure 26 Average on shape factors versus the range* of expected utility

* Range is defined as the difference between the maximal and the minimal values. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 26 take the following values $\{.4,.2,.4,.4,.4,.4,.2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ took values distributed uniformly in the range (.05,.95).

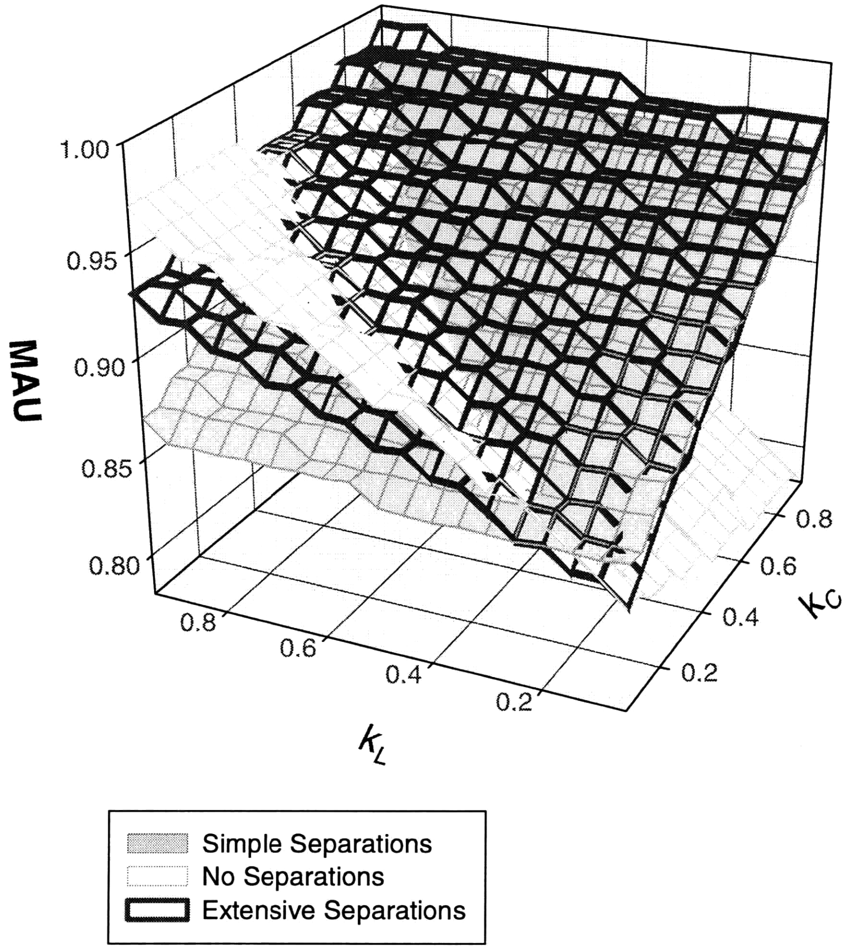

Figure 27 Sensitivity of multiattribute utility function to cost and land use scaling factors for three large scale retrieval alternatives.

4.5.2 Sensitivity to attribute scaling factors

4.5.2.1 Sensitivity to two scaling factors

Figure 27 represents a sensitivity analysis of the multiattribute utility function (nominal[31] MAU) to two scaling factors. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 27 take the following values $\{k_C, .2, .4, k_L, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ were set to (0.5). One can note that the optimal strategy (the alternative that has highest utility) varies dramatically with the scaling factors. For example, stakeholders that place a high emphasis on the environmental impact on the Hanford site ("Land use" attribute) and are less concerned about cost, would conclude that the best strategy to follow is one in the "No Separations" group. Under the "No Separations" scenario almost all the tank waste would be sent off site. As a stakeholder becomes more interested about cost (higher cost scaling factor k_C), "Extensive Separations" and "No Separations" alternatives become more appealing. As one can see on the graph, "Extensive Separations" dominates "Simple Separations" for many cost - land use scaling factors combinations. For very small values of k_L the two alternatives look identical.

There is however one caveat: not all the technologies implied by "Extensive Separations" class of alternatives have been developed or tested under industrial conditions. Consequently, by choosing an alternative in this class one would risk a possible failure of the technological process. In this situation a simpler, proven, contingency alternative would have to be followed (probably one in the "Simple Separations" group). Starting with an uncertain technology, reaching a dead-end and then continuing with a fall-back strategy might result in delays and higher financial and environmental costs. The expected cost might be calculated as a follows:

$$C = p \cdot C^{ES} + (1-p) \cdot (1+f) \cdot C^{SS}$$ **Equation 55**

---

[31] We define the nominal value of the multiattribute utility (MAU) as the MAU calculated using the average values of the uncertain parameters. This nominal value is not necessarily the average (expected) value of the multiattribute utility. (i.e. given that $U = f(z_1, z_2, \ldots z_q)$, $f(\bar{z}_1, \bar{z}_2, \ldots, \bar{z}_q)$, named "nominal" value throughout this document of the multiattribute utility U is not necessarily equal to the expected value $\overline{U}$.

Symbol p represents the probability that technologies involved in alternative ES will be successful while f is a strictly positive factor related to additional costs due to the transition from one technology to the other. Evaluating factors p and f is beyond the scope of the present work.

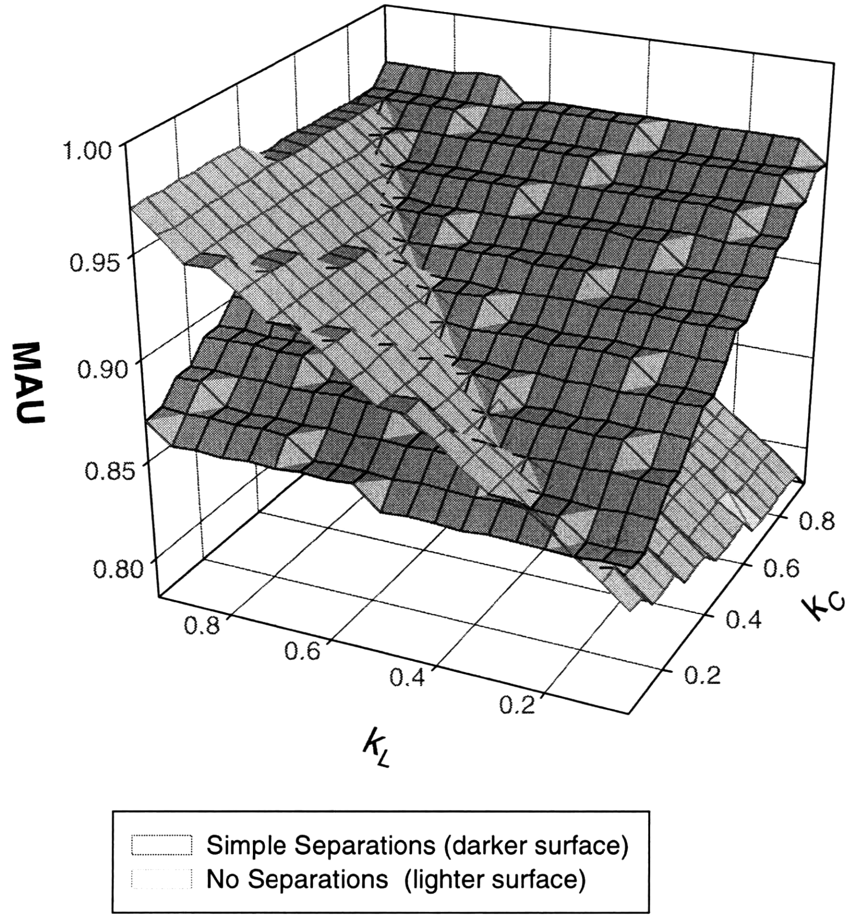

Figure 28 Sensitivity of multiattribute utility to cost and scaling factors for "simple separations" and "no separations" alternatives

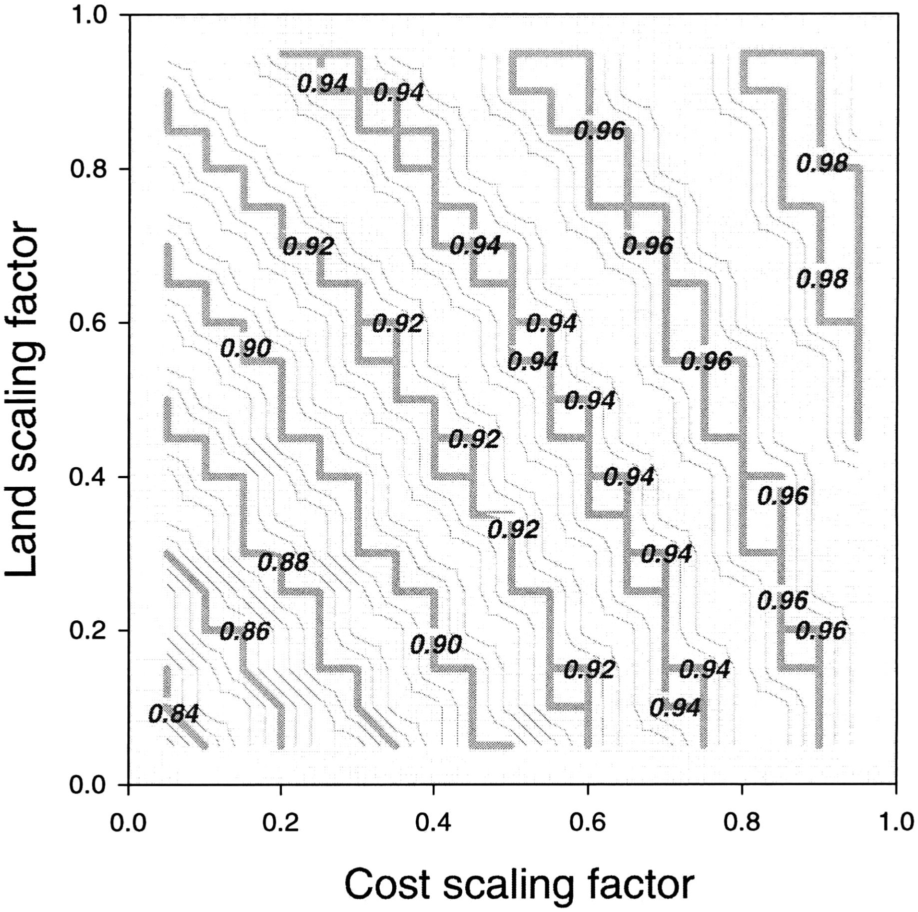

Figure 29 Contour plot: multiattribute utility for "extensive separations" alternative as a function of cost and land use scaling factors

Figure 29 shows that alternative "Extensive Separations" becomes more desirable (has a higher multiattribute utility) as stakeholders become more concerned about cost and land use. The multiattribute utility function associated with this alternative attains the highest value in the north east corner of the diagram. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 29 take the following values $\{k_C, .2, .4, k_L, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ were set to (0.5).

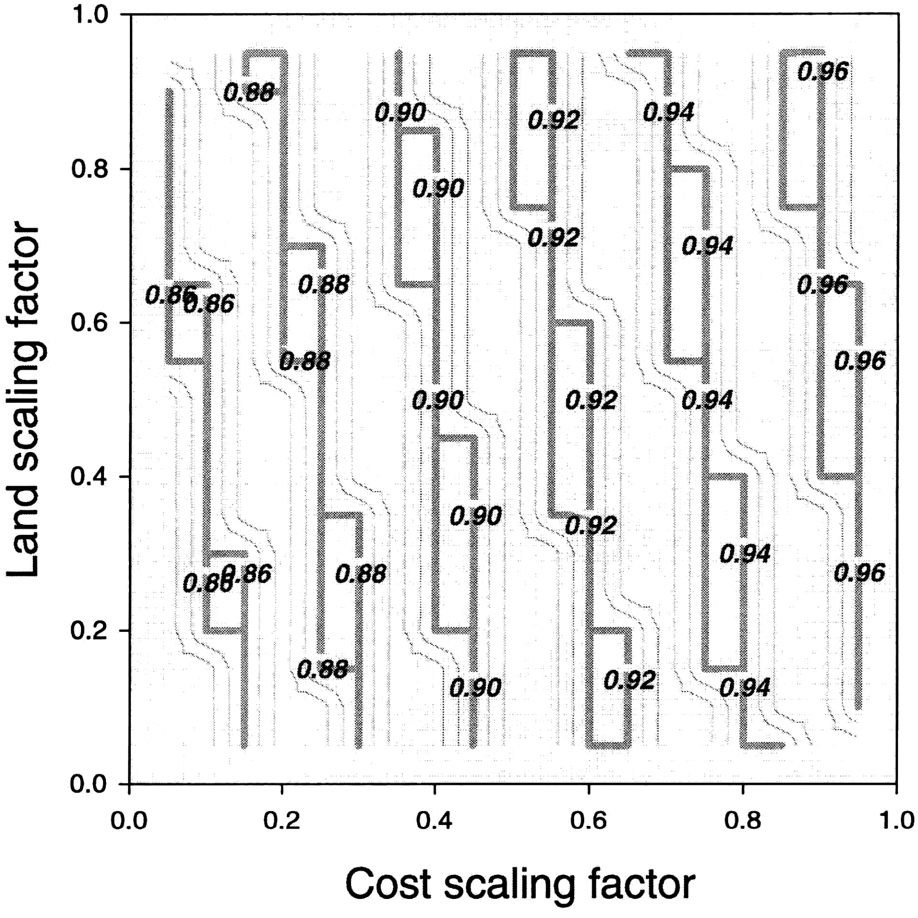

Figure 30 Contour plot: multiattribute utility for "simple separations" alternative as a function of cost and land use scaling factors

Figure 30 shows that "Simple Separations" alternative becomes more desirable as the sensitivity to cost increases but its multiattribute utility is less sensitive to the land use factor. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 30 take the following values $\{k_C, .2, .4, k_L, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ were set to (0.5).

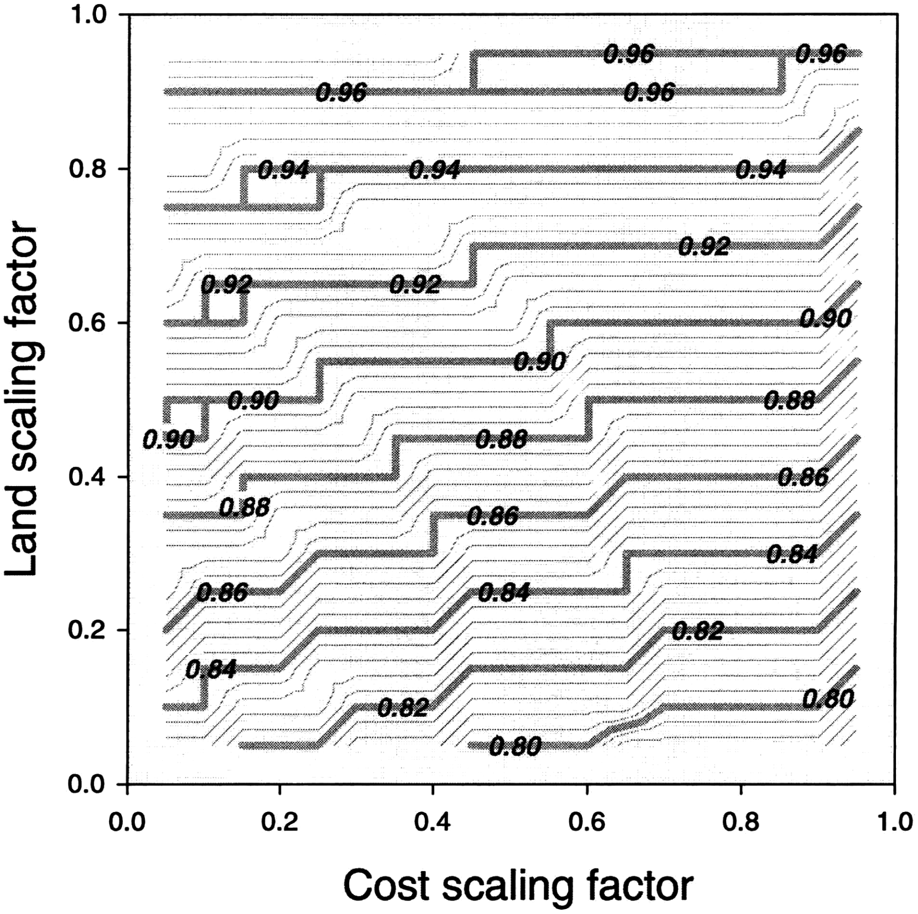

Figure 31 Contour plot: multiattribute utility for "no separations" alternative as a function of cost and land use scaling factors

Figure 31 shows that the desirability of the alternative "No Separations" (as measured by the multiattribute utility) depends strongly on the emphasis a stakeholder places on land use and less on the cost factor. As cost becomes more important the desirability of the alternative decreases slightly (the land use scaling factor k_L being kept constant). The scaling coefficients $\{k_C,k_D,k_S,k_L,k_P,k_W,k_E\}$ used in the calculations for Figure 31 take the following values $\{k_C,.2,.4,k_L,.4,.4,.2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ were set to (0.5).

4.6 Sensitivity to cost factor

As one can see in Figure 32 for low values of k_C, i.e. for stakeholders that are less concerned about the cost, alternative "No Separations" dominates the other alternatives. If cost becomes important this alternative is dominated by the other two. The scaling coefficients $\{k_C, k_D, k_S, k_L, k_P, k_W, k_E\}$ used in the calculations for Figure 32 take the following values $\{k_C, .2, .4, .4, .4, .4, .2\}$. All "shape" factors $\{c_i\}$ and $\{r_i\}$ were set to (0.5).

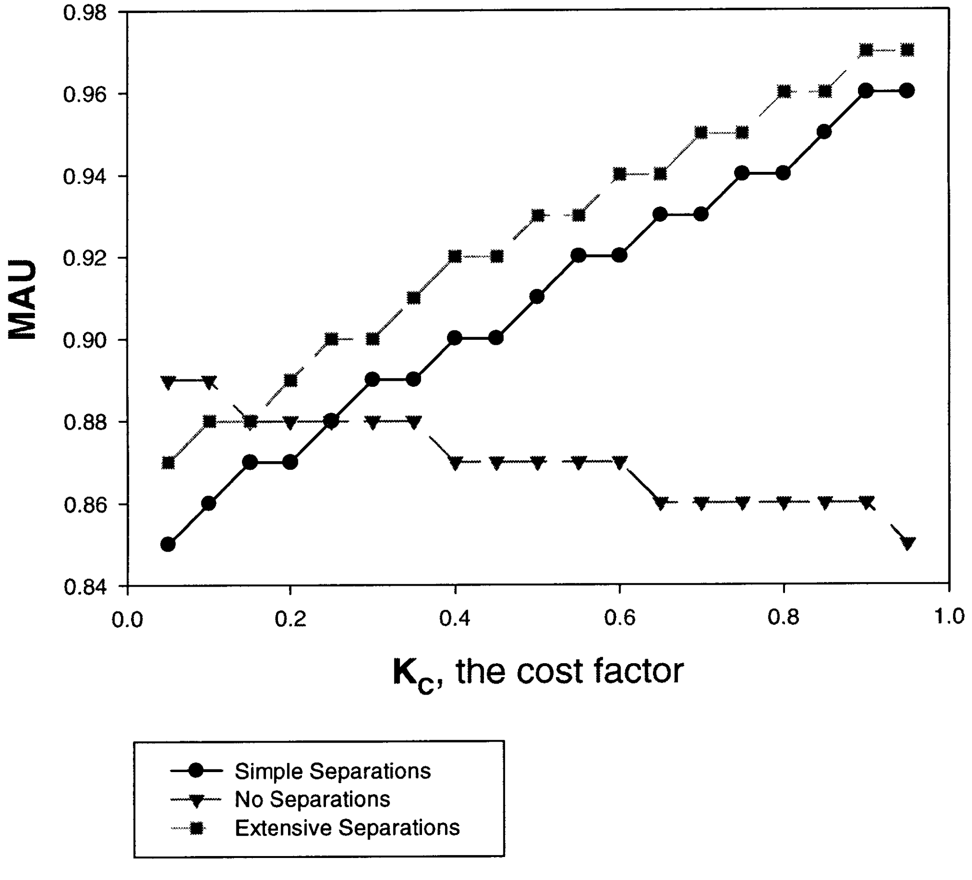

Figure 32 Sensitivity of multiattribute utility to cost scaling factor

4.7 "In place" option

The in-place scenario involves minimal retrieval of material from tanks. Two major alternatives "vitrification in place" and "tank filling" belong to this category. In both cases most of the waste would remain in place. According to the "vitrification in place" scenario, most of the tank waste would be immobilized in place by vitrifying the tanks and their contents. In the "tank filling" alternative waste would be stabilized by removing the liquids from tanks, filling the tanks with gravel and building a barrier over tank farms. The DOE cleanup agreements with the State of Washington and the Environmental Protection Agency require that the tank waste be removed from the site. Implementation of either "in-place" option would require some form of regulatory relief.

The model, at least in the present version, does not allow for detailed calculation of probability distribution functions for cost in the case of on-site alternatives as it permits for other cases presented in previous sections. In this case we had to rely on point estimates for cost available from references like [DOE, 95].

Figure 14 and Figure 15 allow a comparison of the estimated costs for "in place" options[32] to the costs associated with other alternatives. One can see that the "in place" alternative dominates other strategies in terms of expected nominal cost[33]. One can also argue that the uncertainty in calculating the nominal costs for the "in place" options would not in any case exceed the uncertainty in the calculation of costs for other alternatives, i.e. the points representing the two strategies should lie south-west of "3". This is due to the fact that the on-site alternatives make use of more mature technologies (unlike "extensive separations" alternative). The costs associated with the "in place" options are much lower than for other alternatives due to various reasons. One of those reasons is that in the "in place" scenario, waste does not have to be shipped off-site. In addition to a lower cost, containment in place option would pose fewer health risks to clean-up workers, because most of the waste will not have to be retrieved from tanks. Removing the entire content of the tanks and sending the high level waste off-site would have long term health benefits to the public but those benefits might be very well outweighed by the health risk to workers retrieving waste from the tanks. Figure 33 is a performance profile of the "in place" alternatives with respect to seven attributes.

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[32] The symbol associated with the "in place" alternative is "=== IP ==="

[33] We assume that the "nominal" values given in [DOE,95] are mean values.

The seven attributes of interest in Figure 33 are **C** - cost, **D** - schedule, **S** - regional socioeconomic impact, **L** - land use (dominated by the volume and radioactivity of the waste stored on site), **P** - health effects on public, **W** - health effects on workers, **E** - extra-regional impact (dominated by the volume of waste shipped off-site). These attributes are presented in more detail in Figure 12 and section 3.2.4.3.

As shown in Figure 33, the "in place" alternative costs less (attribute **C**), will take a shorter time to complete (**D**), and is less hazardous for workers on site (**W**). A trade-off will have to be made however between the long term health effects on public (where the "in place" alternatives fares worse) and other attributes. The other in place alternative, "tank filling" or "fill and cap" is expected to cost even less and has a similar performance profile.

The present analysis of the in place options is by no means complete. It led us however to the conclusion that this class of alternatives should be given further consideration. One should emphasize that calculations for this alternative are preliminary and further study is necessary. Development and use of containment in place technologies will be necessary under any scenario. Other alternatives would also have to use underground barriers and similar containment in place technologies to prevent migration of radionuclides from tanks that already leaked or would leak during retrieval operations. Even under the most aggressive retrieval strategies contaminated material will still remain in place. For example emptied tanks will remain in place since it would be too costly and too dangerous for personnel to dig them out. Given its reduced cost and risk one can conclude that there is substantial merit in pursuing the "in place" option in more detail despite present DOE commitments.

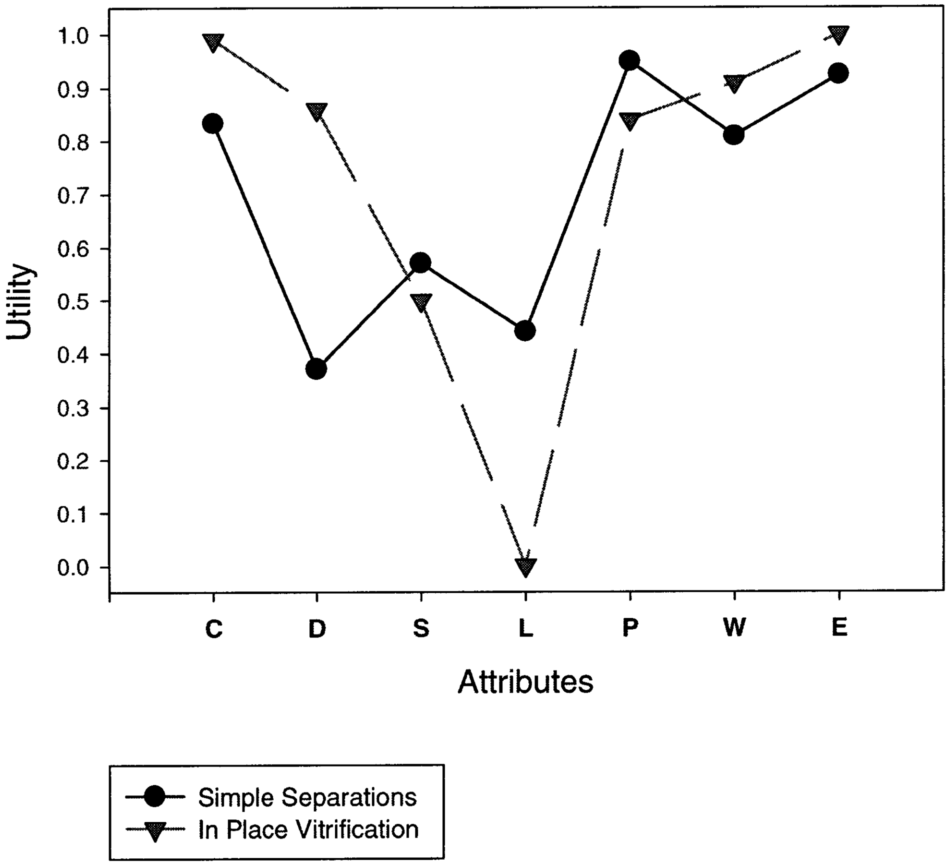

Figure 33 Performance profile for "In Place Vitrification" and "Simple Separations" alternative

The symbols used for attribute are: **C** - cost, **D** - schedule, **S** - regional socioeconomic impact, **L** - land use, **P** - health effects on public, **W** - health effects on workers, **E** - extra-regional impact. The attributes are presented in more detail in Figure 12 and section 3.2.4.3.

5. Conclusions and Recommendations

5.1 Conclusions

In this work we created an integrated multiattribute decision analysis model of the Hanford Tank Waste Remediation System (TWRS) to evaluate several clean-up alternatives, we suggested a new approach to decision making when uncertainties are large and used the model to identify strategies with higher values of the multiattribute utility.

5.1.1 The Model

The model, named MAATWRS, is intended to help decision makers consider the best solutions by providing insight into the implications of uncertainty and stakeholder preference. MAATWRS represents a complement to the deterministic approach. Specifically this model allows decision makers to:

- evaluate a wide range of TWRS strategies
- analyze tradeoffs among multiple attributes (like duration, costs, environmental impact, etc.)
- test strategies' robustness using sensitivity analysis methods
- search for better alternatives.

The model would also allow a decision maker to simulate the behavior of other interested parties and identify the optimal decisions from their point of view.

The decision model can be broken conceptually into two parts. The first part, “Physical Model”, associates to each of the available alternatives a set of consequences (that might happen with a certain likelihood). The second part evaluates the desirability of various sets of consequences. The two parts, in combination, determine the relative merits of the alternatives.

The model incorporates several modules: cost, socioeconomic impact, land use, health effects on public and workers, extra-regional impact, single and multiattribute utility functions, etc. One of its modules, “Ins” is based on the “Insight” model from Westinghouse Hanford [Johnson, 93], [McConville, 95]. Data used for building other modules come from various DOE documents like [DOE, 94], [DOE, 95], [Boomer, 93]. The computer model is built using a combination of Excel, Visual Basic, @Risk and DPL.

The present model has the following characteristics:

- It uses multiattribute utility analysis to evaluate tank waste strategies.
- It is comprehensive. The essence of this work is to perform an integrated, general analysis. This allows a rigorous and disciplined process of decision making with respect to TWRS strategies. Nevertheless the model has to remain simple enough to be manageable. One has to make the right trade-off between complexity and the integral view.
- It remains simple. Final decisions will, of course, be taken after analyzing in more detail the options identified with a simpler model. Performing extremely detailed analyses however, may be computationally expensive and often unnecessary in the early stages of the decision making process. A simplified model is portable, runs on readily available machines and, in consequence, can be reviewed by (and is able to collect input from) a broad array of people. Such a simplified model helps the decision maker identify early in the project which areas need a more detailed treatment and which do not.
- It has the capability to perform sensitivity analyses and test the strategies' robustness. The model allows the user to investigate whether the optimal TWRS strategy changes when certain parameters change. The proposed solutions should be acceptable even under extreme circumstances. There are uncertainties associated with the parameters involved in risk, cost and duration calculations.
- It has the capability to simulate the preferences of various stakeholders. It would be very helpful for the decision makers in DOE to be able to simulate in advance the behavior of different stakeholders in order to identify the strategies that might have a better chance of being accepted by all interested parties. Scaling coefficients k_i used in calculating the multiattribute utility function and factors determining the "shape" of single attribute utilities have a high impact on the choice of an optimal strategy. This is one of the reasons for decoupling the sensitivity study of "physical parameters" from the sensitivity analysis of scaling and "shape" coefficients. Different stakeholders might have different sets of scaling coefficients and utility functions. By changing the nominal values of scaling and shape factors the decision maker might play the role of various stakeholders and find the optimal decision from their point of view.
- It is a tool to identify new alternatives. Another purpose of the model is to help in identifying new strategies with an increased value of the multiattribute utility function.

- The model is flexible due to its modular structure. This makes it a good starting point for a larger scale integrated model. It can be refined and expanded as more data becomes available. The same methodology may be used to analyze other TWRS activities.

5.1.2 A proposed decision analysis approach

We introduced a mean-variance (MV) method for multiattribute utility, to compare alternatives (inspired by the portfolio optimization theory used in finance) and created "performance profiles" for various options. The MV method does not necessarily represent a better procedure of ranking alternatives than the usual method implied by the expected utility hypothesis. It is, however, an approach easier to understand and communicate to the public.

5.1.3 Findings

Throughout Chapter 4 we illustrated the general method by presenting several applications. We considered for illustration purposes three classes of large scale retrieval alternatives: "Simple Separations", "No Separations" and "Extensive Separations". The analysis revealed that "No separations" approach has the lowest value of the multiattribute utility mainly due to the high cost associated with disposal of all the vitrified waste in a national geologic repository. Advanced separations alternatives dominate other options in terms of expected multiattribute utility and predictability. The calculations for advanced separations assumed, however, that the technologies involved by those alternatives will be successful on an industrial scale. We performed sensitivity analyses of multiattribute utility to scaling and shape factors. The optimal strategy (i.e. the alternative with the highest utility among those three major strategies) varies dramatically with cost and land use scaling factors. "Extensive Separations" dominates "Simple Separations" for many cost - land use scaling factors combinations.

We also presented results of the analysis of other scenarios. Using an approach based on genetic algorithms we searched for alternatives with a reduced program cost.

A particularly interesting option is the "In Place" alternative. According to this option all or most of the tank waste should be left or treated in place. This alternative is clearly in contradiction with the Tri Party Agreement and other regulations but has the advantage of a lower cost. In addition, the costs are easier to predict because the procedures implied by those alternatives are relatively simple. One can also argue that it has less damaging health effects on Hanford workers given that it involves minimal retrieval of waste from tanks. We created performance profiles for "in place" alternatives and compared them with other alternatives in terms of cost and expected utilities. We concluded that given their perceived advantages, the "in place" alternatives should be pursued in more detail despite present DOE commitments. Development and use of in place containment technologies will be necessary under any scenario; even under the most aggressive retrieval strategies contaminated material will still remain in place.

5.2 Limitations and recommendations

We do not consider the aforementioned results as the ultimate evaluation of Hanford tank waste strategies and are aware of the many uncertainties in the data and imperfections in the model. This model is not yet the ideal tool for identifying optimal remediation strategies. It would take much more work to create such a tool. Present work is a first step in the achievement of a more general goal of developing a planning tool for TWRS activities. Many approximations and simplifications had to be made. In practical problems however, an approximate solution to the right problem can be far better than the exact solution to the wrong problem

5.2.1 Choice of attributes

Selection of attributes is a very important step in building a multiattribute utility decision model. There are two areas that need further consideration:

- How sensitive is the optimal strategy to the choice of attributes? Almost certainly the optimal strategy is heavily influenced by the choice of attributes. We used a simplified set of attributes to evaluate various alternatives. Probably more attributes should be included and the set of attributes should be restructured after getting input from stakeholders.
- Are those attributes really utility independent? The method used in the present model to calculate a multiattribute utility function from single attribute utilities assumes certain independence conditions[34]. In selecting the set of attributes to be considered for this model we took into account the issue of utility independence. We are however aware that this is only a first approximation and independence should be studied in more detail and tested in practice.

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[34] Discussed in section 3.2.2.3.

5.2.2 The 'in-place' option

The model, at least in the present version does not allow for detailed calculation of probability distribution functions for cost in the case of on site alternatives. We had to rely only on point estimates for cost, available from [DOE, 95].

As shown in the previous chapter, the "in place" alternative costs less, will take a shorter time to complete, and is less hazardous for workers on site. A trade-off will have to be made however between the long term health effects on public (where the "in place" alternatives fare worse) and other attributes. A more precise evaluation of the health effects on workers and public is required in order to study the trade-off in more detail. Other in place alternatives, "fill and cap" for example, which are expected to cost even less and has a similar performance profile should also be evaluated.

Another method that would eliminate the need to send the immobilized waste to a national geologic repository was introduced in [Curtis, 95]. According to this alternative the entire amount of waste would be vitrified and disposed of on site. The Hanford tank waste remediation problem would be decoupled from the national repository problem. The cost of disposing of the immobilized waste in a national geologic repository represents a large fraction of the total program cost under any of the alternatives presented in Chapter 4. One can argue that it should be less expensive to dispose of the entire amount of vitrified waste onsite. This would result in a reduced total program cost. As it is the case with other "In Place" alternatives, implementation of this approach might also need some form of regulatory relief. A possible continuation of the present work is to expand MAATWRS in order to evaluate the alternative proposed in [Curtis, 95].

The present analysis of the in place options is by no means complete. One should emphasize that calculations for this alternative are preliminary and further study is necessary. It led us however to the conclusion that this class of alternatives should be given further consideration.

5.2.3 Physical Model Refinement

There are several areas in the physical model that need refinement:

- Quantification of new alternatives, such as the disposition in place of all waste after vitrification

- Data refinement. One of the issues of concern is data quality. There are uncertainties associated with data in the model (cost estimates, for example, are proverbially uncertain). This information needs continuous updating and revision (e.g. tank content, cost and schedule data).
- Detailed treatment of strategies for retrieval of waste from tanks and of the optimal blending problem
- Contingency planning. Not all the technologies considered in the model have been tested in industrial conditions. Therefore each strategy based on unreliable processes should be hedged with a contingency alternative. MAATWRS may be extended to study the higher financial and environmental costs associated with fall back alternatives.
- Health effects due to non-radioactive chemicals
- Development of a scaling model as suggested in Appendix D.

5.2.4 MAU Model Enhancement

Several improvements can be made to the multiattribute utility part of the model:

- elicitation of scaling factors and measurement of one-dimensional utility functions
- testing for utility independence among attributes
- further exploration of the theoretical foundations of the mean - variance method.

Appendix A. Use of genetic algorithms

We considered various optimization techniques and chose an approach based on genetic algorithms. These algorithms, just like evolution in nature, make the strategy vectors mutate, cross over and evolve towards optimal solutions. Genetic algorithms differ from more traditional methods in several ways:

- transition rules from one possible solution to the other are probabilistic
- genetic algorithms search from a population of possible solutions, not a single one
- solutions are evaluated based on an objective function only (do not rely on derivatives or other information).

The algorithms are implemented in the model using an application named Evolver available from Axcelis Inc.

A1. Searching for less expensive alternatives

We used genetic algorithms to identify strategies with a reduced value of the total cost. As shown in section 3.4 each alternative is represented by a "strategy vector" composed of various controls (switches). By changing the values of those controls one can "create" various alternatives. We used an approach based on genetic algorithms to identify a set of controls corresponding to the lowest cost alternative. We then performed a Monte Carlo simulation and generated probability distribution functions for cost, multiattribute utility and other parameters of interest associated with this alternative. For this particular application we used strings of controls of the following form:

$$\Lambda^j = \{R_{M1}, R_{M2}, [P^t_{TF}], H_{TF}, L\} \qquad \textbf{Equation 56}$$

The symbols in Equation 56 are defined below:

Λ^j	String of controls associated with alternative j.
R_{M1}	Number of units in the primary Single Shell Tank retrieval system.

R_{M2}	Number of units in the secondary Single Shell Tank retrieval system.
P_{TF}^{t}	Pretreatment Technology and Pretreatment Facility for group of tanks t. The list of valid combinations is given in Table 14.
H_{TF}	High Level Waste Technology and High Level Waste Form. The list of possible combinations and their associated numerical codes in string Λ^j are given in Table 15.
L	Low Level Waste Form. Possible LLW forms and their associated numerical codes in string Λ^j are listed in Table 13.

For example the string of integers in Equation 57 denotes an alternative with the following characteristics: single shell tank waste would be retrieved using 20 sluicing systems, 2 mechanical arms[35]; all waste will undergo a pretreatment process consisting of enhanced sludge wash, selective Sr & TRU precipitation in a new enhanced sludge wash pretreatment facility; a Joule heated melter with a capacity of 10 metric tons per day will be used to immobilize HLW in low temperature, non crystalline glass; LLW will be immobilized as glass cullet in sulfur cement in 5300 m^3 vaults.

$$\Lambda^j = \{4,1,8,8,8,\ldots,8,4,2\}$$ **Equation 57**

The search for better alternatives start with the random generation of a population $\Lambda_0 = \{\Lambda^j \mid j = 1, p\}$ of p strings of the type presented in Equation 57. Each string Λ^j in the

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[35] Waste from double shell tanks will be retrieved using mixer pumps under any scenario.

population is evaluated using an objective (fitness) function $f_j = f(\Lambda^j)$ (in this particular case the objective function is the total cost).

$$\Lambda^j \to f_j \qquad \textbf{Equation 58}$$

The strings in a population undergo three types of operations:

- Reproduction. Individual strings are copied according to their fitness, i.e. strings with a lower total cost have a higher probability of contributing to offspring in the next generation.
- Crossover. The member of the strings resulting from the reproduction step are matched at random. Then each pair undergoes crossover as follows: if a random integer $q \in [1, Q-1]$, where Q is the length of the string, is generated and each string in the pair is cut at position q; a new pair is created by swapping[36] all digits between positions $q+1$ and Q. Table 12 presents an example for the case of two strings Λ^a and Λ^b; in this example $Q = 5$ and $q = 3$.
- Mutation. Mutation is an operator that randomly changes characters in strings. This operator plays a secondary role but is necessary in order to avoid trapping the entire population of strings in local minima or maxima of the objective function.

Table 12 Crossover operator - example

Initial pair	$\to$	**New pair**
$\Lambda^a = \{4,1,8,4,2\}$	4 1 8 | 4 2	$\Lambda^\alpha = \{4,1,8,$*2,3*$\}$
$\Lambda^b = \{$*5,2,6,2,3*$\}$	*5 2 6 | 2 3*	$\Lambda^\beta = \{$*5,2,6,*4,2$\}$

$$\Lambda^j = \{4,1,8,4,2\} \qquad \textbf{Equation 59}$$

We searched for alternatives with lower cost using strings of the form presented in Equation 59. These strings are a simplified form of those presented in Equation 57; we assumed that waste of all types will undergo the same pretreatment processes and replaced the sequence of 17 characters for each type of waste in Equation 57 with a single character. The least expensive strategy we found using this method turned out to be $\Lambda^* = \{4,2,6,5,2\}$. Λ^* denotes an alternative with the following characteristics: single shell tank waste would be retrieved using 20 sluicing systems, 4 mechanical arms[37]; all waste will undergo a pretreatment process consisting of CLEAN advanced separations in a new solvent extraction pretreatment facility; a gas fired melter will be used to immobilize HLW in high temperature, non crystalline glass cullet; LLW will be immobilized as glass cullet in sulfur cement in 5300 m^3 vaults. The alternative identified using the model has to be reviewed in order to further verify it's feasibility from a practical point of view. There may be constraints not included in the model or other inaccuracies.

Table 13. Codes used to identify low level waste forms in strings Λ^j

Code	Low level waste form
1	Salt grout (5300 m^3 per vault)
2	Glass in sulfur cement (5300 m^3 per vault)
3	Glass (15 m^3 container)
4	Mineral grout (5300 m^3 per vault)
5	Ceramic grout (5300 m^3 per vault)
6	Salt polyethylene (1.14 m^3 per container)
7	In situ vitrification (7300 m^3 per melt)
8	No low level waste form

---

[36] The second part of the second (first) string is attached to the first part of the first (second) string.

[37] Waste from double shell tanks will be retrieved using mixer pumps under any scenario.

Table 14 Pretreatment technologies
Codes associated with the list of valid pretreatment process and pretreatment facility combinations identified in [Johnson, 93] and [McConville, 95].

Code	Pretreatment process	Pretreatment facility
1	None, route to off-site disposal	None
2	Sludge wash, Cesium exchange, Strontium and TRU selective precipitation	In tank, large scale
3	Sludge wash, Cesium exchange, Strontium and TRU selective precipitation	New sludge wash or enhanced sludge wash pretreatment facility
4	Sludge wash, Cesium exchange, Strontium and TRU selective precipitation	Distributed compact processing unit
5	TRU, Sr, Tc separation, Organic destruction	New solvent extraction pretreatment facility
6	CLEAN advanced separations	New solvent extraction pretreatment facility
7	Enhanced sludge wash, selective Sr and TRU precipitation	In tank, large scale
8	Enhanced sludge wash, selective Sr and TRU precipitation	New sludge wash or enhanced sludge wash pretreatment facility
9	Enhanced sludge wash, selective Sr and TRU precipitation	Distributed compact processing unit
10	None, route to onsite disposal	None

Table 15. Codes used to identify high level waste technologies and forms in strings Λ^j.

Codes associated with the list of possible high level waste technologies - high level waste forms combinations identified in [Johnson, 93] and [McConville, 95].

Code	High level waste technology	High level waste form
1	HWVP Joule heated melter	Low temperature, non-crystalline glass
2	HWVP Joule heated melter	High temperature, non-crystalline glass
3	Combustion melter	High temperature, non-crystalline glass cullet
4	Joule heated melter, 10 MT per day	Low temperature, non-crystalline glass
5	Gas fired melter	High temperature, non-crystalline glass cullet
6	Hot isostatic press (HIP)	HIP Ceramic (2500 kg per container)
7	Joule heated melter, 10 MT per day	High temperature, non-crystalline glass
8	Calciner	Calcined in casks (10 m^3 per container)
9	Spray calciner	Ceramic pellets (1500 kg per container)

A2. Other possible applications of genetic algorithms

Genetic algorithms may also be used with this model for other purposes:

- Look for combinations of values of the control parameters in the strategy vector that would find optimal values for certain attributes (other than cost) or maximize the expected multiattribute utility
- Test alternatives for robustness by searching for worst case scenarios. Identify combinations of values of physical parameters that would, for example, maximize cost or minimize the expected multiattribute utility associated with a given strategy.

Appendix B. Visual basic code for functions used in MAATWRS

B1. Utility module

Figure 34 Visual Basic module for the utility function presented in Figure 8

```
Function utility(x, a, b, r, c)
If ((b - a) < 0 Or r < 0 Or r > 1 Or c < -1 Or c > 1 Or b < 0 Or a < 0) Then
utility = "check parameters"
Else
   M = a + r * (b - a)
   '
   If c < 0 Then
      h = c * (1 - r)
   Else
      h = c * r
   End If
   '
   If x < a Then
      linear = 1
   Else
      If (x > b) Then
         linear = 0
      Else
         linear = 1 - (x - a) / (b - a)
      End If
   End If
   '
   If ((x < a) Or (x > b)) Then
      triang = 0
   Else
      If (x < M) Then
         triang = h * ((x - a) / (M - a))
      Else
         triang = h * ((b - x) / (b - M))
      End If
   End If
   '
   utility = linear + triang
   '
End If
End Function
```

Figure 35 Visual Basic module that calculates the normalizing parameter K by solving Equation 20

```
Function findK(kArray)
   xacc = 0.0000001
   xacc2 = 0.02
   MAXIT = 500
   a = -1.000000001
   b = -0.00001
   c = 0.000001
   d = 100000
theSum = Application.Sum(kArray)
If theSum <= (1 - xacc2) Then
fl = bigK(c, kArray)
Do While fl * bigK(d, kArray) < 0
d = 0.8 * d
Loop
d = d / 0.8
findK = findBigK(c, d, kArray, MAXIT, xacc)
Else
   If theSum >= (1 + xacc2) Then
   findK = findBigK(a, b, kArray, MAXIT, xacc)
   Else
      If Abs(theSum - 1) < xacc2 Then findK = 0
   End If
End If
End Function

Function bigK(K, kArray)
Product = 1
For Each x In kArray
Product = Product * (K * x + 1)
Next x
bigK = K + 1 - Product
End Function
```

Figure 36 Visual Basic module used (in combination with module in Figure 35) to solve Equation 20

```
Function findBigK(x1, x2, kArray, MAXIT, xacc)

   fl = bigK(x1, kArray)
   fh = bigK(x2, kArray)
If (fl * fh > 0) Then
findBigK = "Root must be bracketed in findBigK"
Else
   If (fl < 0) Then
      xl = x1
      xh = x2
   Else
      xl = x2
      xh = x1
      swap = fl
      fl = fh
      fh = swap
   End If
   dx = xh - xl
   j = 1
   Do While j <= MAXIT
      rtf = xl + dx * fl / (fl - fh)
      f = bigK(rtf, kArray)
      If (f < 0) Then
         del = xl - rtf
         xl = rtf
         fl = f
      Else
         del = xh - rtf
         xh = rtf
         fh = f
      End If
      dx = xh - xl
      If ((Abs(f) < xacc * xacc) Or Abs(del) < xacc) Then
      findBigK = rtf
      Exit Do
      Else
      findBigK = "Maximum number of iterations exceeded in findBigK"
      End If
      j = j + 1
   Loop

End If
End Function
```

Figure 37 Visual Basic module that calculates MAU using Equation 19 or Equation 23

```
Function MAU(kArray, uArray, K)
  If K = 0 Then
    MAU = Application.SumProduct(kArray, uArray)
  Else
    N = 0
    For Each x In kArray
      N = N + 1
    Next x
    MAU = 1
    i = 1
    For i = 1 To N Step 1
      MAU = MAU * (K * kArray(i) * uArray(i) + 1)
    Next i
    MAU = (MAU - 1) / K
  End If
End Function
```

B2. Other functions

B2.1 lognormal

```
Function function_miu(nominal, maximum)
mean = nominal
stddev = (maximum - mean) / 3
sqrt = ((mean) ^ 2 + (stddev) ^ 2) ^ (0.5)
a = (mean ^ 2) / sqrt
function_miu = Ln(a)
End Function
```

```
Function function_sigma(nominal, maximum)
mean = nominal
stddev = (maximum - mean) / 3
a = Ln(1 + (stddev / mean) ^ 2)
function_sigma = a ^ (0.5)
End Function
```

```
Function function_mean_lognormal(miu, sigma)
e = 2.718281828
function_mean_lognormal = e ^ (miu + sigma * sigma / 2)
End Function
```

```
Function solveForMiu(y, W, M)
solveForMiu = Ln(y * M)
End Function
```

```
Function solveForSigma(y, W, M)
solveForSigma = (Ln(y)) ^ (0.5)
End Function
```

```
Function Ln(x)
e = 2.718281828
Ln = Log(x) / Log(e)
End Function
```

```
Function Equation(y, W, M)
a = W / M
Equation = (y ^ (1.5)) * (1 + 3 * ((y - 1) ^ (0.5))) - a
End Function
```

```
Function solveEquation(x1, x2, W, M, MAXIT, xacc)

   fl = Equation(x1, W, M)
   fh = Equation(x2, W, M)
If (fl * fh > 0) Then
solveEquation = "Root must be bracketed in solveEquation"
Else
   If (fl < 0) Then
      xl = x1
      xh = x2
   Else
      xl = x2
      xh = x1
      swap = fl
      fl = fh
      fh = swap
   End If
   dx = xh - xl
   j = 1
   Do While j <= MAXIT
      rtf = xl + dx * fl / (fl - fh)
      f = Equation(rtf, W, M)
      If (f < 0) Then
         del = xl - rtf
         xl = rtf
         fl = f
      Else
         del = xh - rtf
         xh = rtf
         fh = f
      End If
      dx = xh - xl
      If ((Abs(f) < xacc * xacc) Or Abs(del) < xacc) Then
      solveEquation = rtf
      Exit Do
      Else
      solveEquation = "Maximum number of iterations exceeded in solveEquation"
      End If
      j = j + 1
    Loop

End If
End Function
```

B2.2 exponential

```
Function function_aThExponential(beta, a)
If (beta <= 0 Or a >= 1 Or a < 0) Then
function_aThExponential = "check parameters"
Else
function_aThExponential = -beta * Ln(1 - a)
End If
End Function
```

Appendix C. Notes regarding software

C1. List of modules

The table below present a list and brief description of the various parts of the model. More specific comments can be found in the program itself as annotations.

Table 16 List of Excel and Visual Basic modules
The attributes we refer to in the present table are presented in Figure 12 and section 3.2.4.3.

Name	Description
Strategy	It consist of three parts: strategy, definitions, portfolio
MAU	Collects the single attribute utilities from other modules and calculates a multiattribute utility function
Cost	Calculates the utility associated with the attribute total program cost.
Schedule	Calculates the utility associated with attribute "Schedule". It has two parts: "duration" and "completion date".
Socioeconomic	Calculates the utility associated with the attribute "Socioeconomic Impact". It has two parts: "average" and "fluctuation"
Land Use	Calculates the utility associated with the attribute "Land Use". It has two parts: "LLW Volume" and "Radioactivity"
Public_0	Calculates the utility associated with the attribute "Health Effects on Public". It has seven parts: "Public_0", "Public_1" through "Public_7"
Workers_0	Calculates the utility associated with the attribute "Health Effects on Workers". It has seven parts: "Worker_0", "Worker_1" through "Worker_7"
Extra	Calculates the utility associated with the attribute "Extra-regional Impact". It has two parts: "Extra" and "Volume"
INS	The Insight spreadsheet available from Westinghouse Hanford. [Johnson, 93], [McConville, 95]
Utility Function	Visual Basic module used to generate utility functions of the form presented in Figure 8. More details are given in Appendix B.

Continued on next page

Continuation of Table 16

Name	Description
Lognormal_Distributions	Visual Basic module used to linked to the used of lognormal probability distribution function in modules Public and Workers.
Exponential_Distributions	Visual Basic module used to linked to the used of exponential probability distribution function in modules Public and Workers.
Module 3	Visual Basic module used to generate a multiattribute utility function single attribute utility functions. More details are given in Appendix B.
Module 4	Visual Basic module used to calculate the "big K" scaling factor used in the calculation of the multiattribute utility function. More details in Appendix B.

C2. Why a Windows^{TM} environment and not UNIX?

Using Windows (rather than UNIX, an operating environment more popular in the academic community) offers several advantages:

- the software is more common (off-the shelf), cheaper and can run on relatively inexpensive machines.
- using Visual Basic and Excel "add-ins" allows modularity, hence expandability.
- Windows and Windows NT are increasingly becoming the operating environment of choice for many corporations.

C3. @RISK

@RISK, available from Palisade Corporation, is an add-in program to Microsoft Excel. @RISK was used with the present model to perform Monte Carlo simulation. Input variables in the model are specified as probability distributions. The probability distributions are entered directly into the spreadsheet using custom distribution functions. At each iteration the spreadsheet is recalculated with a new set of sampled values from the input probability distributions. Results are collected and probability distributions for output variables are created. @RISK can also generate sensitivity and scenario analysis reports.

C4. Evolver

Evolver^{TM} available from Axcelis, Inc. incorporates genetic algorithms that can be used to solve optimization problems. Genetic algorithms mimic Darwinian natural selection and let populations of solutions evolve towards optimal solutions. The program can be used either as an "add-in" to an exiting spreadsheet model or can be incorporated in Windows^{TM} programs written in languages that support "DLL" standard (Visual Basic, C, C++, etc.). The use of genetic algorithms with the present model is presented in Appendix A.

C5. DPL

DPL^{TM} available from ADA Decisions Systems, is a decision analysis program that allows the use of both decision trees and influence diagrams. DPL stands for Decision Programming Language. Models can be created using either the DPL graphical interface or the DPL language. DPL language is more powerful and flexible than a DPL influence diagram. The DPL models can be linked to spreadsheet models using Dynamic Data Exchange.

Appendix D

The analysis in this appendix is not part of the MAATWRS decision model. We present it here a starting point for a possible expansion of the model.

D1. Scaling Model. Scaling of radioactive releases from the vitrification plant with respect to campaign duration

Notations:

T	throughput of the vitrification plant
T_B	base throughput of the vitrification plant (Kg/yr)
d	campaign duration (yr)
d_B	base campaign duration
N	normal operation release (rem/yr)
N_B	base normal operation release (rem/yr)
A	accident and abnormal operation release (rem/yr)
A_B	base accident and abnormal operation release (rem/yr)
F	ratio of A_B and N_B
D	total dose
$n_{A,B}$	scaling coefficients

The total dose is the sum of contributions due to normal releases and accidental and abnormal releases:

$$D = (N + A) \cdot d$$

Equation 60

We have the following relation between the plant throughput and campaign duration:

$$T \cdot d = T_B \cdot d_B = m$$

Equation 61

where m is the total mass of the waste to be vitrified.

It seems plausible that that the radioactivity released in normal, abnormal or accidental conditions would depend on the plant throughput *T*. I assumed the following relations of proportionality:

$$N \sim T^{n_N}$$ **Equation 62**

and

$$A \sim T^{n_A}$$ **Equation 63**

where n_A and n_N are some scaling coefficients.

Using Equation 61, Equation 62, Equation 63 we find:

$$N / N_B = (T / T_B)^{n_N} = (d_B / d)^{n_N}$$ **Equation 64**

$$A / A_B = (T / T_B)^{n_A} = (d_B / d)^{n_A}$$ **Equation 65**

Using Equation 60, Equation 64 and Equation 65 the total dose as function of the duration D(d) can be expressed as follows:

$$D(d) = N_B \cdot (d_B / d)^{n_N} \cdot d + A_B \cdot (d_B / d)^{n_A} \cdot d$$ **Equation 66**

or

$$D(d) = N_B \cdot {d_B}^{n_N} \cdot d^{1-n_N} + A_B \cdot {d_B}^{n_A} \cdot d^{1-n_A}$$ **Equation 67**

Plots of the function *D(d)* for different values of the parameters n_A and n_N are given in Figure 38

The expression for the dose per year *D(d)/d* is:

$$D(d) / d = N_B \cdot (d_B / d)^{n_N} + A_B \cdot (d_B / d)^{n_A}$$ **Equation 68**

We will consider the following interesting case:

$$n_A > 1$$ **Equation 69**

and

$$0 < n_N < 1$$ **Equation 70**

On **Figure 38** one can see that for n_N=.25 and n_A=2 the dose *D(d)* has a minimum for a certain value of the campaign duration. Let us denote this optimal value of the campaign duration d^*. One can show that in conditions given by Equation 69 and Equation 70 a minimum of *D(d)* exists for the following value of *d*:

$$d^* = \left(\frac{n_A - 1}{1 - n_N} \cdot F\right)^{\frac{1}{n_A - n_N}} \cdot d_B$$ **Equation 71**

Figure 39 gives the variation of d^* with n_A and n_N. Figure 40 gives d^* as a function of the parameter *F*.

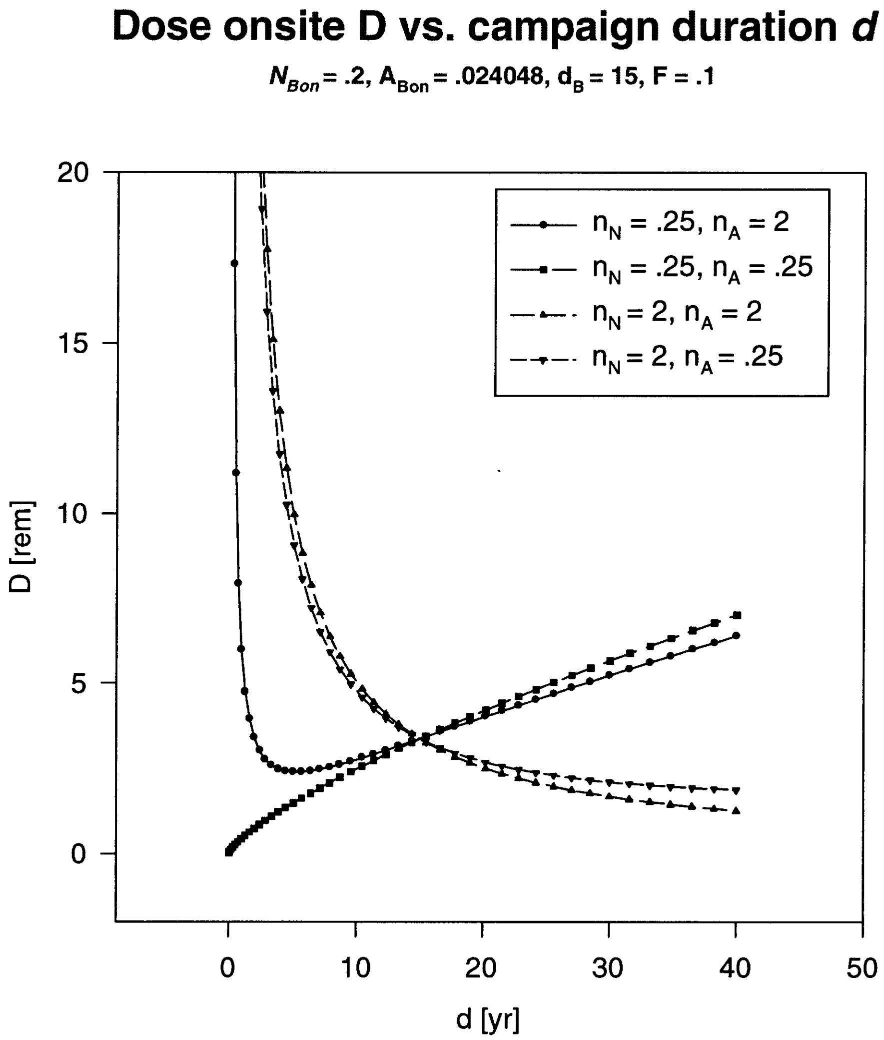

Figure 38 Dose onsite D vs. campaign duration *d*

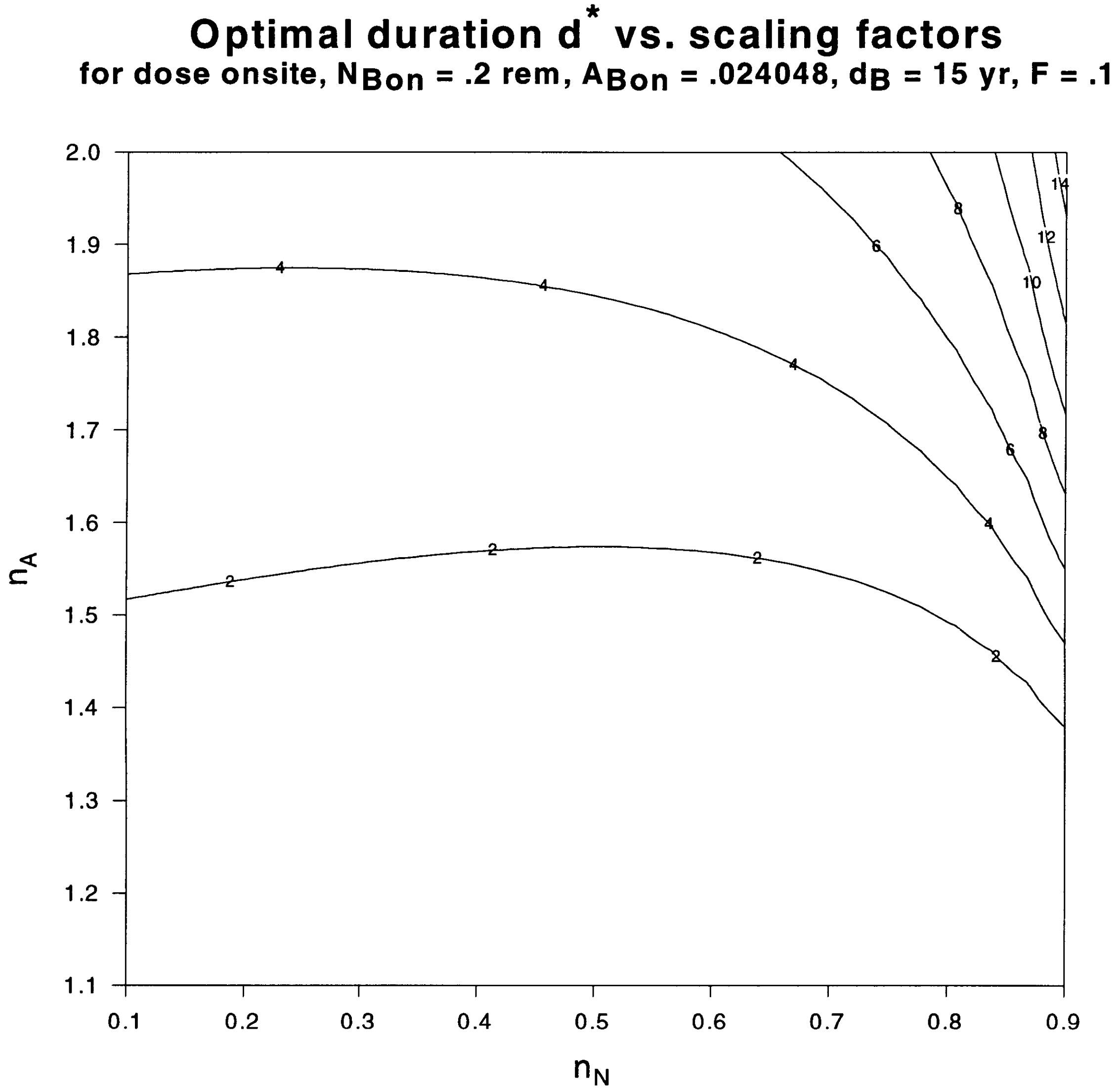

Figure 39 Optimal duration d^* vs. scaling factors n_A and n_N. Contour plot.

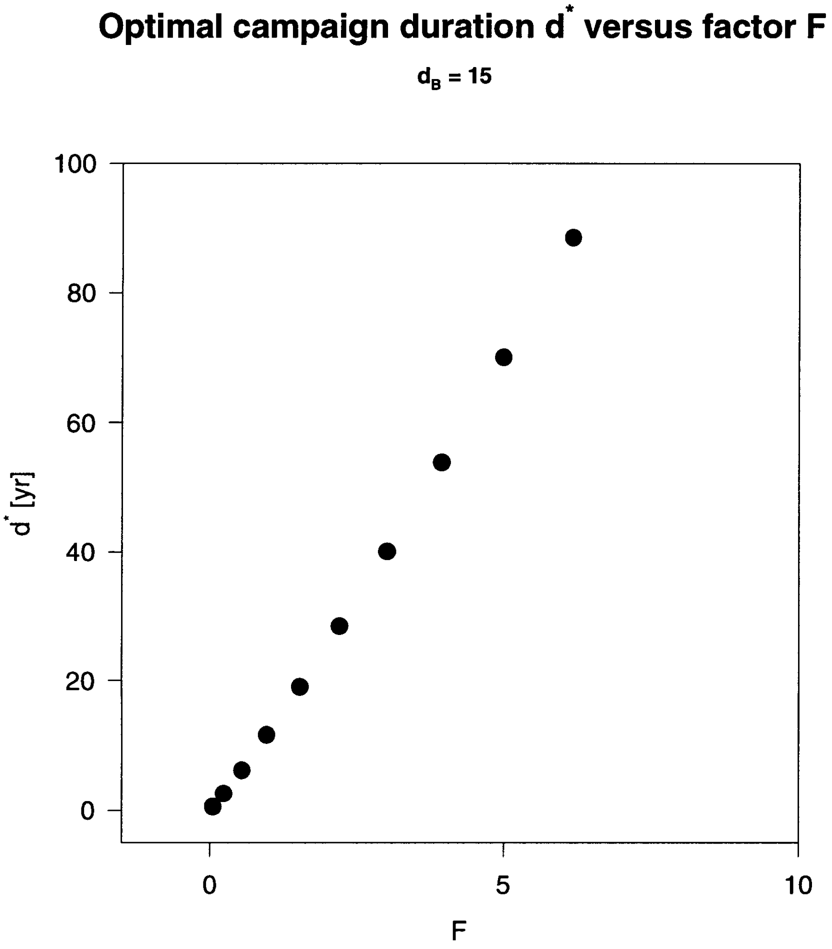

Figure 40 Optimal campaign duration *d** vs. factor F

D1.1 C code used for scaling

Figure 41 C code used to calculate d^* as a function of n_A and n_B according to Equation 71. The contour plot is presented in Figure 39

```
...\safety\...\contour.cpp
-------------------------------------------------
# include <stdio.h>
# include <math.h>


double dstr(double nN,double nA,double f,double dB )
{
return pow(((nA-1)/(1-nN))*f,1/(nA-nN))*dB;
}

void main(void)
{
FILE *dpolar;
dpolar=fopen("dplr.dat","w+");
double aa=1.1,bb=2,cc;
int ii=1,KK=50;
while (ii<=KK) {
cc=aa+(bb-aa)*pow((double(ii)/double(KK)),2);
        double a=.1,b=.9,c;
        int i=1,K=50;
        while (i<=K) {
        c=a+(b-a)*pow((double(i)/double(K)),2);
        fprintf(dpolar,"%lf   %lf    %g\n",c,cc,dstr(c,cc,.1,15));
        i=i+1;
        }
ii=ii+1;
}
}
```

```
# include <stdio.h>
# include <math.h>

double dose(double d,double nN,double nA,double NB,double AB,double dB )
{
double normal, abnorm;
normal=NB*pow(dB,nN)*pow(d,1-nN);
abnorm= AB*pow(dB,nA)*pow(d,1-nA);
return normal+abnorm;
}
```

```
double dose_yr(double d,double nN,double nA,double NB,double AB,double dB )
{
double normal, abnorm;
normal=NB*pow(dB,nN)*pow(d,-nN);
abnorm= AB*pow(dB,nA)*pow(d,-nA);
return normal+abnorm;
}
```

Figure 42 Code used to create data for Figure 38 using Equation 67.

```
...\safety\...\dose.cpp
----------------------------------
double dstr(double nN,double nA,double f,double dB )
{
return pow(((nA-1)/(1-nN))*f,1/(nA-nN))*dB;
}

void main(void)
{
FILE *offsite;
FILE *onsite;
FILE *offsite_yr;
FILE *onsite_yr;
FILE *dstar;
offsite=fopen("offs.dat","w+");
onsite=fopen("ons.dat","w+");
offsite_yr=fopen("offs_yr.dat","w+");
onsite_yr=fopen("ons_yr.dat","w+");
dstar=fopen("dstr.dat","w+");
#define NB   .0000066
#define AB   .000784
#define NBon   .2
#define ABon   .024048
double a=.000001,b=40,c;
int i=1,K=45;
while (i<=K) {
c=a+(b-a)*pow((double(i)/double(K)),2);
fprintf(offsite,"%lf      %g      %g      %g
%g\n",c,dose(c,.25,2,NB,AB,15),dose(c,.25,.25,NB,AB,15),dose(c,2,2,NB,AB,15),dose(c,2,.25,NB,
AB,15));
fprintf(onsite,"%lf      %g      %g      %g
%g\n",c,dose(c,.25,2,NBon,ABon,15),dose(c,.25,.25,NBon,ABon,15),dose(c,2,2,NBon,ABon,15),do
se(c,2,.25,NBon,ABon,15));
fprintf(offsite_yr,"%lf      %14.9f      %14.9f      %14.9f
%14.9f\n",c,dose_yr(c,.25,2,NB,AB,15),dose_yr(c,.25,.25,NB,AB,15),dose_yr(c,2,2,NB,AB,15),dose
_yr(c,2,.25,NB,AB,15));
fprintf(onsite_yr,"%lf      %14.9f      %14.9f      %14.9f
%14.9f\n",c,dose_yr(c,.25,2,NBon,ABon,15),dose_yr(c,.25,.25,NBon,ABon,15),dose_yr(c,2,2,NBon
,ABon,15),dose_yr(c,2,.25,NBon,ABon,15));
i=i+1;
}
double aa=.000001,bb=125,cc;
int ii=1,KK=45;
while (ii<=KK) {
cc=aa+(bb-aa)*pow((double(ii)/double(KK)),2);
fprintf(dstar,"%lf      %g\n",cc,dstr(.25,2,cc,15));
ii=ii+1;
}
}
```

Figure 43 C code used to calculate d^* as function of parameter F according to Equation 71. Results are plotted in Figure 40

```
# include <stdio.h>
# include <math.h>

double dstr(double nN,double nA,double f,double dB )
{
return pow(((nA-1)/(1-nN))*f,1/(nA-nN))*dB;
}

void main(void)
{
FILE *dstar;
dstar=fopen("dstr.dat","w+");
double aa=.000001,bb=125,cc;
int ii=1,KK=45;
while (ii<=KK) {
cc=aa+(bb-aa)*pow((double(ii)/double(KK)),2);
fprintf(dstar,"%lf      %g\n",cc,dstr(.5,1.4,cc,15));
ii=ii+1;
}
}
```

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