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Plutonium-238 Transuranic Waste Decision Analysis

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Plutonium-238 Transuranic Waste Decision Analysis

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ACKNOWLEDGEMENT

The authors would like to thank the following expert panel participants for the time and effort that were contributed to this project: Douglas Berry (Westinghouse Savannah River Company), Michael J. Connolly (Lockheed Martin Idaho Technologies Company), Murthy Devarakonda (International Technology Corporation), Sinisia M. Djordjevic (DJINDECO Consulting), D. Bruce LeBrun (Department of Energy – Los Alamos Area Office), Eugene Mroz (Los Alamos National Laboratory), Gerald A. O’Leary (Rocky Mountain Remediation Service), John Schierloh (Los Alamos Technical Assistance – Rocky Flats Environmental Technology Site), Marilyn M. Warrant (Sandia National Laboratories), and Ruth F. Weiner (Sandia National Laboratories). In addition, the authors would like to recognize the contributions of Michael Brown (Department of Energy – Carlsbad Area Office), Darlene Steward (S.M. Stoller Corporation), Richard Bild (Sandia National Laboratories), and Paul Drez (Drez Environmental Associates) to the development of this report. We would also like to thank those individuals at S.M. Stoller Corporation and the Sandia National Laboratories — Carlsbad, New Mexico office who provided review comments and general support services to prepare this report.

Abstract

Plutonium-238 Decision Analysis Report

The Transuranic Package Transporter-II (TRUPACT-II), which was certified by the Nuclear Regulatory Commission (NRC), has been selected as the Type B packaging to ship contact-handled transuranic (TRU) waste to the Waste Isolation Pilot Plant (WIPP) for disposal. The TRUPACT-II payload criteria currently limit the U.S. Department of Energy’s (DOE) ability to ship some of the plutonium-238 (Pu-238) TRU waste, unless the waste is treated or repackaged at the site before shipment.

Five TRU waste sites have more than 2,100 cubic meters of Pu-238 TRU waste that exceed the wattage restrictions of the TRUPACT-II. The DOE must decide if Pu-238 TRU waste should be repackaged or treated or whether the TRUPACT-II payload restriction should be modified based on ongoing or future research and regulatory action by the NRC. The purpose of this report, then, is to evaluate strategies to enhance the management, and thus enable the efficient transportation of Pu-238 TRU waste to the WIPP for disposal.

Decision analysis was selected as the tool to evaluate various strategies. This report describes the decision analysis process, sets forth the performance measures that were used to evaluate each of the strategies, documents the results of the analysis and provides recommendations that could lead to improved management of Pu-238 TRU waste.

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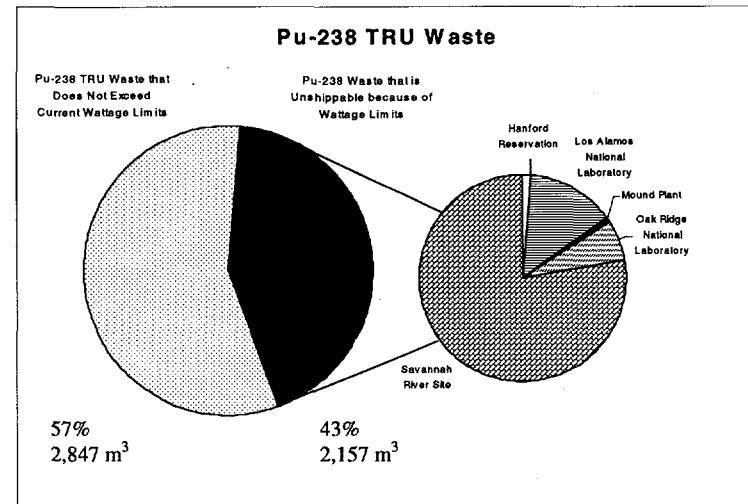
Plutonium-238 Transuranic Waste Decision Analysis

EXECUTIVE SUMMARY

The Transuranic Package Transporter-II (TRUPACT-II) has been designed and selected as the Type B packaging to ship contact-handled transuranic (TRU) waste to the Waste Isolation Pilot Plant (WIPP). Payload criteria, established pursuant to the Certificate of Compliance issued by the U.S. Nuclear Regulatory Commission (NRC), constrain the U.S. Department of Energy's (DOE) ability to ship much of its heat-source plutonium-238 (Pu-238) TRU waste. The TRUPACT-II payload criterion of primary concern is the decay heat (wattage) limit. This criterion requires that waste packages meet the decay heat limits contained in the TRUPACT-II Content Codes. Decay heat (wattage) limits are calculated values selected to ensure that the concentration of hydrogen in any layer of confinement in a payload container does not exceed five percent during a maximum 60-day shipping period.

Five DOE waste sites have an estimated 2,157 cubic meters (approximately 10,373 drum equivalents) of Pu-238 TRU waste that exceed the wattage restrictions of the TRUPACT-II. These sites are faced with a need to develop waste management practices in the near term that will enable the transportation of Pu-238 TRU waste to the WIPP in a manner that is both cost effective and minimizes the number of shipments. The DOE must decide to what extent Pu-238 TRU waste should be repackaged or treated, or whether the DOE can establish sufficient technical bases that would enable the NRC to modify the TRUPACT-II payload restrictions.

The Problem
Hydrogen is generated in sufficient quantities from the decay of the Pu-238 isotope to exceed NRC-prescribed requirements thereby precluding shipment in the TRUPACT-II.



To illustrate the magnitude of the decision to be made, the repackaging of the 2,157 cubic meters of waste to meet the current wattage limits would result in about 32,000 cubic meters (about 152,716 drum equivalents) of Pu-238 TRU waste to be shipped. This would require 20 percent of the WIPP's contact-handled TRU waste capacity of 168,500 cubic meters to accommodate the disposal of Pu-238 TRU waste. It also would require 50 percent of the shipping resources allotted for contact-handled TRU waste in *The National TRU Waste Management Plan, Revision 1* (DOE, 1997), while the pre-packaged volume (2,157 cubic meters) is now only 5 percent of the total stored contact-handled-TRU waste volume.

For these reasons, the issue of concern can be stated as:

What are the most appropriate means for the DOE Complex to manage Pu-238 TRU waste, thus enabling the efficient transportation to the WIPP?

Decision analysis was selected as the tool to address this issue. Decision analysis is a method that provides a logical framework for addressing complex problems and provides the decision maker with a quantitative means to evaluate the merits of decisions in light of the technical and regulatory uncertainties inherent in any decision.

Five strategies (paths) to address the issue of concern were analyzed. Each strategy, if approved by the NRC, would either reduce the number of drums that would be generated during repackaging (Paths 1 and 5), or would increase the number of drums that could be shipped without further modification (Paths 2, 3, and 4):

- *Path 1* – The DOE petitions the NRC to allow hydrogen getter materials to be added to the headspace of the drums during repackaging.
- *Path 2* – The DOE petitions the NRC for a change in the wattage limits based on the results of matrix depletion and hydrogen generation studies.
- *Path 3* - The DOE petitions the NRC to allow the use of hydrogen headspace gas sampling as a method to certify containers for shipment in a TRUPACT-II, based on studies that demonstrate the relationship of hydrogen concentration in the headspace of the drum to the hydrogen concentration in the innermost layer of confinement.
- *Path 4* – The DOE petitions the NRC to allow the use of hydrogen getter materials in the inner containment vessel of the TRUPACT-II.
- *Path 5* - The DOE petitions the NRC to approve the use of advanced filters in the repackaging of all waste.

For each path, if the NRC denies the petition, a further decision is made to either treat or repackage the Pu-238 TRU waste.

The decision analysis model used to evaluate each path, plus combinations of multiple paths, was composed of a waste volume model and a cost model. The waste volume model was based on a container-specific inventory provided by each of the five sites

Performance Measures
Three performance measures were used to quantify the relative merits of the strategies:

- *Volume disposed by 2006*
- *Demand on planned shipping resources*
- *Total system life-cycle cost.*

Sites Analyzed

*Hanford Reservation
Los Alamos National Laboratory
Mound Plant
Oak Ridge National Laboratory
Savannah River Site*

that store heat-source Pu-238 TRU waste. *The National TRU Waste Management Plan, Revision 1* (DOE, 1997), provided the underlying assumptions regarding each site's planned waste processing logic, shipping rates and durations. The cost model was based mainly on information provided by the Savannah River Site, Idaho National Engineering and Environmental Laboratory, and the Carlsbad Area Office.

The decision analysis demonstrated that none of the strategies under consideration will fully enable the DOE to transport Pu-238 TRU waste without repackaging or treatment. However, when considering both the technical and regulatory uncertainties (i.e., expected value), drum certification based on headspace gas sample analysis (Path 3) offers the best single strategy to maximize near-term waste disposal (volume disposed by 2006) and minimize total system life-cycle cost. If samples of the headspace gas from Pu-238 TRU waste drums in storage show that hydrogen concentrations are indeed within the range analyzed, between 1,000 and 3,000 drums of the 10,373 drum equivalents in the inventory could be transported and disposed of in the WIPP without treatment or repackaging. The actual outcome of headspace gas sample analysis is uncertain, but by initiating a program to sample the headspace gas on a population of Pu-238 TRU waste drums and seek the NRC's approval for this certification method, the uncertainties will be reduced. Such a program may demonstrate that individual drum testing is a viable strategy that will enable the transportation of a significant part of the Pu-238 TRU waste inventory.

Most Appropriate Means to Manage Pu-238 TRU Waste

Performance Measure	Best Strategy for Achievement
Near-term disposal	Headspace hydrogen samples
Volume reduction	Thermal treatment
Cost efficiency	Repackaging

From a volume reduction perspective, thermal treatment to remove organic materials and water from the Pu-238 TRU waste is the best single strategy for overall volume reduction of the Pu-238 TRU waste inventory. In the context of this decision analysis treatment has little uncertainty, however, it is also the highest cost option, with a total system life-cycle cost more than double that required for repackaging. If volume reduction is the decision maker's highest priority, the Pu-238 TRU waste inventory should be treated in its entirety.

Repackaging is the lowest cost single strategy. It is also the option that produces the largest volume of Pu-238 TRU waste for disposal. Most of the research studies that are being pursued will tend to reduce the volume produced when Pu-238 TRU waste is repackaged. However, because of the limitations on the overall effectiveness of these studies and the associated technical and regulatory uncertainties, repackaging will produce a shipping need that far exceeds the current baseline planning resources as described in *The National TRU Waste Management Plan* (DOE, 1997), regardless of the strategy. If cost efficiency is the decision maker's highest priority, the Pu-238 TRU waste inventory should be repackaged.

When multiple strategies are considered in combination in light of only technical uncertainties, as much as 3,000 drums of Pu-238 TRU waste could be shipped from all sites by 2006. The remaining inventory could then be repackaged in as few as 11,000 drum equivalents if advanced

Multiple Strategies

The application of multiple strategies could be the most beneficial, if the technical uncertainties can be reduced.

bag and drum filters are used in conjunction with hydrogen getters in the inner containment vessel of the TRUPACT-II. These estimates, while impressive, must be considered in light of the uncertainties of whether the NRC would approve higher wattage limits because of matrix depletion, the use of hydrogen headspace gas sampling to certify waste containers, the use of hydrogen getters in the inner containment vessel of the TRUPACT-II, and advanced drum and bag filters when repackaging. These estimates also could be refined, as noted

above, by initiating programs to collect data needed to reduce uncertainties.

In attempting to fully address the fundamental question concerning the decision maker, it should be recognized that the analyses presented herein are strategic in nature. Tactical decisions to implement a selected strategy must be made at the TRU-waste site level. Tactical decisions should target specific portions of the inventory with the appropriate mix of remedial strategies. For example, a few drums of very high wattage waste could be repackaged to stay below wattage limits instead of focusing on volume limits of the TRUPACT-II. In other words, repackaging waste to ship maximum wattage may be more prudent in some instances than repackaging to fill TRUPACT-IIs – the primary advantage being the cost avoidance associated with creating and maintaining a facility for processing large waste volumes.

This decision analysis was conducted within the context of existing regulations; evaluating possible changes to existing regulations was beyond the scope of this analysis. These regulations result in decay heat limits that ensure that the concentration of hydrogen in any layer of confinement in a payload container does not exceed five percent. Even the best strategy, drum certification by gas generation testing and sampling, or a combination of strategies, does not allow shipment of all the Pu-238 TRU waste without some repackaging or treatment of the waste. Continued development of technology to mitigate or prevent gas generation and to understand the phenomena is required. The goal is to increase the wattage limits of waste that can be safely and legally transported. Increased knowledge of this waste may also identify additional options.

ACRONYMS AND ABBREVIATIONS

DOE	Department of Energy
eV	electron volts
NRC	Nuclear Regulatory Commission
psia	pounds per square inch absolute
Pu	plutonium
STP	standard temperature and pressure
TRU	transuranic
TRUCON	TRUPACT-II Content Codes
TRUPACT-II	Transuranic Package Transporter-II
WIPP	Waste Isolation Pilot Plant

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Plutonium-238 Transuranic Waste Decision Analysis

1. INTRODUCTION

1.1 Introduction to the Problem

A number of transuranic (TRU) isotopes have been developed since the 1940s as part of the nation's nuclear defense production and research activities. The plutonium isotope, plutonium-239 (Pu-239), is the primary nuclear material found in nuclear weapons. Another isotope, Pu-238, has been used as a heat source for various applications including space exploration and medical research. The specific activity of Pu-238 is nearly 300 times greater than that of Pu-239, and the higher alpha decay rate creates a significant self-heating effect in the Pu-238 isotope. When used as a heat source in Radioisotopic Thermal Generators, Pu-238 fuel pellets can be stacked in arrays to produce temperatures exceeding 1000° Celsius.

An unwanted byproduct of nuclear research and production activities is TRU waste. As of 1995 more than 65,000 cubic meters of TRU waste are estimated to be in storage at 15 Department of Energy (DOE) sites around the U.S. (DOE, 1997). This waste is to be shipped to the Waste Isolation Pilot Plant (WIPP) for disposal. The Transuranic Package Transporter-II (TRUPACT-II), which was certified by the Nuclear Regulatory Commission (NRC), has been designed as the Type B packaging to ship contact-handled TRU waste to the WIPP. The TRUPACT-II has payload criteria which limit its ability to ship some of the Pu-238 TRU waste unless the waste is treated or repackaged at the site before shipment (DOE, 1998a).

The TRUPACT-II payload criterion of primary concern for Pu-238 TRU waste is the decay heat or wattage limit. This criterion requires that waste packages meet the decay heat limits contained in the TRUPACT-II Content Codes (TRUCON). Decay heat (wattage) limits are calculated values selected to ensure that the concentration of hydrogen in any layer of confinement in a payload container (e.g., drum or standard waste box) does not exceed five percent during a maximum 60-day shipping period. Hydrogen is produced in waste containers when paper, plastics, and water absorb energy from the decay of radioactive isotopes (radiolysis). The requirement stated in the *Safety Analysis Report for the TRUPACT-II Shipping Package* (DOE, 1998b) is that:

The hydrogen generated over a period of time that is twice the expected shipment period shall be limited to a molar quantity that would be no more than 5 percent by volume of any payload container gas void, if present within any layer of confinement, at STP [Standard Temperature and Pressure] (i.e., no more than 0.063 g-moles/cubic foot at 14.7 psia [pounds per square inch absolute] and 70°F).

What is the Problem?

Hydrogen is generated, via the decay of the Pu-238 isotope in heat-source TRU waste, in sufficient quantities to exceed NRC-prescribed requirements thereby precluding shipment in the TRUPACT-II.

Wattage limits have been established for each shipping category that can be shipped in a TRUPACT-II. The shipping categories have four main components: waste type, waste material type, payload container (e.g., drum, standard waste box), and number of layers of confinement. Table 1 (DOE, 1989) describes the waste type and waste material type categories.

TABLE 1. SHIPPING CATEGORY COMPONENTS FOR TRU-WASTE IN THE TRUPACT-II

Waste Type	Waste Material Type	Typical Material Description
I	I.1	Absorbed, adsorbed, or solidified inorganic liquids
I	I.2	Soils, solidified particulates, or sludges formed from precipitation
I	I.3	Concreted inorganic particulate waste
II	II.1	Solid inorganic materials (e.g., glass, metal, crucibles, other solid inorganics) packaged in plastic bags
II	II.2	Solid inorganic materials packaged in metal cans
III	III.1	Solid organic materials (e.g., plastics, cellulose, cemented organic solids, other solid organics)
IV*	IV.1	Solidified organics (e.g., cemented or immobilized organic liquids and solids)

*Wattage limits have not been established for Waste Type IV.

Based on inventory information provided by the sites, there exist about 5,000 cubic meters (24,000 drum equivalents) of Pu-238 TRU waste at the Savannah River Site, Los Alamos National Laboratory, Oak Ridge National Laboratory, Hanford Reservation, and Mound Plant (Table 2, Figure 1). The Idaho National Engineering and Environmental Laboratory was not considered in this analysis because it was assumed that all of its Pu-238 TRU waste would be treated in the Advanced Mixed Waste Treatment Facility¹. Most (4,562 cubic meters) of the Pu-238 TRU waste is solid organic (Waste Type III). There are 322 cubic meters of Waste Type II and 116 cubic meters of Waste Type I. Almost half of the Pu-238 TRU waste currently in storage (2,157 cubic meters) exceeds the current wattage limits of the TRUPACT-II and cannot be shipped unless treated or repackaged, with attendant volume changes.

TABLE 2. VOLUMES (CUBIC METERS) OF Pu-238 TRU WASTE IN STORAGE IN THE UNITED STATES

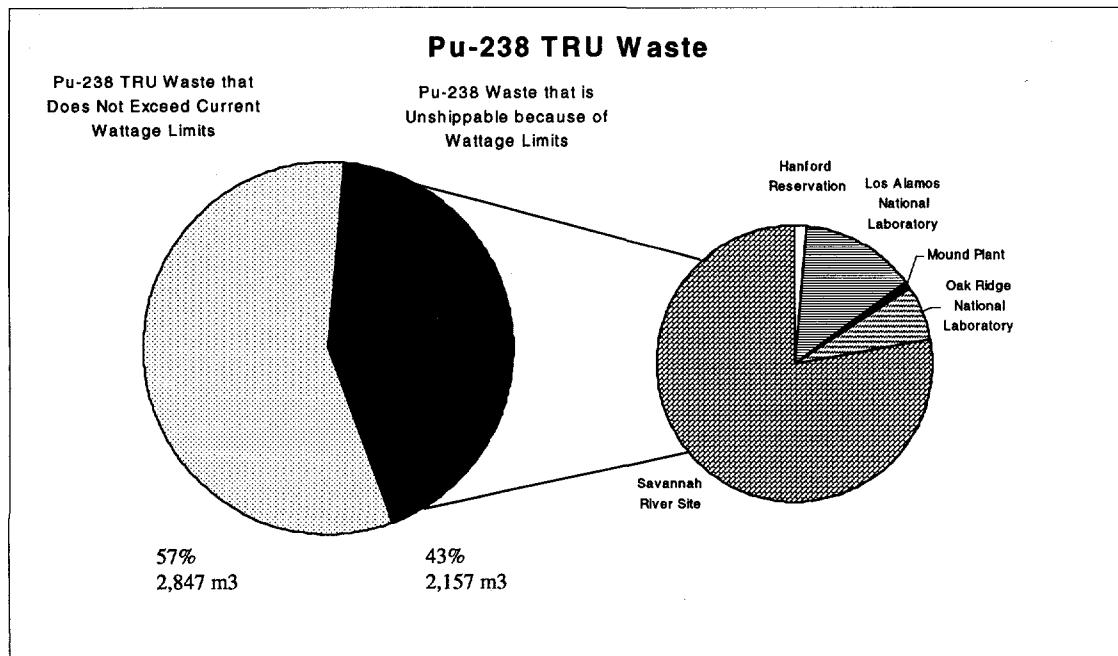
Waste Type	Hanford Reservation		Los Alamos National Laboratory		Mound Plant		Oak Ridge National Laboratory		Savannah River Site		Total for Five Sites	
	T ^a	U ^b	T	U	T	U	T	U	T	U	T	U
I	0	0	8.1	5.2	108.2	0	0	0	0	0	116.3	5.2
II	0	0	258.8	195.7	63.6	0.8	0	0	0	0	322.4	196.5
III	45.7	31.1	115.5	113.4	65.2	13.8	222.5	14.6	4113.3	1779.7	4562.2	1952.6
IV	0	0	0	0	2.8	2.8	0	0	0	0	2.80	2.8
Total	45.7	31.1	382.4	314.3	239.8	17.4	222.5	14.6	4113.3	1779.7	5003.7	2157.1

^a T =Total Pu-238 Volume at the Site

^b U = Unshippable because wattage of the waste exceeds the wattage limits of the TRUPACT-II. This includes waste currently packaged in boxes that would exceed wattage limits if repackaged, with no volume expansion, into drums.

¹ At the time this study was initiated, the Idaho National Engineering and Environmental Laboratory was going to be thermally treating its Pu-238 TRU waste in the Advanced Mixed Waste Treatment Facility. Since then, the treatment technology has changed to supercompaction. This change may mean that a decision analysis for Pu-238 waste at the Idaho National Engineering and Environmental Laboratory is warranted.

FIGURE 1: Pu-238 TRU WASTE VOLUMES AT THE DOE GENERATOR SITES



1.2 Problem Statement

Five DOE waste sites have, collectively, more than 2,100 cubic meters (approximately 10,373 drum equivalents) of Pu-238 TRU waste that exceed the wattage restrictions of the TRUPACT-II. These sites are faced with a need to develop waste management practices that will enable the transportation of Pu-238 TRU waste to the WIPP for disposal. The DOE's Carlsbad Area Office has long recognized the need to address the issue of hydrogen generation in TRU waste during transport. To provide support and peer review of related test programs at the TRU waste sites, the Carlsbad Area Office formed a working group in 1992 and has provided funding for various studies, such as matrix depletion and hydrogen generation, and the use of hydrogen getters (Westinghouse Waste Isolation Division, 1998). The current status of these studies is summarized in Appendix E.

The DOE must decide if Pu-238 TRU waste should be repackaged or treated, or whether the DOE can establish sufficient technical bases to enable the NRC to modify the TRUPACT-II payload restrictions. The decisions are complex, affected by such factors as the volumes of Pu-238 TRU waste to be shipped after treatment or repackaging, uncertainties associated with a reliance on the outcomes of pending studies, costs, and other factors.

To illustrate the magnitude of the decisions to be made, using best-current-practices² repackaging of the 2,157 cubic meters of waste to meet the current wattage limits would result in about 32,000 cubic meters (about 152,716 drum equivalents) of Pu-238 TRU waste to be shipped to the

² One large liner bag, one small filtered bag, one-inch punctured liner, two-inch carbon composite filter.

WIPP. This would require 20 percent of the WIPP's contact-handled TRU waste capacity of 168,500 cubic meters to accommodate the disposal of Pu-238 TRU waste. It would also require 50 percent of the shipping resources allotted for contact-handled TRU waste (for both stored waste and newly generated waste) in *The National TRU Waste Management Plan* (DOE, 1997), while the pre-packaged volume (2,157 cubic meters) is now only 5 percent of the total stored contact-handled-TRU waste volume.

For these reasons, the issue of concern addressed herein can be stated as:

What are the most appropriate means for the DOE Complex to manage Pu-238 TRU waste, thus enabling the efficient transportation to the WIPP?

2. DECISION ANALYSIS

2.1 Introduction

Decision analysis is a method that provides a logical framework for addressing complex problems faced by a decision maker (Keeney and Raiffa, 1993). In the context of managing Pu-238 TRU waste, decision analysis provides the responsible decision maker with a quantitative means to evaluate the merits of decisions in light of the technical and regulatory uncertainties inherent in any decision. The probability of success for the management of Pu-238 TRU waste has two uncertainties – technical uncertainty and regulatory uncertainty. In broad terms technical uncertainties address the question of whether a proposed solution will be effective (i.e., will research bear a positive result). Regulatory uncertainties address the question of whether the NRC will accept a technical solution that the DOE may propose. Regulatory success depends on a positive result upon petitioning the NRC for a change in the Certificate of Compliance for the TRUPACT-II.

Recognizing these uncertainties, decision analysis offers the ability to augment and quantify intuition and judgment when considering decisions with multiple and conflicting objectives. Such decisions include those with alternatives (strategies) that, for example:

Decision Analysis
A tool to enable a decision maker to weigh the benefits of potential solutions against the uncertainties inherent in the implementation of those solutions.

- may not fully remedy a problem (i.e., cannot render all Pu-238 TRU waste transportable to the WIPP)
- may be exceptionally costly to implement in terms of schedule or funding consequences (e.g., committing to build thermal treatment facilities)
- involve complex interactions (e.g., NRC regulatory decisions, scientific basis for increasing wattage limits)
- offer competing objectives (e.g., cost maintenance versus disposal of all Pu-238 TRU waste).

Given this decision-making setting it is clear that the selection of appropriate strategies to enhance the management of Pu-238 TRU waste, and thus enable its efficient transportation to the WIPP for disposal, is a difficult decision.

2.2 Decision Analysis Process

The decision analysis process to assess the Pu-238 TRU waste problem included the following steps:

1. **identification of strategic decisions** that could lead to the improved management of Pu-238 TRU waste. In this context, decisions involve strategies (alternatives) that are being, or have been, considered to lead to more efficient packaging and transport.
2. **identification of uncertainties** associated with those strategic decisions. Each of the strategic decisions has an associated uncertainty (e.g., degree of effectiveness, regulatory uncertainty) about the outcome of the decision. Uncertainties are quantified through the use of expert elicitation (judgment).
3. **compilation of the decision tree.** The decision tree is the strategy-by-strategy vehicle that links the decisions with their associated uncertainties in such a way as to enable analysis of a variety of outcomes. It provides the basis for the decision analysis model.
4. **definition of performance measures.** Performance measures are used to quantify the relative merits of each possible outcome of the decision tree. The performance measures include total system life-cycle cost, volume disposed by 2006, and demand on shipping resources.
5. **development of the decision analysis model.** The decision analysis model is the analytical tool used to quantify the possible outcomes of the decision tree in terms of the performance measures. Separate computational models for each performance measure are developed and linked to the decision tree for evaluation.
6. **data collection and expert elicitation.** Data collection involves the development of source information to support calculation of the individual performance measures. Data collection also includes development of background information needed to conduct expert elicitation. Expert elicitation focuses the professional judgment of subject matter experts to develop probability distributions by considering relevant experimentally-derived data and information, knowledge of data-related uncertainties, and other factors. These probability distributions are in turn used to assess the uncertainties in the decision tree.
7. **model analysis and results evaluation.** Once supporting information has been collected and the experts have been polled about the uncertainties in the decision tree, each strategy is evaluated in terms of the performance measures. Sensitivity analyses are run to determine the key uncertainties in the decision tree, and expected values for the performance measures are calculated. The path with the best-expected outcome can be identified.

Steps 1 through 6 are discussed below. The results of the decision analysis, step 7, are discussed in Sections 3.0 and 4.0.

2.2.1 Decisions

The decision analysis process started with a “brainstorming” session to develop a list of relevant decisions that must be made. Once a decision list was compiled, the decisions were classified as policies, tactical decisions, or strategic decisions. **Policies** are decisions that have already been

made and will serve as guides and boundaries for future decisions. The decision that Pu-238 TRU waste will be disposed of in the WIPP is a *policy*. **Tactical decisions** are determinations that do not set the general course of a program or activity, but are needed to implement the program or activity. Determinations that set the general course of the program or activity are **strategic decisions**. Strategic decisions reflect the likely approaches for the improved management and transportation of Pu-238 TRU waste and include research decisions, regulatory decisions, and treatment decisions (Table 3).

The strategic decisions shown in Table 3 reflect the basic approaches that have been considered within the DOE Complex to improve the efficiency of shipping Pu-238 TRU waste in the TRUPACT-II. However, there have been a few strategies put forth by various stakeholders that were initially considered during development of the decision analysis model, but were eventually eliminated from detailed study. These include the development of an explosion-proof overpack, development of a vented TRUPACT-II, and the use of an existing or a new certified Type B packaging. These strategies were eliminated either because they would be in violation of NRC regulations (overpack, venting), or because increased efficiencies in transport could not be demonstrated (new packaging, alternate packaging). More detailed discussions of these options are provided in Appendix A.

2.2.2 Uncertainties

Most of the strategic decisions shown in Table 3 have an uncertain outcome. That is, the effectiveness of the proposed research or the outcome of interactions with the NRC is unknown and cannot be predicted with certainty. Uncertainties are numerically estimated through the use of expert judgment. For example, headspace hydrogen gas sample concentrations could be used to show that hydrogen buildup in the innermost layer of confinement is below five percent for a number of Pu-238 TRU waste drums. However, the number of drums for which this can be demonstrated is uncertain (i.e., effectiveness of strategy) and can only be estimated at this time through the use of expert elicitation. The success of the strategy cannot be certain unless headspace gas measurements are taken on every drum.

2.2.3 Decision Tree

Combining strategic decisions and resulting uncertainties in the logical order in which management decisions are likely to be made results in a decision tree that can be used to quantitatively evaluate (model) the Pu-238 TRU waste problem (Figure 2). The logic presented in the decision tree shows a reliance first on the effectiveness of ongoing or proposed studies as they may improve efficiencies in the shipment of Pu-238 TRU waste in a TRUPACT-II, and second on treatment or repackaging the waste that still cannot be shipped in a TRUPACT-II. There are two strategic decisions represented (by squares) in the decision tree: (1) a research/regulatory decision and (2) a treatment/repackaging decision. From a management perspective, the research/regulatory decision would occur first. Once the outcome of the proposed research is estimated, decisions about treatment/repackaging options would then be made. Based on experience within the DOE Complex with thermal treatment systems, it is assumed that all Pu-238 TRU waste can be treated to remove organics and/or water and virtually eliminate the generation of hydrogen, or that waste can be repackaged to meet TRUPACT-II requirements (with subsequent volume expansion).

TABLE 3. STRATEGIC DECISIONS FOR TRANSPORTATION OF Pu-238 WASTE

Strategic Decisions	Significant Uncertainties	How This Is Represented in the Decision Tree
Research Decisions		
DOE uses the result of current experimental work on the use of hydrogen getters in waste drums to support an amendment of the TRUPACT-II payload restriction	The expected reaction rate for hydrogen getter materials in Pu-238 waste drums under testing conditions required by NRC is uncertain.	Branch off of first decision node; Path 1
DOE uses the result of current experimental work on matrix depletion and hydrogen generation to support an amendment of the TRUPACT-II payload restriction	The effective G-value for Pu-238 TRU waste is uncertain.	Branch off of first decision node; Path 2
DOE funds an investigation into the use of headspace hydrogen gas samples to show compliance with the "no greater than five percent hydrogen in the innermost layer of confinement" limit	The expected distribution of steady-state headspace hydrogen concentrations in Pu-238 TRU waste drums is uncertain.	Branch off of first decision node; Path 3
DOE funds an investigation into the use of hydrogen getter materials in the inner containment vessel of the TRUPACT-II to support an amendment of the TRUPACT-II payload restriction	The expected reaction rate for hydrogen getter materials in Pu-238 waste drums under testing conditions required by the NRC is uncertain.	Branch off of first decision node; Path 4
DOE funds an investigation into advanced filters for liner bags or drums	The expected diffusivity characteristic of hydrogen transport through advanced filters is uncertain.	Branch off of first decision node; Path 5
Regulatory Decisions		
DOE petitions the NRC to allow higher wattage limits for repackaged waste with hydrogen getters added to the headspace of the drums	NRC approval is uncertain.	Uncertainty Node on Path 1
DOE petitions the NRC to allow transportation of some Pu-238 waste "as is" in the TRUPACT-II because of matrix depletion and/or hydrogen generation study results	NRC approval is uncertain.	Uncertainty node on Path 2
DOE petitions the NRC to accept headspace hydrogen sample results as evidence that the five percent limit in the innermost layer of confinement has been met	NRC approval is uncertain.	Uncertainty Node in Path 3
DOE petitions the NRC to allow transportation of some Pu-238 waste if hydrogen getters are added to the inner containment vessel of the TRUPACT-II	NRC approval is uncertain.	Uncertainty Node in Path 4
DOE petitions the NRC to allow higher wattage limits for waste repackaged in bags or drums with advanced filters	NRC approval is uncertain.	Uncertainty Node in Path 5
Treatment Decisions		
DOE treats the Pu-238 waste	No uncertainty; it is assumed that all Pu-238 waste can be treated to remove water and organics.	Branch off of second decision node
DOE repackages the Pu-238 waste	No uncertainty; it is assumed that all Pu-238 TRU waste can be repackaged to meet TRUPACT-II requirements.	Branch off of second decision node

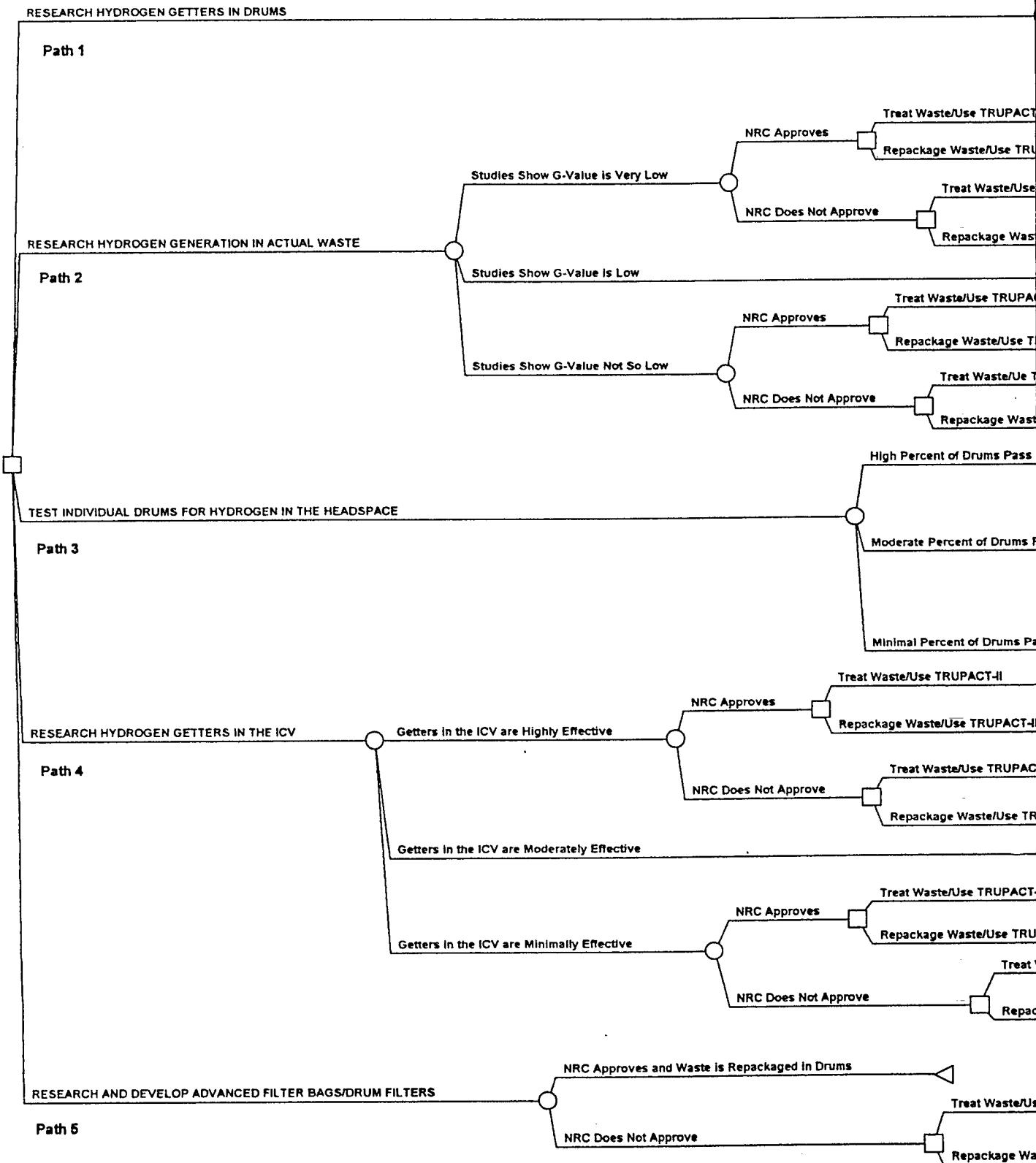
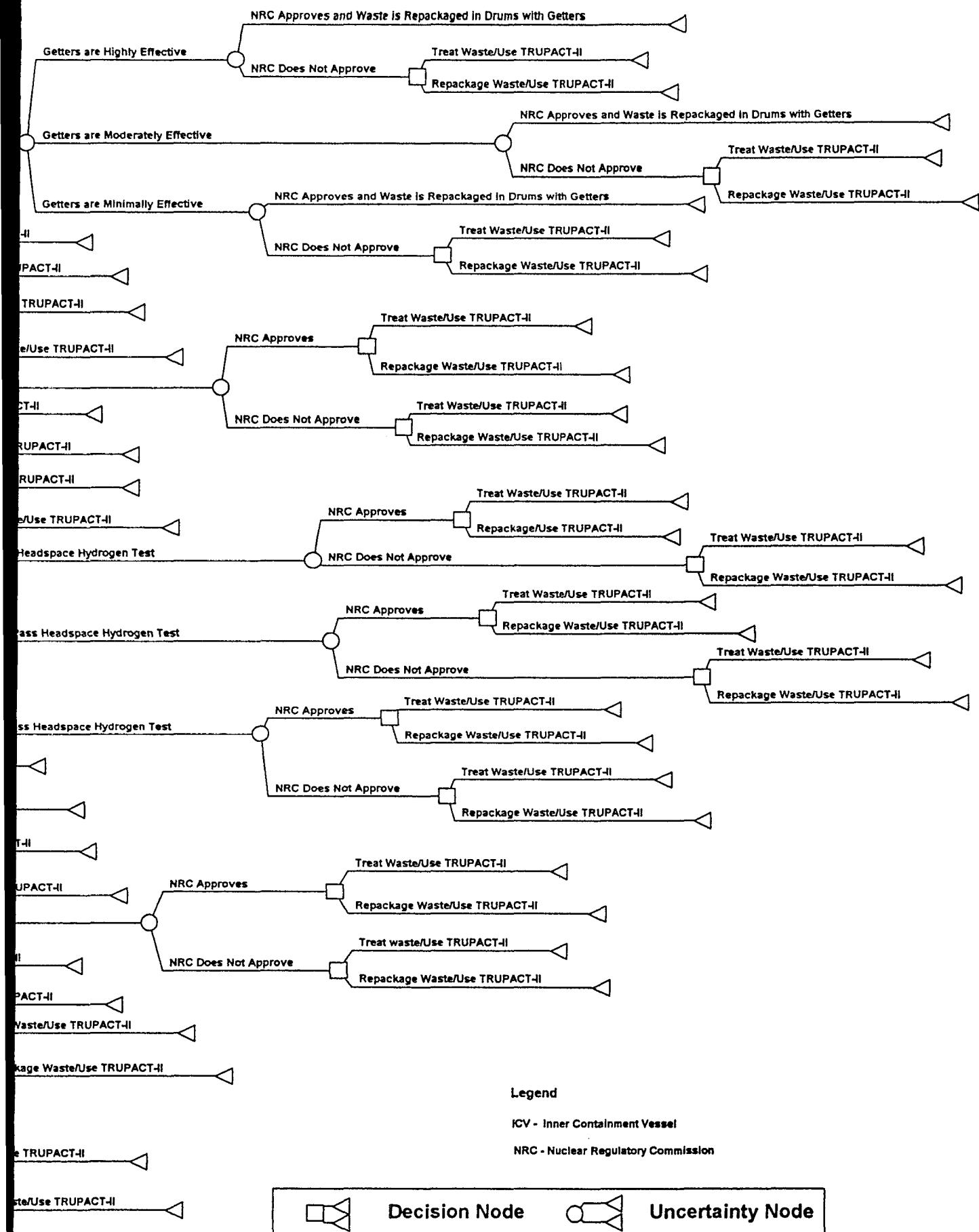


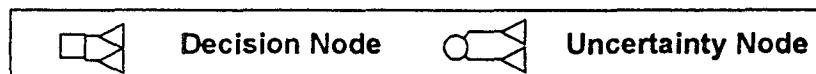
Figure 2. DECISION TREE FOR Pu-238 TRU WASTE MANAGEMENT



Legend

ICV - Inner Containment Vessel

NRC - Nuclear Regulatory Commission



9/30/98

It should be noted that the research and regulatory decisions shown in Table 3 were combined into one decision node in the decision tree because the two decisions are linked. That is, any effort to petition the NRC for a change in the packaging criteria would result from DOE research. The result is five paths emanating from the research/regulatory decision node (first square node in the decision tree) as follows:

- *Path 1* - DOE research shows that adding hydrogen getter materials to the headspace of the drums can reduce the number of drums produced when Pu-238 TRU waste is repackaged for shipment to the WIPP. The DOE petitions the NRC to allow the use of hydrogen getter materials in TRU waste drums. The NRC either approves or denies the petition. If the NRC approves the petition, all of the waste is repackaged with getters and transported to the WIPP in the TRUPACT-II. If the NRC denies the petition, a further decision is made to either treat or repack the waste without getters and transport it to the WIPP in the TRUPACT-II.
- *Path 2* - Matrix depletion and hydrogen generation studies show that the effective G-values (number of molecules of gas generated per 100 electron volts [eV]) for actual TRU waste are lower than the G-values currently used to calculate wattage limits. The DOE petitions the NRC for a change in wattage limits for TRU waste based on the study results. The NRC either approves or denies the petition. Containers that qualify based on the new, higher wattage limits are shipped in the TRUPACT-II without treatment or repackaging. The remaining Pu-238 TRU waste is either treated or repackaged and shipped to the WIPP in the TRUPACT-II.
- *Path 3* - The DOE has demonstrated that the hydrogen concentration in the headspace of the drum is related mathematically to the hydrogen concentration in the innermost layer of confinement. The DOE petitions the NRC to allow the use of hydrogen headspace gas sampling as a method to certify containers for shipment in the TRUPACT-II³. If the NRC approves the use of headspace gas sample results to certify containers for shipping to the WIPP, sampled containers that show less than five percent hydrogen concentration in the innermost layer (calculated from the headspace sampling results) will be shipped to the WIPP in the TRUPACT-II without treatment or repackaging. The remaining Pu-238 TRU waste is either treated or repackaged and shipped to the WIPP in the TRUPACT-II.
- *Path 4* - DOE research shows that adding hydrogen getter materials to the inner containment vessel of the TRUPACT-II can increase the number of Pu-238 TRU waste drums that can be shipped without repackaging. The DOE petitions the NRC to allow the use of hydrogen getter materials in the inner containment vessel. The NRC either approves or denies the petition. Containers that qualify based on the new wattage limits are shipped in the TRUPACT-II without treatment or repackaging. The remaining Pu-238 TRU waste is either treated or repackaged and shipped to the WIPP in the TRUPACT-II.

³ It is recognized that other methods to certify containers for shipment are under development; headspace gas sampling was selected for purposes of analysis.

- *Path 5* - The DOE conducts experiments to develop and test advanced bag and drum filters, and then petitions the NRC to allow the use of the filters. If the NRC approves the use of advanced filters, all of the waste is repackaged using advanced bag and drum filters and shipped in the TRUPACT-II.

The research/regulatory decision has two associated uncertainties (represented by circles in the decision tree) that impact strategy effectiveness. First, there is a technical uncertainty about the outcome of the research. Research results may or may not be favorable. Uncertainty in research results is represented in the decision tree by a three-state uncertainty node⁴ where the DOE investigations lead to: (1) highly positive results, (2) moderately positive results, or (3) minimally positive results. For example, the first uncertainty node shown in Path 1 represents uncertainty about the results of the hydrogen getter study where researchers are measuring the rate of reaction for getter materials in various environments (including various temperatures, pressures, and the presence of potential poisons). The higher the getter reaction rate, the more effective getter materials will be in allowing the shipment of higher wattage drums. The three states shown for technical uncertainty in Path 1 correspond to three different reaction rates: (1) a "high" rate, (2) a "moderate" rate, and (3) a "low" rate. "High," "moderate," and "low" are relative and are determined through expert elicitation.

The second uncertainty associated with the research decision is the outcome of interactions with the NRC. The NRC may approve or deny a petition to modify the Certificate of Compliance for the TRUPACT-II. Thus, a two-state node in the decision tree represents NRC uncertainty. Section 2.2.6 provides additional information about the probability distributions used to quantify technical and regulatory uncertainties.

2.2.4 Performance Measures

Three performance measures were used to quantify the relative merits of the alternatives represented by the paths of the decision tree⁵. These measures provide an index to compare the relative merits of the various paths. As such, they may not reflect the outcome if the DOE pursued a particular path. For example, the cost estimates may not be "accurate" because the assumptions may prove unrealistic, because certain activities are not considered, or because costs may vary among sites. However, the performance measures are constructed to enable a consistent comparison among the paths.

Performance Measures
Measures to quantify the decision maker's intuition and judgment.

1. **Volume Disposed by 2006.** This measure is defined as the volume (55-gallon drums) of Pu-238 TRU waste that can be disposed by the end of fiscal year 2006 (DOE, 1998c). This measure was chosen as a means to discriminate among the strategies by reflecting the time requirements to implement various technical solutions, and thus the ability to comply with the goals established by the DOE to accelerate cleanup at its sites (DOE, 1998c), and to maximize disposal of the waste in the near-term. For example, the time to complete research

⁴ While uncertainties are frequently represented by continuous probability distributions, in decision analysis, continuous probability distributions are simplified by using discrete states (Applied Decision Analysis, 1997).

⁵ Appendix A provides additional information on the suite of measures considered.

programs and obtain NRC approval of the use of hydrogen getters when compared to the time to construct a thermal treatment facility affects the extent to which TRU waste can be disposed by 2006.

2. **Demand on Shipping Resources.** This measure is defined as the volume (55-gallon drum equivalents) of Pu-238 TRU waste that exceeds current projected shipping resources as stated in *The National TRU Waste Management Plan* (DOE, 1997). *The National TRU Waste Management Plan* describes each site's planned waste processing logic, shipping rates, and durations. Only a fraction of the total waste shipments from each site (proportional to the volume fraction of Pu-238 TRU waste) are available for shipping Pu-238 TRU waste. Strategies that produce relatively large volumes of Pu-238 TRU waste during processing will create a volume that could not be shipped, given the current shipping assumptions of *The National TRU Waste Management Plan*.
3. **Total System Life-Cycle Cost.** This measure is defined as the entire suite of costs associated with the implementation of each strategy. Life-cycle costs (1998 dollars) were chosen as a means to discriminate among strategies, recognizing that costs are an important component of the decision-making process to allocate waste management funds. Thus, life-cycle costs include those associated with the conduct of each study (e.g., advanced filter research) and the NRC regulatory review process. Life-cycle costs also include those from the transport of Pu-238 TRU waste and those from initial design through closure of repackaging and treatment facilities and their ancillary facilities (e.g., characterization and loading facilities).

2.2.5 Decision Analysis Model

The decision analysis model is the analytical tool used to quantify the possible outcomes of the decision tree (Figure 2) in terms of the performance measures. Separate computational models for each performance measure were developed and linked to the decision tree for evaluation.

2.2.5.1 Performance Measure Model - Waste Volumes

The foundation for calculating Pu-238 TRU waste volumes is a container-specific inventory provided by each of the generator sites. The inventory was evaluated first on a container-by-container basis to determine which containers exceeded the current wattage limits for the shipping categories. Containers that met the wattage limits were eliminated from further evaluation⁶.

For containers that exceeded the wattage limits for the TRUPACT-II, a spreadsheet was developed to analyze the following questions:

1. What if the waste were repackaged using the best currently approved filters, and hydrogen getters were added to the headspace of the drum? How would the wattage limit change and what volume expansion could be expected (Path 1 in the decision tree)?
2. What if studies show that the effective G-value is lower than previously assumed, and the NRC agrees to accept a lower effective G-value for a waste type? How would the wattage

⁶ This analysis does not address the issue of absolute shippability (i.e., meeting other waste acceptance criteria). The drum may not be shippable because of other concerns.

limit change, and would the container be shippable under the new wattage limit (Path 2 in the decision tree)?

3. What if the DOE can show that a headspace gas sample analysis on the container can be used to accurately determine (through calculation) the concentration of hydrogen in the innermost layer of confinement? If the NRC approves this method, will analysis of the headspace gases from this container show that it is shippable (Path 3 in the decision tree)?
4. What if the container were loaded in the TRUPACT-II "as is," and hydrogen getters were added to the inner containment vessel? How would the wattage limit change, and could the container be shipped (Path 4 in the decision tree)?
5. What if a more advanced set of bag and drum filters were developed and tested, and the waste were repackaged using the new filters? How would the wattage limits change and what volume expansion could be expected (Path 5 of the decision tree)?

The model was then used to evaluate each of the Pu-238 TRU waste containers to determine the number of containers that could be shipped "as-is," the number of containers that would be produced through repackaging, and the number of containers that would be produced through treatment. The evaluation was performed for each of the five paths of the decision tree (Figure 2). Additional information about calculated volumes can be found in Appendix B.

2.2.5.1.1 Volume Disposed by 2006

The evaluation for this performance measure assumed that currently funded and proposed research efforts, and regulatory decisions from the NRC could be accomplished within a few years (i.e., by 2006). Therefore, waste that could be shown to be shippable as a result of research and regulatory efforts (i.e., "as is") would be shippable in the near term. Conversely, it was assumed that any waste requiring repackaging (e.g., Path 1-getters in the container) or treatment to meet the payload restrictions of the TRUPACT-II could not be disposed of in the near term.

For repackaging, it was assumed that facilities identified in *The National TRU Waste Management Plan* (DOE, 1997) would be unavailable until all other contact-handled TRU waste was processed. This is because of the unique contamination concerns (e.g., relatively easy spread of Pu-238 fines) that arise with Pu-238 TRU waste (Congdon, 1996). For treatment the evaluation assumed that a treatment facility would be constructed on each site. Design of the facility, obtaining the necessary funding, and construction and startup could not be accomplished prior to 2006. Consequently, only waste that could be shipped "as is" under the strategies outlined in the decision tree is (Figure 2) available for disposal in the near term (by 2006).

2.2.5.1.2 Demand on Shipping Resources

The evaluation for this performance measure required a comparison of the Pu-238 TRU drum equivalents that could be shipped "as is", or produced through repackaging or treatment, to the shipping resources available for contact-handled Pu-238 TRU waste as outlined in *The National TRU Waste Management Plan* (DOE, 1997). In *The National TRU Waste Management Plan*, shipping from the sites has been coordinated to optimize use of the WIPP waste handling capacity and the projected shipping fleet size for contact-handled TRU waste. Each of the sites has been scheduled to make a given number of shipments over the lifetime of the WIPP. Based

on *The National TRU Waste Management Plan*, the current volume of Pu-238 TRU waste in storage would require a small portion of the scheduled shipments of contact-handled TRU waste from each site (Table 4).

TABLE 4. NUMBER OF Pu-238 TRU WASTE SHIPMENTS BASED ON THE NATIONAL TRU WASTE MANAGEMENT PLAN

Total Shipments	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
Contact-Handled TRU Waste	2,333	2,111	45	63	3,013	7,565
Pu-238 TRU Waste	6	84	4	1	306	401

2.2.5.2 Performance Measure Model - Cost

The cost model, which calculates costs for each of the paths of the decision tree, consists of two parts – fixed costs and volume-dependent costs. Fixed costs include costs for performing studies and developing and submitting proposals to the NRC. Costs for building and/or operating treatment or repackaging facilities, transportation costs, and other associated costs that depend on the amount of waste to be processed and transported are calculated from the information developed in the waste volume model.

Fixed costs for the Pu-238 decision analysis include:

- Costs for performing studies to develop a method for calculating hydrogen concentration in the innermost layer of confinement based on headspace gas measurements.
- Costs for performing studies to determine the effectiveness of adding getters to the inner containment vessel.
- Costs for performing studies to determine the effectiveness of advanced filters.

However, costs for performing these studies were set to zero, primarily because these costs have already been incurred or the studies are already funded.

Interactions with the NRC, including the cost for developing the application to the NRC for approval of changes to transportation requirements based on the results of studies and working with the NRC during the review period, have also been funded. Therefore, no costs for the NRC applications have been included in the cost model.

Volume-dependent costs are costs associated with disposition of waste after the outcomes of studies and NRC decisions have been determined. If the NRC approves the DOE's petition for Path 2 (Matrix Depletion), Path 3 (Drum Testing), or Path 4 (Getters in the inner containment vessel), some of the waste may be transportable "as is" without repackaging. Costs for this waste would include any fixed costs (discussed in Appendix C-1.1); costs for loading and unloading the waste and, in the case of Path 4, adding getters to the inner containment vessel; and costs for transporting the waste. Regardless of the NRC's decision, some or all of the waste from each site

will be either repackaged or treated and the resulting TRUPACT-II-compliant waste will be transported to the WIPP. In this analysis, treatment of Pu-238 TRU waste would involve thermal treatment to remove residual moisture and destroy organic materials in the waste. For purposes of this analysis, it was assumed that a treatment facility would include open-dump-and-sort, thermal treatment/vitrification, treatment for "special" wastes (e.g., size reduction), and packaging and loading capabilities. A facility, sized to accommodate the amount of waste to be treated, would be built at each of the five sites. Costs for the treatment facilities account for the waste types and amounts to be treated, and are scaled from the conceptual costs developed for a similar waste treatment facility at the Savannah River Site. The facility capital expenditures were scaled by waste volume using the correlation provided by Peters and Timmerhaus (1968). Operating costs were based on information provided by the Savannah River Site.

For purposes of this analysis, it was assumed that a repackaging facility would include open-dump-and-sort, and repackaging the waste into bags and drums (with or without hydrogen getters) to meet current wattage limits using the "best" currently approved bag and drum filters⁷. Loading facilities also would be required. It was further assumed that separate repackaging facilities would be required at each of the sites. Costs for the repackaging facilities account for the waste types and amounts to be repackaged, and are scaled from the conceptual costs developed for a similar repackaging facility at Savannah River Site. The facility capital costs were scaled by waste volume at each site using the correlation provided by Peters and Timmerhaus (1968). Operating costs were based on information obtained from the Savannah River Site.

Transportation costs include costs for preparing the waste for shipment, loading and unloading, and shipping (per-mile costs) to the WIPP. Preparation of waste considers the costs, for example, of adding getters to drums or the inner containment vessel of the TRUPACT-II. It was assumed that the current fleet of TRUPACT-IIs and tractor/trailers would be used and thus fleet costs were set to zero. The cost information was derived primarily from the *Contact-Handled-Waste Packaging Optimization Report Revision 1* (DOE, 1995a) and the *Evaluation of Feasibility Studies for Private Sector Treatment of Alpha and TRU Mixed Wastes* (DOE, 1995b).

Additional information can be found in Appendix C.

2.2.6 Data Collection

Generally, data collection involved the identification of the information needed to support the computational models (e.g., inventory, cost elements, time values, and waste processing volumes). Information relevant to the ongoing and proposed studies, relevant regulatory information, NRC application review practices, and thermal treatment and waste repackaging practices were reviewed. The following discussion focuses on key aspects of the data collection process: the inventory and the expert elicitation process.

⁷ It is recognized that other less invasive means are being considered to repackage containers. For example, it has been proposed that high-pressure grout injection or abrasive systems could shred inner bags prior to the addition of hydrogen getter materials.

2.2.6.1 Inventory

Each of the five sites with heat source Pu-238 TRU waste in storage (Hanford Reservation, Los Alamos National Laboratory, Mound Plant, Oak Ridge National Laboratory, Savannah River Site) were contacted to obtain information relevant to the inventory of interest, including:

- container types (e.g., drums, boxes), volumes on a container basis, and numbers
- activities and/or gram loadings of plutonium isotopes
- waste descriptions and appropriate site identifier codes
- TRUCON codes, and
- wattages.

The information, which was requested on a container-by-container basis, was then normalized to 55-gallon drum equivalents.

Not all sites provided the same type of information. For example, only the Savannah River Site provided estimates of container wattages, and thus wattages for the other sites were calculated based on the container activity or gram loading of all plutonium isotopes. In some instances TRUCON codes were provided, and waste descriptions and packaging configurations (waste type, waste material types, number of layers of confinement) could be determined. If TRUCON codes were not submitted, they were estimated for the containers based on other submitted information. For other sites, package configurations could only be surmised based on the waste descriptions. The sites verified the approaches to estimating wattages and package configurations.

The inventory information, specifically the wattages, waste descriptions, and package configurations (container type, layers of internal confinement), was then used to identify the containers of Pu-238 TRU waste that could be shipped (based on wattage restrictions) in a TRUPACT-II and those that could not be shipped. For drums, a direct comparison between the watts per drum and the wattage limit per drum was made. If the watts in a drum exceeded the wattage limit, that drum was included in the inventory of waste that is not shippable. If the watts in a drum did not exceed the wattage limit, that drum was eliminated from the inventory of waste that cannot be shipped.

Pu-238 TRU waste currently residing in boxes will have to be repackaged, at the very least, before it can be shipped to the WIPP. Some of the Pu-238 TRU waste in boxes could be repackaged into drums with no volume expansion and still meet the wattage limits. This volume of Pu-238 TRU waste was eliminated from the inventory of waste that cannot be shipped. Some of the Pu-238 TRU waste in boxes, if repackaged into drums using the current site-specific packaging configuration, would not meet the wattage limits unless the volume is expanded (a smaller volume of waste per drum). This volume of Pu-238 TRU waste was included in the inventory of waste that is not shippable because of TRUPACT-II wattage limits.

This drum equivalent, "unshippable" inventory provides the baseline for the decision analysis (Table 2).

2.2.6.2 Expert Elicitation

Expert elicitation was used to quantify the uncertainties identified in the decision tree. Experts familiar with the DOE research into the use of hydrogen getters, matrix depletion, headspace gas sample results for TRU waste, and advanced filters comprised panels on technical uncertainty (see Appendix D). Experts familiar with the NRC review and approval process, as well as past NRC decisions, comprised a panel on regulatory uncertainty (see Appendix D). Notes from the elicitation workshop are included as Appendix D.

Expert Elicitation
The project used subject matter experts recommended by the TRU waste sites to quantify the technical and regulatory uncertainties identified in the Pu-238 TRU waste decision tree.

2.2.6.2.1 Expert Elicitation - Adding Hydrogen Getters to the Drums

Uncertainties associated with adding hydrogen getters to the Pu-238 TRU waste drums include a technical uncertainty regarding the outcome of ongoing hydrogen getter research and a regulatory uncertainty regarding whether the NRC would approve the use of hydrogen getters in Pu-238 TRU waste drums.

Preliminary research on hydrogen getters indicates that the performance of hydrogen getters in some environments is uncertain (Appendix D). Even though hydrogen getters have been shown to have ample capacity, reaction rate, and ability to mitigate hydrogen buildup in the headspace of the drum, uncertainties about their performance in the presence of certain compounds (poisons) or at low temperatures remain. For these reasons an elicitation was performed.

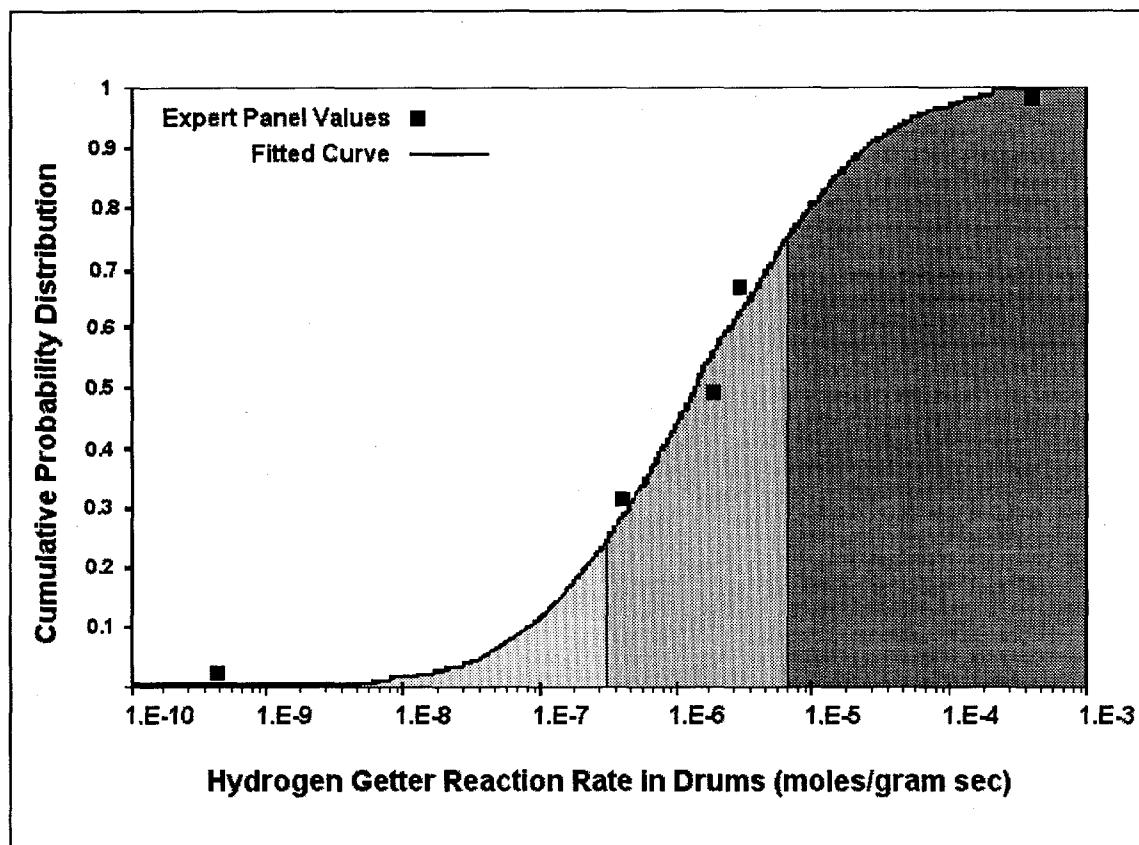
The expert panel examined a number of issues in addition to those mentioned above. The panel felt that the effect of variations in pressure would be small compared to the effect of temperature, primarily because of the range of operating temperatures specified by the NRC (-20°F to 146°F) for Type B packagings. Therefore, pressure variations were not considered in the elicitation. Accident scenarios also were not considered because the panel felt that containment of the waste was an issue of greater importance than buildup of hydrogen gas during accident scenarios.

The deliberations of the panel resulted in the probability distribution for hydrogen getter reaction rates shown in Figure 3. The expert panel agreed that hydrogen getter reaction rates could vary from on the order of 1.0E-10 moles/gram second to 1.0E-4 moles/gram second, but the most likely value was around 3.0E-6 moles/gram second. The panel assigned a lognormal distribution to the range of values with a 33 percent chance that the reaction rate would be less than or equal to about 8.0E-7 moles/gram second, and a 67 percent chance that the reaction rate would be less than or equal to around 3.0E-6 moles/gram second.

When the probability distribution was discretized for application to the decision tree (Figure 2), three intervals of uncertainty, shown by shading in Figure 3 were defined. For the lower uncertainty interval, there is a 25 percent probability that the reaction rate is less than or equal to 3.8E-7 moles/gram second. This uncertainty interval is represented on the decision tree by the interval midpoint (8.2E-8 moles/gram second) and is assigned a probability of 0.25. For the middle interval, there is a 50 percent probability that the reaction rate is between 3.8E-7

moles/gram second and 7E-6 moles/gram second. This uncertainty is represented on the decision tree by the interval midpoint (3.0E-6 moles/gram second) and is assigned a probability of 0.5. For the upper interval, there is a 25 percent probability that the reaction rate is greater than or equal to 7E-6 moles/gram second. This uncertainty is represented on the decision tree by the interval midpoint (2.5E-5 moles/gram second) and is assigned a probability of 0.25.

FIGURE 3. CUMULATIVE PROBABILITY DISTRIBUTION FOR TECHNICAL UNCERTAINTY IN PATH 1



After the panel on technical uncertainty developed the cumulative probability distribution for hydrogen getter reaction rate, a panel of three experts on the NRC approval process discussed the probability of NRC approval for Path 1. In general, the panel was pessimistic about NRC approval for Path 1 (Table 5). All panel members were polled, and the most optimistic response given was a 50 percent chance of approval. The least optimistic response given was a 10 percent probability of approval. The other response was a 20 percent probability of approval. Appendix D provides details from the technical and regulatory elicitations including, for example, the results of technical and regulatory discussions among the subject matter experts, definitions of the elicitation variables, working assumptions, and details of the resulting probability distributions.

TABLE 5. PROBABILITY OF NRC APPROVAL

NRC Approval of:	Highest Panel Member Response for Probability of Approval	Intermediate Panel Member Response for Probability of Approval	Lowest Panel Member Response for Probability of Approval
Adding Hydrogen Getters to the Drums (Path 1)	.50	.20	.10
Lowering G-values Based on Hydrogen Generation Tests (Path 2)	.60	.30	.25
Drum Certification Based on Headspace Hydrogen Tests (Path 3)	.70	.60	.40
Adding Hydrogen Getters to the Inner Containment Vessel of the TRUPACT-II (Path 4)	.75	.75	.70
Using Advanced Drum and Bag Filters (Path 5)	.95	.90	.80

2.2.6.2.2 Expert Elicitation - Matrix Depletion/Hydrogen Generation Studies

Uncertainties associated with Path 2 include a technical uncertainty regarding the outcome of ongoing matrix depletion and hydrogen generation studies, and a regulatory uncertainty of whether the NRC would approve new G-values.

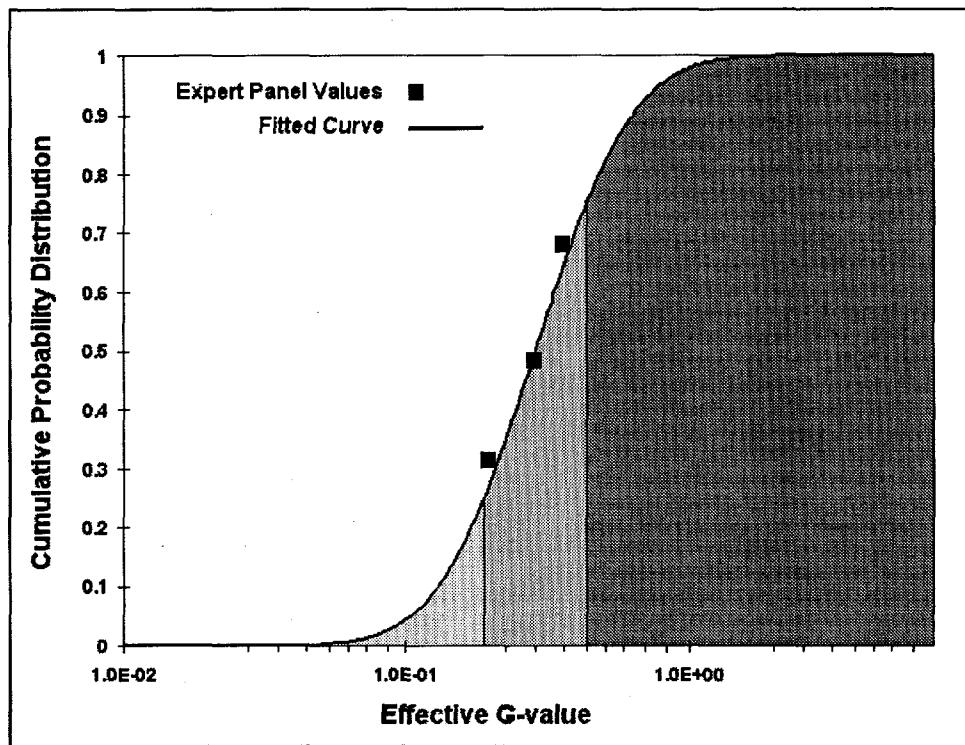
Recent studies of hydrogen generation in actual waste (IT Corporation, 1997) and studies of matrix depletion in polypropylene indicate that the effects of matrix depletion are measurable in a meaningful time frame. However, there is still uncertainty about the effect that loading and transporting of drums has on matrix depletion, how much matrix depletion can be evidenced in Pu-238 TRU waste drums, and if variations in temperature affect matrix depletion. An elicitation on the effective G-value for Pu-238 TRU wastes was performed, and the cumulative probability distribution for Waste Type III shown in Figure 4 was developed.

The expert panel (see Appendix D) determined that matrix depletion would not affect Waste Type I because it contains adsorbed water, which is able to move more freely within the waste matrix, and therefore does not become depleted near the Pu-238 particles as fixed molecules do. Therefore, Waste Type I was not considered in the elicitation. The panel also determined that there were too few data on Waste Type II to make an accurate determination of G-values for Type II waste. The panel assigned G-values for Waste Type II based on their estimates for Type III waste. The G-values selected for Waste Type II were essentially one-half those selected for Waste Type III, a precedent set in the *Safety Analysis Report for the TRUPACT-II Shipping Package* (DOE, 1998b).

The panel agreed that the G-value for Waste Type III would not fall outside the range of 0 to 4.1 (4.1 is the value given in the *Safety Analysis Report for the TRUPACT-II Shipping Package* [DOE, 1998b]). The most likely G-value identified by the panel was about 0.3. The panel assigned a lognormal distribution to the range of values with a 33 percent chance that the G-value would be less than or equal to 0.18 and a 67 percent chance that the G-value would be less than or equal to 0.4.

When the probability distribution for Waste Type III was discretized for application to the decision tree (Figure 2), three intervals of uncertainty, shown by shading in Figure 4, were defined. For the lower interval, there is a 25 percent probability that the G-value is less than or equal to 0.17. This uncertainty interval is represented in the decision tree by the interval midpoint (G-value of 0.13) and is assigned a probability of 0.25. For the middle interval, there is a 50 percent probability that the G-value is between 0.17 and 0.5. This uncertainty interval is represented in the decision tree by the interval midpoint (G-value of 0.3) and is assigned a probability of 0.5. For the upper interval, there is a 25 percent probability that the G-value is greater than or equal to 0.5. This uncertainty is represented in the decision tree by the interval midpoint (G-value of 0.75) and is assigned a probability of 0.25.

FIGURE 4. CUMULATIVE PROBABILITY DISTRIBUTION FOR TECHNICAL UNCERTAINTY IN PATH 2,
WASTE TYPE III



The expert panel (see Appendix D) on regulatory approval were somewhat pessimistic about NRC approval for Path 2 (Table 5). The panel members were polled, and the most optimistic response given was a 60 percent probability of approval. The least optimistic response given was a 25 percent probability of approval. The other response was a 30 percent probability of approval. Appendix D provides details from the technical and regulatory elicitations including, for example, the results of technical and regulatory discussions among the subject matter experts, definitions of the elicitation variables, working assumptions, and details of the resulting probability distributions.

2.2.6.2.3 Expert Elicitation - Headspace Gas Sample Results

Uncertainties associated with Path 3 include a technical uncertainty of how many drums would pass the headspace gas test and a regulatory uncertainty of whether the NRC would approve of the alternate certification method.

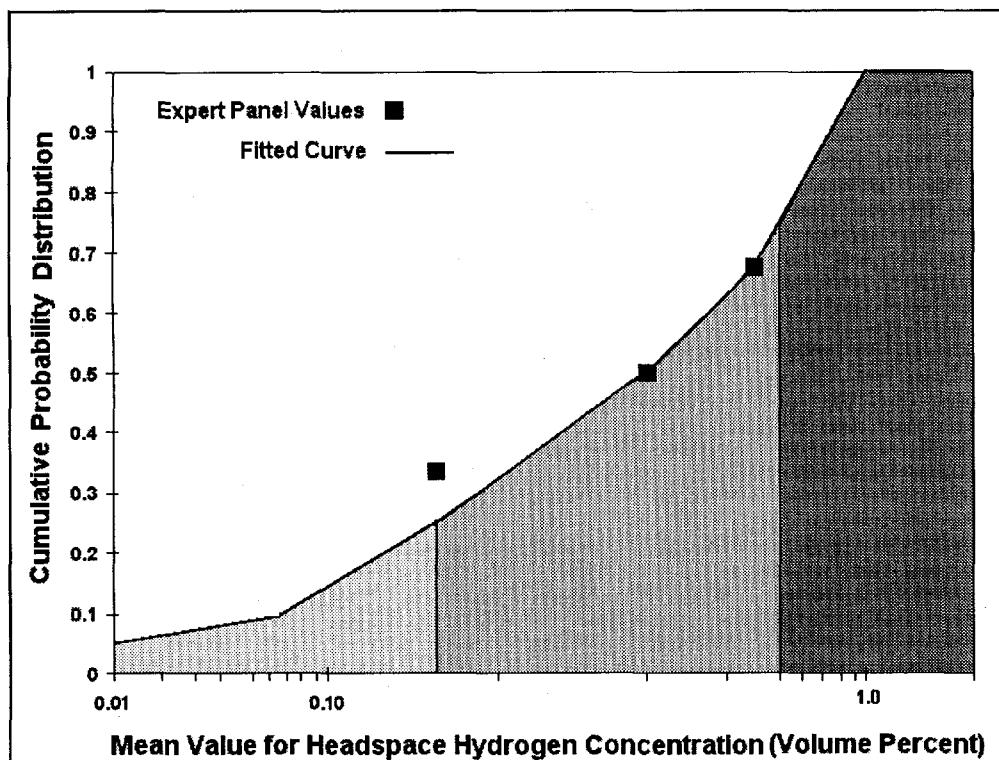
The DOE has demonstrated that the hydrogen concentrations in the headspace of a drum are related to the hydrogen concentrations in the innermost layer of confinement. This relationship could be used to certify containers for shipping to the WIPP. However, headspace concentrations of hydrogen and the distributions that represent these concentrations are not known in the inventory of Pu-238 TRU waste drums in the complex. Thus, the number of drums that could be certified for shipment using the headspace gas sampling technique is uncertain. For this reason an elicitation was performed.

For this elicitation the expert panel (see Appendix D) was asked to consider a population⁸ of Pu-238 TRU waste drums, identifying the mean value for the steady-state headspace hydrogen concentration in that population. The experts considered the potential effects of the layers of confinement, age of the waste, waste type, diffusivity characteristics of drum filters, and the isotopic mix in the Pu-238 TRU waste drums. As a result the panel determined the most likely value for the mean steady-state headspace hydrogen concentration to be 0.3 percent hydrogen; the range given was from 0.04 percent to 1.35 percent. The consensus cumulative probability values for the mean steady-state hydrogen concentration are shown in Figure 5. A curve was fitted to the consensus values. The fitted curve does not, however, represent any standard distribution.

When the curve was discretized for application to the decision tree (Figure 2), three intervals of uncertainty, shown by shading in Figure 5, were defined. For the lower interval, there is a 25 percent probability that the mean steady-state hydrogen concentration for a population of Pu-238 TRU waste drums is less than or equal to 0.14 percent (volume percent hydrogen). This uncertainty interval is represented on the decision tree as the interval midpoint (a mean steady-state hydrogen concentration value of 0.075 percent) and is assigned a probability of 0.25. For the middle interval, there is a 50 percent probability that the mean steady-state hydrogen concentration for a population of Pu-238 waste drums is between 0.14 percent and 0.50 percent. This uncertainty interval is represented on the decision tree by the interval midpoint (a mean steady-state hydrogen concentration value of 0.30 percent) and is assigned a probability of 0.50. For the upper interval, there is a 25 percent probability that the mean steady-state hydrogen concentration for a population of Pu-238 drums will be greater than or equal to 0.50 percent. This uncertainty is represented on the decision tree by the interval midpoint (a mean steady-state hydrogen concentration value of 0.75 percent) and is assigned a probability of 0.25.

⁸ Population refers to the inventory, a portion of an inventory, for which the expert had specific knowledge.

FIGURE 5. CUMULATIVE PROBABILITY DISTRIBUTION FOR TECHNICAL UNCERTAINTY IN PATH 3



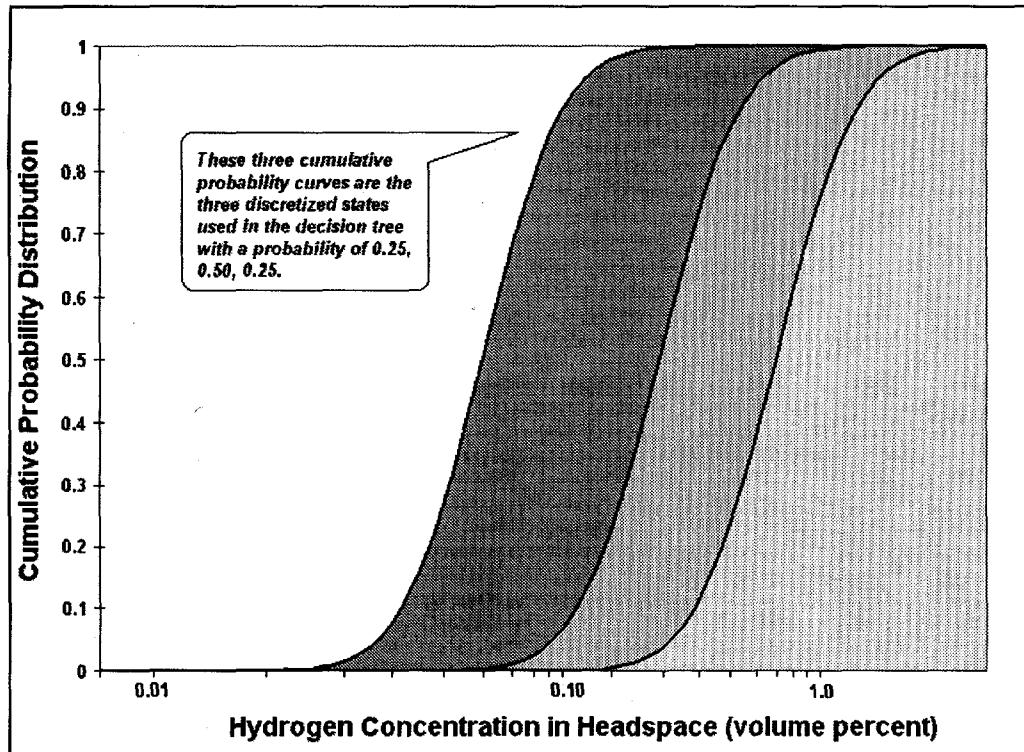
Given the three discrete mean steady-state hydrogen concentration values (0.075 percent, 0.3 percent, and 0.75 percent) chosen from Figure 5, the expert panel was asked to choose a distribution type for headspace hydrogen concentration in the population of Pu-238 drums. They chose a lognormal distribution. Then the expert panel was shown lognormal distributions with various standard deviations. They chose the standard deviation that best represented their belief about variability in headspace hydrogen concentration results. They chose a value for the standard deviation of 0.5. Combining the three discrete mean values, the distribution type, and the standard deviation gives the three curves shown in Figure 6. These are the three discrete states represented on the decision tree for Path 3.

The expert panel agreed that the middle curve shown in Figure 6 was the most likely distribution for the headspace hydrogen concentration in the inventory of Pu-238 TRU waste drums. This distribution was assigned a probability of 0.5 in the decision tree. The curves to the left and right of the center in Figure 5 represent two other states, which the experts agreed each had a probability of occurrence of 0.25 for the decision tree.

The panel (see Appendix D) on regulatory uncertainty was fairly optimistic about NRC approval for Path 3 (Table 5). The panel members were polled, and the most optimistic response given was a 70 percent probability of approval. The least optimistic response given was a 40 percent probability of approval. The other response was a 60 percent probability of approval. Appendix D provides details from the technical and regulatory elicitations including, for example, the results of technical and regulatory discussions among the subject matter experts, definitions of

the elicitation variables, working assumptions, and details of the resulting probability distributions.

FIGURE 6. REPRESENTATIVE STATES FOR HEADSPACE HYDROGEN CONCENTRATIONS, PATH 3



2.2.6.2.4 Expert Elicitation - Hydrogen Getters Research for Use in the TRUPACT-II Inner Containment Vessel

Uncertainties associated with Path 4 include a technical uncertainty regarding the outcome of ongoing hydrogen getter research and a regulatory uncertainty of whether the NRC would approve the use of hydrogen getters in the inner containment vessel of the TRUPACT-II.

Technical uncertainty surrounding the reaction rate for getters was discussed in Section 2.2.6.2.1. The expert panel determined that the issues that contribute to the technical uncertainty do not change if the getters are added to the inner containment vessel instead of the drum headspace. As a result, the probability distribution developed for Path 1 was also used for Path 4. The probability of NRC approval when getters are added to the inner containment vessel instead of the headspace of the drum did change, however. All three members of the regulatory uncertainty panel were polled, and the most optimistic response given was a 75 percent probability of approval (Table 5). The least optimistic response given was a 70 percent probability of approval. The other response was a 75 percent probability of approval. In general, they felt that the NRC was more likely to approve the use of getters in the inner containment vessel than the use of getters in the headspace of the drum. Appendix D provides details from the technical and regulatory elicitations including, for example, the results of technical and regulatory discussions

among the subject matter experts, definitions of the elicitation variables, working assumptions, and details of the resulting probability distributions.

2.2.6.2.5 Expert Elicitation - Research on Advanced Filters

The use of advanced filters in bags and Pu-238 TRU waste drums to control the buildup of hydrogen during transportation constitutes Path 5 on the decision tree. The addition of advanced filters to bags and drums has a significant impact on the wattage limit. Filter manufacturers (e.g., Nuclear Filters Technology, Ultratech) have developed and are testing advanced filters that have significantly lower resistances than the resistances of currently approved filters. These filters appear to meet other NRC requirements for bag and drum filters (e.g., retention of particles) as well.

Although the final filter diffusivities are somewhat uncertain, it appears that they would provide at least a ten-fold decrease in the resistance of the packaging layers of confinement. These filters also appear to meet the NRC's requirements and their characteristics are fairly well known.

Therefore, it has been assumed that a ten-fold decrease in the resistance values are achievable for Path 5. With a ten-fold decrease in the resistance values for bag and drum filters, the per-drum wattage limits begin to approach 2.86 watts per drum (the 40 watts per TRUPACT-II limit) and, while it is possible that more effective filters could be developed, the performance, in terms of increasing the wattage limit, would be essentially unchanged from the performance of the filters considered here. Therefore, the uncertainty in the performance of advanced filters is insignificant and was eliminated from consideration in the decision analysis.

The only uncertainty remaining for Path 5 is the uncertainty associated with NRC approval of advanced filters. The expert panel on regulatory approval (see Appendix D) was optimistic about NRC approval for Path 5. The three panel members were polled, and the responses ranged from an 80 to 95 percent chance of approval (Table 5).

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3. EVALUATING STRATEGIES IN TERMS OF PERFORMANCE

The individual merit of the proposed strategies shown in the decision tree (Figure 2) are quantified in terms of the performance measures defined in Section 2.2.4. Strategies for management of Pu-238 TRU waste have merit if relatively significant volumes of waste can be shipped "as is" by 2006, volume expansion is minimized upon repackaging or treatment, and total life-cycle system cost is minimized.

The analyses of Section 3 address only the technical uncertainties of each of the five strategies (i.e., assumes NRC approval and multiple strategies in combination). The results are presented for three cases (high, medium, low) for each performance measure in terms of the relative number of drum equivalents that could be shipped, the demand upon the shipping resources allotted to Pu-238 TRU waste by *The National TRU Waste Management Plan* (DOE, 1997), and the total life-cycle system cost. The parameter values resulting from the expert elicitations for the high, medium and low cases were discussed in Section 2.2.6.

Section 4 further evaluates the probability of technical success in consideration of the regulatory uncertainties posed by potential decisions by the NRC.

3.1 Evaluating Strategies - Volume Disposed by 2006

Based on the waste volume model (Section 2.2.5), this evaluation assesses the benefits of various studies in terms of the volume (drums) of Pu-238 TRU waste that could be shipped "as is" by 2006. This evaluation is germane only to paths 2, 3 and 4 of the decision tree (Figure 2) as these are the strategies for which the DOE would try to change the TRUPACT-II payload restrictions to enable shipment from the sites, without repackaging or treatment of the waste. As discussed in Section 2.2.5, development of new production-level repackaging or treatment facilities is assumed to be a multi-year endeavor, and the use of existing facilities are assumed to be unavailable until all other contact-handled TRU waste would be processed, because of the unique contamination concerns posed by Pu-238. For these reasons, **Paths 2, 3 and 4 are the only strategies that could result in meaningful Pu-238 TRU waste disposal by 2006** (Paths 1 and 5 require repackaging of all waste).

The results of the expert elicitations (Section 2.2.6.2) were used in the waste volume model to estimate the volume of Pu-238 TRU waste that could be shipped "as is" (i.e., without repackaging or treatment). Table 6 provides the results of this analysis in terms of drums and the relative effect to the current inventory (percent).

As an example of how Table 6 should be interpreted, the number of Pu-238 TRU waste drums that could be shipped as a result of headspace gas sample tests at Hanford could be as high as 39 drums. It could be as low as 30 drums, but it is most likely to be 38 drums, given the uncertainty in the distribution of hydrogen headspace concentrations in the inventory expressed by the expert panel.

TABLE 6. PERCENT OF CURRENTLY "UNSHIPPIBLE" Pu-238 TRU WASTE DRUMS DISPOSED BY 2006^a

		Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
As a Result of Matrix Depletion/Hydrogen Generation Studies (Path 2)							
Percent Drums	High Case	25% 37	17% 254	31% 26	39% 28	20% 1,746	20% 2,091
Percent Drums	Medium Case	24% 36	9% 133	23% 19	25% 18	13% 1,132	13% 1,338
Percent Drums	Low Case	21% 32	4% 64	10% 8	15% 11	10% 830	9% 945
As a Result of Headspace Gas Sample Tests (Path 3)							
Percent Drums	High Case	26% 39	34% 512	36% 30	70% 50	35% 3,018	35% 3,649
Percent Drums	Medium Case	26% 38	34% 509	36% 30	70% 50	35% 3,018	35% 3,645
Percent Drums	Low Case	20% 30	28% 431	25% 21	70% 50	34% 3,018	34% 3,550
As a Result of Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)							
Percent Drums	High Case	2% 3	2% 24	0	1% 1	3% 249	3% 277
Percent Drums	Medium Case	2% 3	2% 24	0	1% 1	3% 249	3% 277
Percent Drums	Low Case	2% 3	2% 24	0	1% 1	3% 249	3% 277

^aThis is the percent of the currently "unshippable" Pu-238 TRU waste drums (site-by-site) that could be shipped and disposed of "as is" without treatment or repackaging.

Based on the results given in Table 6, **placing getters in the inner containment vessel of the TRUPACT-II is not a preferred strategy**. At best, only three percent of the approximately 10,373 drum equivalents that cannot be shipped under the current payload restrictions could be shipped under revised payload restrictions if getters were added to the inner containment vessel of the TRUPACT-II. The effectiveness of getters in the inner containment vessel is minimal because release of hydrogen from the innermost layer of confinement is restricted by the packaging configuration. Most of the drums have two or more layers of confinement offering resistance to the movement of hydrogen. As a result, hydrogen is released to the inner containment vessel at a relatively slow rate, and hydrogen builds up in the inner layers.

Given the uncertainty expressed by the expert panel, **the benefit of ongoing matrix depletion and hydrogen generation studies appears to be less than previously estimated**. For example, the *Test Plan for Hydrogen Getters Research* (Mroz and Weinrach, 1998) states that about 33 percent of the Pu-238 TRU waste that is not shippable under the current payload restrictions for the TRUPACT-II would become shippable. This is because matrix depletion "is expected to result in raising the thermal limits by a factor of three." Although these expectations remain unchanged, the potential benefit of matrix depletion may not prove to be as much for Pu-238 as for Pu-239 TRU waste (Mroz and Weinrach, 1998). Table 6 indicates that, at most, about 17 percent of the Pu-238 TRU waste at Los Alamos National Laboratory could be shipped by 2006 as a result of matrix depletion, and it is more likely that only about 9 percent of the waste could be shipped. The benefit of the matrix depletion and hydrogen generation work is higher for the Mound Plant and Oak Ridge National Laboratory; but overall, it is likely that only about 13 percent of the Pu-238 TRU waste could be shipped as a result of matrix depletion and hydrogen generation studies.

Achieving Early Disposal

Headspace gas sampling offers the best opportunity to achieve early disposal of Pu-238 TRU waste.

Other strategies are relatively ineffective or offer less benefit than previously believed.

In contrast, however, the **use of headspace gas sample results to certify containers for shipment to the WIPP offers potentially significant benefits**. When the distributions provided by the expert panel were translated into the number of drums, up to 35 percent (3,645 drums) of the waste could be shipped. Thus, based on the expert panel results, using headspace sample results to certify drums for shipment has the promise to result in the disposal of significant quantities of Pu-238 TRU waste by 2006, without the need for additional treatment or repackaging.

3.2 Evaluating Strategies – Demand on Shipping Resources

Based on the waste volume model, this evaluation compares the Pu-238 TRU waste drums that could be shipped "as is", or produced through repackaging or treatment, to the shipping resources available for Pu-238 TRU waste as outlined in *The National TRU Waste Management Plan* (DOE, 1997a). *The National TRU Waste Management Plan* describes each site's planned waste processing logic, shipping rates and durations. Only a fraction of the contact-handled TRU waste

shipments from each site (proportional to the volume fraction of Pu-238 TRU waste) are available to ship Pu-238 TRU waste.

As mentioned previously, repackaging of the 2,100 cubic meters (10,373 drum equivalents) of Pu-238 TRU waste to meet the current wattage limits for the TRUPACT-II would result in about 32,000 cubic meters (152,716 drum equivalents) of waste to be shipped to the WIPP. This would require about 50 percent of the shipping resources allotted for contact-handled TRU waste in *The National TRU Waste Management Plan* (DOE, 1997) while the Pu-238 TRU waste volume (2,157 cubic meters) represents only five percent of all TRU waste.

Table 7 provides the results of this evaluation in terms of the percent of allotted shipping resources that would be required to ship repackaged Pu-238 TRU waste. Table 8 provides the percent of shipping resources that would be required to ship treated Pu-238 TRU waste. The drum equivalents, calculated by the waste volume model and used to estimate the impact to shipping resources, are also provided.

As an illustration, at the Hanford Reservation there exists 149 drum equivalents of Pu-238 TRU waste that represent about 0.19 percent of the volume of the Hanford Reservation's contact-handled TRU waste in storage. In *The National TRU Waste Management Plan*, Hanford is scheduled to make 2,333 shipments over the lifetime of the WIPP, with 6 of the shipments devoted to Pu-238 TRU waste. However, repackaging Pu-238 TRU waste at Hanford and adding hydrogen getters to the headspace of the drums would produce about 3,561 drum equivalents of processed Pu-238 TRU waste. This would require about 99 shipments (12 drums/TRUPACT-II; 3 TRUPACT-IIs/shipment). Therefore, the shipping resources required would be about 1,757 percent of the shipping resources allotted for Pu-238 TRU waste (DOE, 1997). Hanford is an extreme example because of a few drums of very high activity Pu-238 TRU waste (see Appendix B).

Need for Shipping Resources

Repackaging of Pu-238 TRU waste is likely to exceed the TRUPACT-II fleet size currently anticipated.

For the most part, the shipping of repackaged Pu-238 TRU waste will surpass the shipping resources allotted in *The National TRU Waste Management Plan* (DOE, 1997) (Table 7). The repackaging of Pu-238 TRU waste after consideration of the benefits of matrix depletion (Path 2), headspace gas sampling (Path 3), hydrogen getters in the inner containment vessel (Path 4) or advanced filters (Path 5) will exceed the allotted shipping resources (DOE, 1997) (Figure 7). Without regard to other factors such as the regulatory uncertainties associated with NRC decisions, it appears from Table 7 that repackaging in

combination with the application of hydrogen getters in the drums (Path 1) places the lowest demands on allotted shipping resources. However, this strategy will still require a reallocation of shipping resources among the sites.

TABLE 7. PERCENT OF ALLOTTED SHIPPING RESOURCES REQUIRED TO SHIP Pu-238 TRU WASTE DRUM EQUIVALENTS TO THE WIPP UNDER REPACKAGING STRATEGIES^a

	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
Repackaging by Itself						
Percent Drum Equivalents	8,259% 16,736	458% 13,851	128% 108	2,554% 907	942% 121,114	943% 152,716
Repackaging In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)						
Percent Drum Equivalents	High Case 3,561	122% 3,698	91% 77	532% 189	198% 25,413	203% 32,936
Percent Drum Equivalents	Medium Case 3,561	122% 3,698	91% 77	532% 189	198% 25,413	203% 32,936
Percent Drum Equivalents	Low Case 3,561	122% 3,698	91% 77	532% 189	198% 25,413	203% 32,936
Repackaging In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)						
Percent Drum Equivalents	High Case 16,732	451% 13,660	121% 101	2,438% 866	935% 120,183	935% 151,543
Percent Drum Equivalents	Medium Case 16,734	456% 13,796	128% 107	2,532% 899	942% 121,075	942% 152,610
Percent Drum Equivalents	Low Case 16,734	456% 13,800	128% 108	2,553% 906	942% 121,114	942% 152,663
Repackaging In Combination With Headspace Gas Sampling (Path 3)						
Percent Drum Equivalents	High Case 16,727	381% 11,533	86% 72	1,733% 615	868% 111,542	867% 140,488
Percent Drum Equivalents	Medium Case 16,730	387% 11,706	86% 72	1,733% 615	868% 111,542	868% 140,665
Percent Drum Equivalents	Low Case 16,734	426% 12,902	126% 106	1,733% 615	868% 111,542	868% 141,899
Repackaging In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)						
Percent Drum Equivalents	High Case 16,734	458% 13,851	128% 108	2,554% 907	942% 121,114	943% 152,714
Percent Drum Equivalents	Medium Case 16,734	458% 13,851	128% 108	2,554% 907	942% 121,114	943% 152,714
Percent Drum Equivalents	Low Case 16,734	458% 13,851	128% 108	2,554% 907	942% 121,114	943% 152,714
Repackaging In Combination With Advanced Filters (Path 5)						
Percent Drum Equivalents	High Case 13,685	379% 11,479	111% 93	2,147% 762	793% 101,864	789% 127,883
Percent Drum Equivalents	Medium Case 13,685	379% 11,479	111% 93	2,147% 762	793% 101,864	789% 127,883
Percent Drum Equivalents	Low Case 13,685	379% 11,479	111% 93	2,147% 762	793% 101,864	789% 127,883

^aThis is the percent of allotted shipping resources (site-by-site) used after the "unshippable" Pu-238 TRU waste is repackaged or shipped "as is".

TABLE 8. PERCENT OF ALLOTTED SHIPPING RESOURCES REQUIRED TO SHIP Pu-238 TRU WASTE DRUM EQUIVALENTS TO THE WIPP UNDER TREATMENT STRATEGIES^a

	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
Treatment by Itself						
Percent Drum Equivalents	373% 756	34% 1,035	35% 29	130% 46	48% 6,203	50% 8,069
Treatment In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)						
Percent Drum Equivalents	High Case 384% 777	39% 1,187	53% 45	177% 63	56% 7,251	58% 9,323
Percent Drum Equivalents	Medium Case 383% 777	37% 1,114	48% 41	160% 57	54% 6,882	55% 8,871
Percent Drum Equivalents	Low Case 382% 774	35% 1,073	40% 34	149% 53	52% 6,701	53% 8,635
Treatment In Combination With Headspace Gas Sample Tests (Path 3)						
Percent Drum Equivalents	High Case 384% 778	42% 1,263	55% 46	210% 74	62% 8,001	63% 10,163
Percent Drum Equivalents	Medium Case 384% 778	42% 1,275	55% 46	210% 74	62% 8,001	63% 10,174
Percent Drum Equivalents	Low Case 381% 773	43% 1,292	50% 42	210% 74	62% 8,001	79% 10,182
Treatment In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)						
Percent Drum Equivalents	High Case 373% 757	35% 1,049	35% 29	132% 47	49% 6,353	51% 8,234
Percent Drum Equivalents	Medium Case 373% 757	35% 1,049	35% 29	132% 47	49% 6,353	51% 8,234
Percent Drum Equivalents	Low Case 373% 757	35% 1,049	35% 29	132% 47	49% 6,353	51% 8,234

^a This is the percent of allotted shipping resources (site-by-site) used after the "unshippable" Pu-238 TRU waste is treated or shipped "as-is."

FIGURE 7. PERCENT OF ALLOTTED SHIPPING RESOURCES TO SHIP Pu-238 TRU WASTE (MEDIUM CASE) UNDER REPACKAGING STRATEGIES

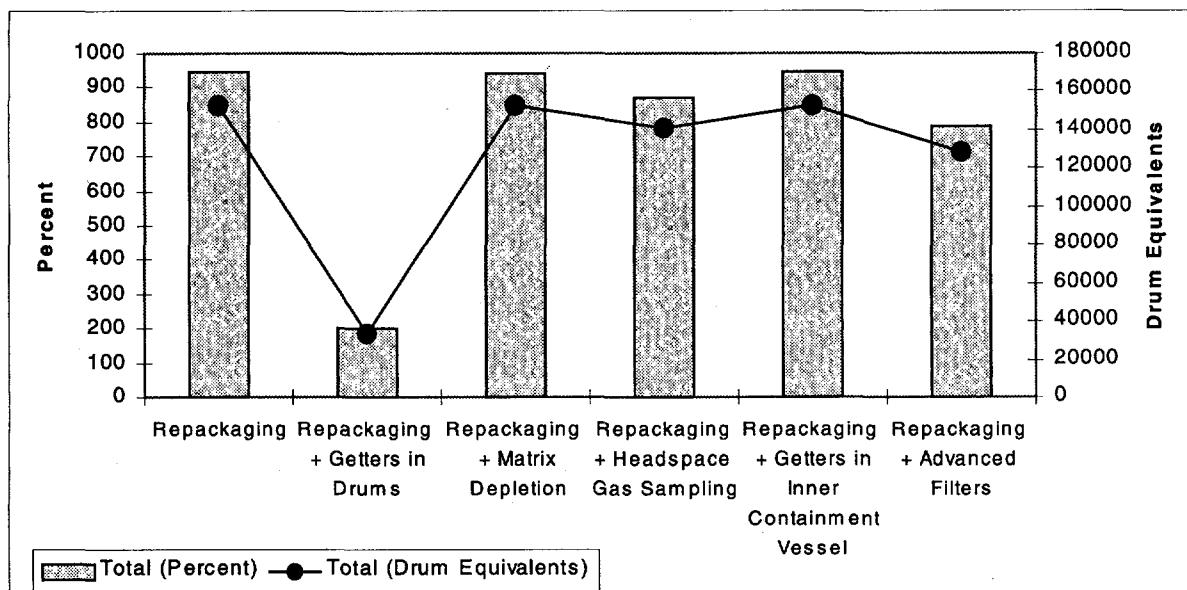


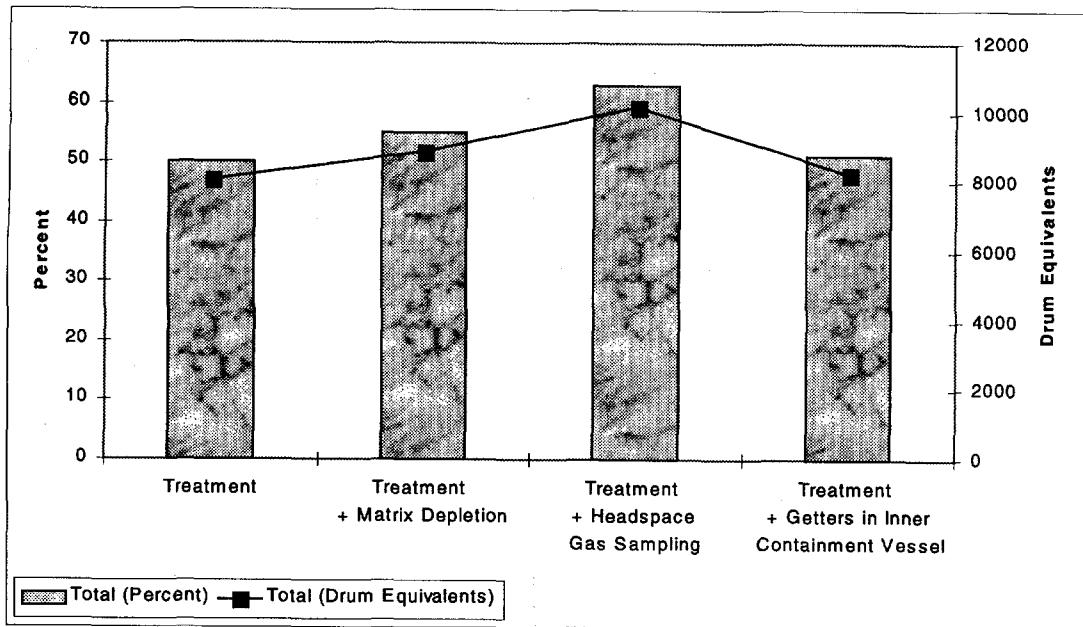
Table 8 shows the demand on shipping resources if treatment were used after consideration of the benefits of matrix depletion/hydrogen generation, hydrogen headspace gas sampling, or the use of hydrogen getters in the inner containment vessel. Treatment is the better option for minimizing the volume of Pu-238 TRU waste to be shipped (Figure 8). Even when a relatively large percent of the waste could be shipped without treatment or repackaging (Table 6), from a volume minimization perspective, treatment is a better option because it reduces the overall waste volume. Treating all of the Pu-238 TRU waste would produce 8,069 drum equivalents to be shipped to the WIPP. These 8,069 drum equivalents of Pu-238 TRU waste would require about 50 percent of the shipping resources currently allotted for Pu-238 TRU waste in *The National TRU Waste Management Plan* (DOE, 1997).

3.3 Evaluating Strategies - Cost

This evaluation assesses the life-cycle costs for treating, repackaging and shipping Pu-238 TRU waste to the WIPP. The cost model, described in Section 2.2.5, allows the relative cost merit of each strategy to be assessed. Figure 9 and Table 9 provide the results of the evaluation on a strategy-by-strategy basis.

Based on the results of the evaluation, it is evident that **a decision to treat the Pu-238 TRU waste will result in the highest relative cost, more than double that of repackaging**. In the absence of shipping increased quantities of Pu-238 TRU waste "as is," the DOE is faced with the potential to construct treatment or repackaging facilities at the five Pu-238 TRU waste sites. Even when the costs are downscaled to reflect lower volume throughput (Peters and Timmerhaus, 1968), the five treatment facilities are estimated to cost \$644 million. In comparison, repackaging facilities are estimated to cost about \$254 million, nearly 40 percent of the cost of treatment.

FIGURE 8. PERCENT OF ALLOTTED SHIPPING RESOURCES TO SHIP Pu-238 TRU WASTE (MEDIUM CASE) UNDER TREATMENT STRATEGIES.



Although treatment costs can be reduced when the benefits of matrix depletion, headspace gas sample tests or the use of getters is considered, treatment remains more costly than repackaging when considered with these same benefits. For example, treatment in combination with matrix depletion (Path 2 – low case) is about 2.5 times more costly than the comparable repackaging strategy (\$602 versus \$240 million) (Table 9).

FIGURE 9. LIFE-CYCLE COSTS FOR REPACKAGING OR TREATMENT OF Pu-238 TRU WASTE

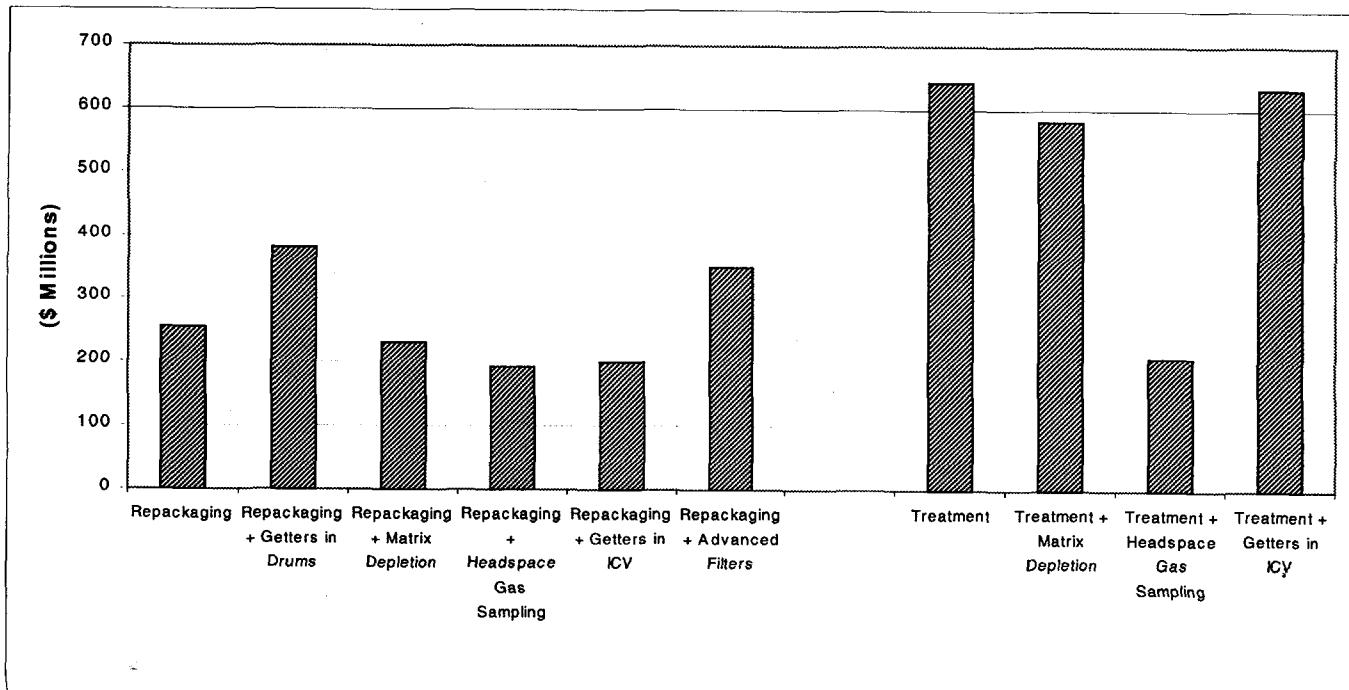


TABLE 9. LIFE-CYCLE COSTS (\$ MILLIONS) FOR TREATING, REPACKAGING, AND SHIPPING Pu-238 TRU WASTE TO THE WIPP

	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
Repackaging Alone	\$15.00	\$48.00	\$5.75	\$7.00	\$179.00	\$254.00
Repackaging in Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)						
High Case	\$27.31	\$64.09	\$6.10	\$7.18	\$275.09	\$379.77
Medium Case	\$27.31	\$64.09	\$6.10	\$7.18	\$275.09	\$379.77
Low Case	\$27.31	\$64.09	\$6.10	\$7.18	\$275.09	\$379.77
Repackaging in Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)						
High Case	\$13.59	\$41.77	\$4.59	\$4.72	\$155.87	\$220.56
Medium Case	\$13.64	\$44.54	\$4.93	\$5.42	\$164.34	\$232.86
Low Case	\$13.81	\$46.08	\$5.42	\$5.86	\$168.36	\$239.52
Repackaging in Combination With Headspace Gas Sample Tests (Path 3)						
High Case	\$13.51	\$35.43	\$4.38	\$2.98	\$135.94	\$192.25
Medium Case	\$13.55	\$35.33	\$4.38	\$2.98	\$135.94	\$192.38
Low Case	\$13.89	\$37.54	\$4.83	\$2.98	\$135.94	\$195.19
Repackaging in Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)						
High Case	\$14.98	\$46.98	\$5.75	\$6.47	\$175.96	\$250.00
Medium Case	\$14.98	\$46.98	\$5.75	\$6.47	\$175.96	\$200.00
Low Case	\$14.98	\$46.98	\$5.75	\$6.47	\$175.96	\$200.00
Treatment Alone						
	\$30.00	\$132.00	\$20.00	\$18.00	\$443.00	\$644.00
Treatment in Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)						
High Case	\$24.84	\$117.18	\$16.09	\$13.54	\$376.42	\$548.07
Medium Case	\$24.98	\$124.57	\$17.29	\$15.41	\$400.15	\$582.40
Low Case	\$25.53	\$128.70	\$19.07	\$16.64	\$411.65	\$601.59
Treatment in Combination With Headspace Gas Sample Tests (Path 3)						
High Case	\$24.57	\$100.64	\$15.39	\$8.71	\$325.49	\$474.79
Medium Case	\$24.71	\$100.84	\$15.39	\$8.71	\$325.49	\$475.13
Low Case	\$25.80	\$105.96	\$16.95	\$8.71	\$325.49	\$482.91
Treatment in Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)						
High Case	\$29.00	\$131.00	\$20.00	\$18.00	\$435.00	\$634.00
Medium Case	\$29.00	\$131.00	\$20.00	\$18.00	\$435.00	\$634.00
Low Case	\$29.00	\$131.00	\$20.00	\$18.00	\$435.00	\$634.00

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Conversely, however, a significant cost savings will be realized when some of the waste can be shipped from the sites without treatment or repackaging because of the benefits of matrix depletion/ hydrogen generation, hydrogen headspace gas sampling, or the use of hydrogen getters in the inner containment vessel. An illustration of the cost savings that may be realized involves the use of headspace hydrogen gas sampling to certify individual drums for shipment. On average, 35 percent of the currently unshippable Pu-238 TRU waste could be shipped "as is" based on headspace gas sampling (Table 6). However, if the remaining 65 percent is to be treated, the DOE will save \$161 million by shipping 35 percent of the waste "as is" (Table 9; \$644 - \$483 million). If the remaining 65 percent is to be repackaged, the DOE will save \$59 million by shipping 35 percent of the waste "as is" (Table 9; \$254 - \$195 million).

Life-Cycle Costs

Repackaging costs can benefit from the successful application of matrix depletion, hydrogen headspace gas sampling, or the use of hydrogen getters in the inner containment vessel of the TRUPACT-II.

3.4 Evaluating Multiple Strategies in Combination

Previously, the merits of individual strategies to improve the management of Pu-238 TRU waste were assessed on a path-by-path basis. For each path the technical uncertainties were considered in terms of the three performance measures. Currently, however, multiple strategies are being pursued to maximize the ability to ship Pu-238 TRU waste.

For this analysis, two alternatives that combine the benefits of various strategies are considered:

- A combination of matrix depletion (Path 2), getters in the inner containment vessel of the TRUPACT-II (Path 4), and repackaging with advanced filters (Path 5).
- A combination of matrix depletion (Path 2), hydrogen headspace gas sampling (Path 3), getters in the inner containment vessel (Path 4), and repackaging with advanced filters (Path 5).

The waste volume model was applied incrementally on a strategy-by-strategy basis to the Pu-238 TRU waste inventory. That is, the benefits (i.e., increased wattages) from the initial strategy (i.e., matrix depletion) were applied to the inventory to determine the waste that could be shipped "as is." The benefits from the second strategy were applied to the remaining inventory and so on, to ascertain the volume of waste that could be disposed of "as is" by 2006, and the volume of waste that would result from repackaging the waste after accounting for disposal of waste "as is." The cost model estimated the total system life-cycle cost. The results are shown in Table 10.

It is evident from Table 10 that the management of Pu-238 TRU waste can be enhanced by combining certain strategies. Consistent with the previous single strategy analysis, it is also evident that hydrogen headspace gas sampling to certify waste for shipping in the TRUPACT-II is expected to be more beneficial than is matrix depletion.

TABLE 10. BENEFITS OF COMBINED STRATEGIES

Combination	Drums Disposed by 2006	Drum Equivalents from Repackaging	Total System Life-Cycle Cost (\$millions)
Paths 2, 4 and 5			
High case	2,091	12,825	272
Medium case	1,338	13,578	281
Low case	945	13,971	286
Paths 2, 3, 4 and 5			
High case	3,649	11,192	251
Medium case	3,645	11,212	251
Low case	3,550	11,366	253

The interpretation of these results, as those provided previously, should be tempered with the recognition that the regulatory uncertainties are as yet unaccounted for – the following section provides this accounting.

4. ASSESSING PROBABILITY OF SUCCESS AND EXPECTED BENEFIT

Evaluating the merits of the strategies for improving the management of Pu-238 TRU waste heretofore has focused on quantifying three performance measures. This evaluation only considered the technical uncertainties associated with each strategy.

Decision analysis also can provide the decision maker with a better understanding of the effect of all potential uncertainties involved with a decision and how those uncertainties affect the overall probability of success. A proposed management strategy for Pu-238 TRU waste may have outstanding performance measure scores, but, if the combined technical and regulatory uncertainties are high, the probability of successfully implementing the strategy will be low. The probability of success hinges, therefore, on these uncertainties.

The following sections address regulatory uncertainty (technical uncertainty was addressed in Section 3) by calculating expected values and performing sensitivity analyses as a means to supplement the decision maker's judgment about the strategy that will yield the "best" results. For most decisions the "best" strategy is the one with the highest expected value. In the context of Pu-238 TRU waste management, therefore, "best" is defined as the path with the higher expected values for volumes disposed by 2006 and the lower expected values for shipment of wastes and cost.

4.1 Regulatory Uncertainty

Regulatory uncertainty addresses the question of NRC acceptance of a technical solution that the DOE may propose. Regulatory success depends on a positive result upon petitioning the NRC for a change in the Certificate of Compliance for the TRUPACT-II.

Table 11 shows the results of the expert panel for the probability of NRC approval. The strategy assigned **the highest probability of regulatory success was the repackaging strategy, in which advanced drum and bag filters are used**. The expert panel agreed that this strategy is only a slight modification to the status quo and as such would have a high likelihood of NRC approval.

TABLE 11. PROBABILITY OF NRC APPROVAL

NRC Approval of:	"optimistic" NRC	"moderate" NRC	"pessimistic" NRC
Adding Hydrogen Getters to the Drums (Path 1)	.50	.20	.10
Lowering G-values Based on Hydrogen Generation Tests (Path 2)	.60	.30	.25
Drum Certification Based on Headspace Hydrogen Tests (Path 3)	.70	.60	.40
Adding Hydrogen Getters to the Inner Containment Vessel of the TRUPACT-II (Path 4)	.75	.75	.70
Using Advanced Drum and Bag Filters (Path 5)	.95	.90	.80

The strategy assigned the lowest probability of regulatory success was the repackaging scenario, in which hydrogen getters would be added to the headspace of every drum. The expert panel noted that the NRC has made negative declarations about hydrogen recombiners and indicated that hydrogen getters may be refused in the same manner. Also, the experts stated that the effect of poisons on the getter reaction rate could prevent the effective use of hydrogen getters.

Sensitivity to NRC approval is explored in Section 4.2 by examining three cases: (1) "optimistic" NRC, where the highest panel member responses are assigned for the probability of regulatory success, (2) "moderate" NRC, where the intermediate panel member responses are assigned for the probability of regulatory success, and (3) "pessimistic" NRC, where the lowest panel member responses are assigned for the probability of regulatory success.

4.2 *Expected Value*

Expected value is a measure of both the benefit that can be derived from a strategy and the probability of success (i.e., technical and regulatory uncertainty) for that strategy. For each performance measure expected values are calculated for each branch and then summed. As an example, the expected value for the volume of Pu-238 TRU waste disposed by 2006 is calculated as:

$$(DE)_{\text{expected}} = \sum_{\text{branches}} (DE) * p_t * p_r$$

where

$(DE)_{\text{expected}}$ = the expected value for drum equivalents disposed
 (DE) = drum equivalents disposed following a branch in the decision tree
 p_t = probability of technical success
 p_r = probability of regulatory success

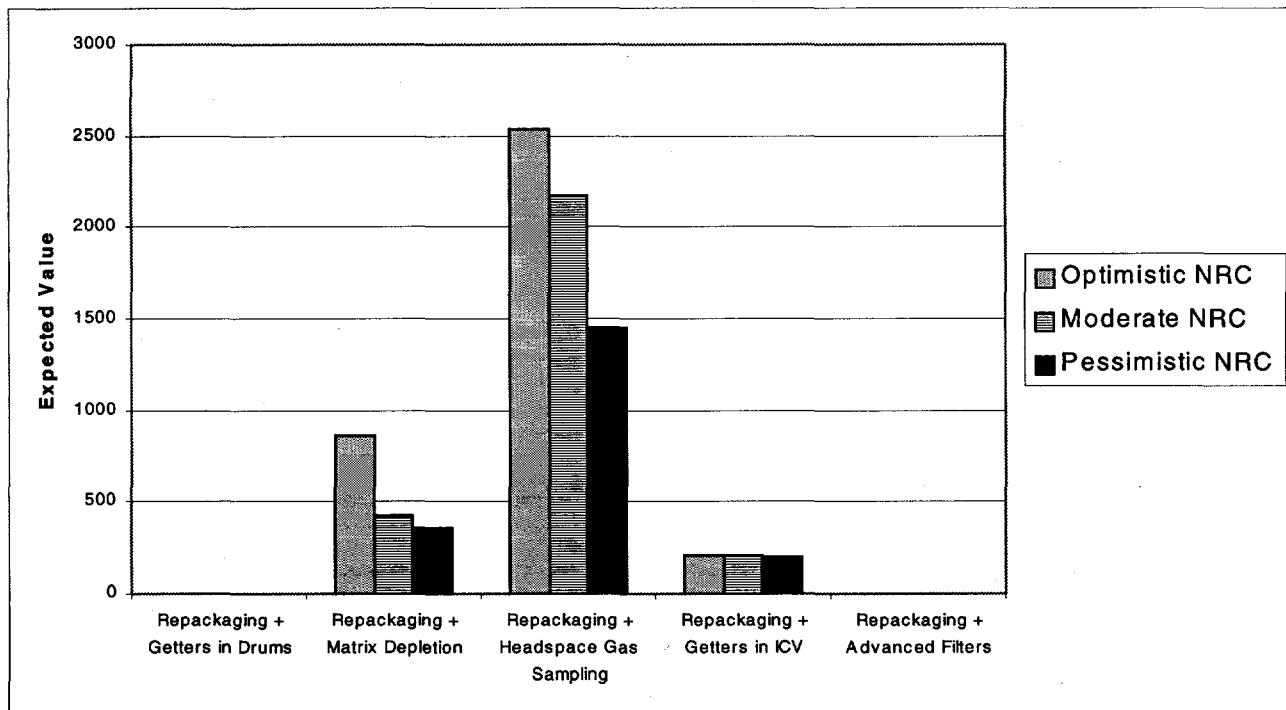
The following sections discuss expected values in the context of their sensitivity to NRC approval.

4.2.1 *Expected Value – Volume Disposed by 2006*

Figure 10 and Table 12 show the expected values for the drum equivalents of Pu-238 TRU waste disposed by 2006. In all cases, Path 3 (headspace hydrogen sampling) clearly has the best-expected outcome regardless of the regulatory uncertainties. For Path 3, the expected value for drums disposed by 2006 ranges from 1,449 (pessimistic NRC) to 2,536 (optimistic NRC). This is roughly 10 times the near-term disposal volume for Path 2 and 18 times the near-term disposal volume for Path 4. The primary difference in the expected values for Path 3, as compared to all other paths, is due to the relatively robust effectiveness of headspace hydrogen gas sampling as determined by the expert panel (Table 6) and the relatively high probability of NRC approval (Table 11) of this method to certify drums for shipment.

As discussed in Section 2.2.5, there are no near-term disposal volumes expected for Paths 1 and 5, for which all of the waste will be repackaged.

FIGURE 10. EXPECTED VALUE FOR DRUMS OF WASTE DISPOSED BY 2006



4.2.2 Expected Value – Demand on Shipping Resources

As discussed in section 3.2, treatment offers the better option to reduce the volume of Pu-238 TRU waste to be shipped to the WIPP (Tables 7 and 8), however, at a significant cost penalty (Table 9). The volumes produced through repackaging can be reduced, especially if hydrogen getters are added to the drums, at a significant cost advantage. For these reasons the analysis is limited to a determination of expected value for shipments of Pu-238 TRU waste after repackaging (Figure 11, Table 13).

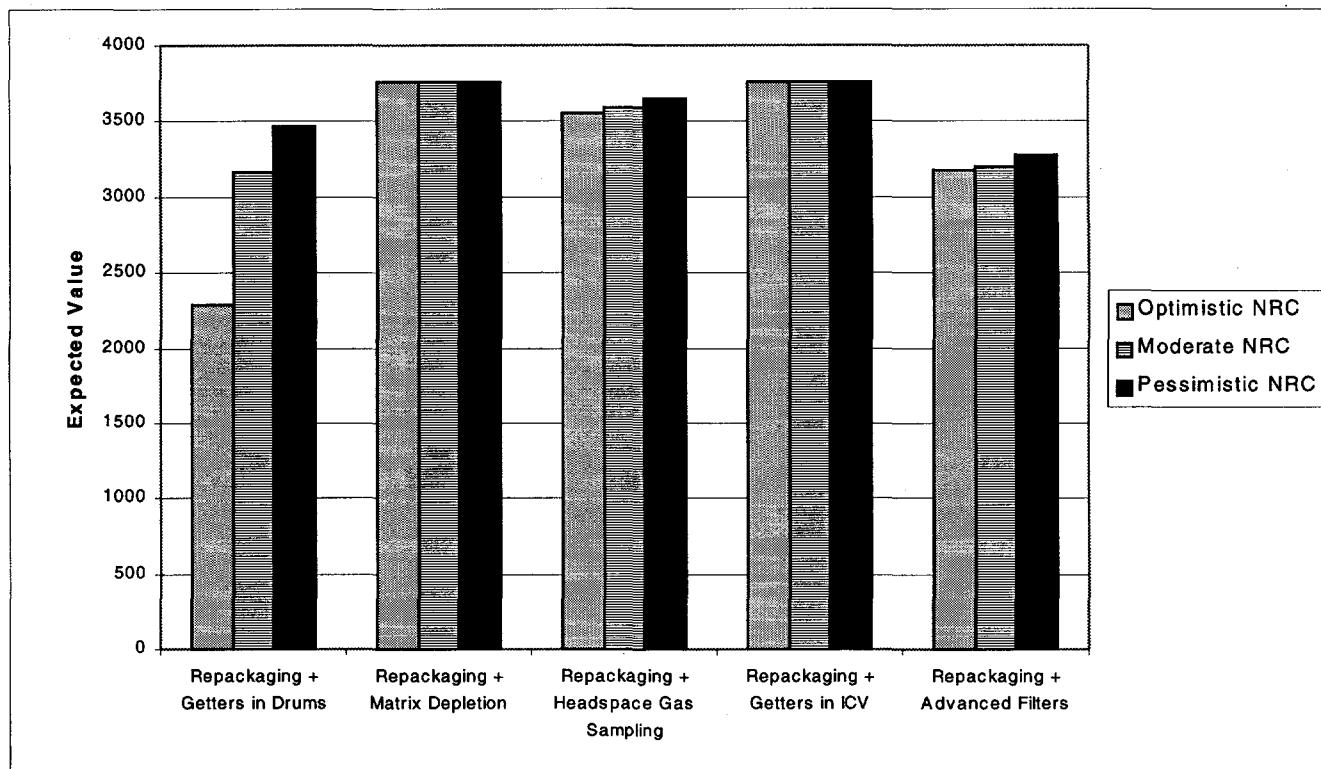
The results indicate a modest sensitivity to the response of the NRC. In the case of an “optimistic” NRC, repackaging and placing getters in the headspace of the drums has the best-expected outcome. The expected value is 92,184 drum equivalents, or 2,287 shipments of Pu-238 TRU waste. This may be misleading, however, because the low expected value reflects the combination of very low repackaged volumes (Table 7) and the probability (0.50) of NRC approval.

TABLE 12. EXPECTED VALUE FOR DRUMS OF Pu-238 TRU WASTE DISPOSED BY 2006

	Hanford Reservation	Los Alamos National Laboratory	Mound	Oak Ridge National Laboratory	Savannah River Site	Total
Optimistic NRC						
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	21	88	11	11	726	857
In Combination With Headspace Gas Sample Tests (Path 3)	25	343	19	35	2,113	2,536
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	2	18	0	1	187	208
Moderate NRC						
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	11	44	5	6	363	428
In Combination With Headspace Gas Sample Tests (Path 3)	22	294	17	30	1,811	2,173
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	2	18	0	1	187	208
Pessimistic NRC						
In Combination with Matrix Depletion/Hydrogen Generation Studies(Path 2)	9	37	5	5	303	357
In Combination With Headspace Gas Sample Tests (Path 3)	15	196	11	20	1,207	1,449
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	2	17	0	1	174	194

With a "moderate" NRC, repackaging and placing getters in the headspace of the drums still offers the best-expected outcome, although the differences between strategies is not as distinct. Again, the very low repackaged volumes (Table 7) dominate the results for Path 1, even though the probability (0.20) of NRC approval is lower.

FIGURE 11. EXPECTED VALUE FOR SHIPMENTS OF Pu-238 TRU WASTE AFTER REPACKAGING



For a "pessimistic" NRC, repackaging with advanced drum and bag filters has the best-expected outcome. The expected value is about 132,861 drum equivalents, or 3,270 shipments of Pu-238 TRU waste. In this instance the differences between the two strategies are similar as for a "moderate" NRC approval.

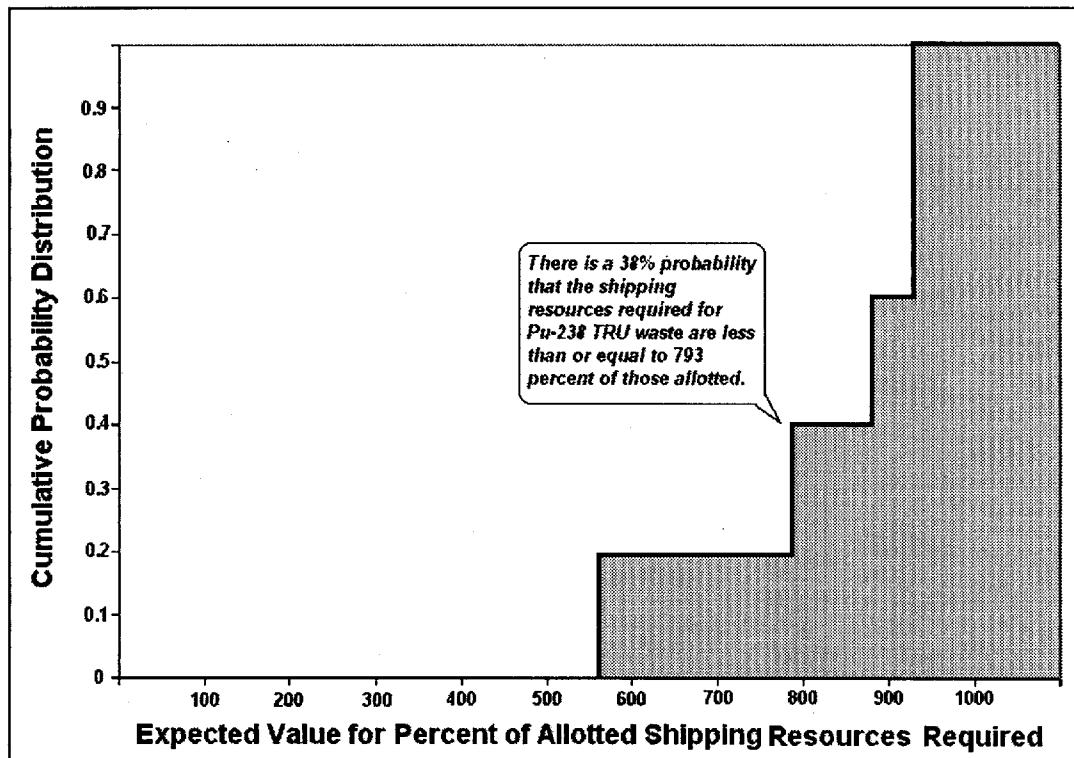
The expected values (Table 13) demonstrate, with the exception of Path 1 and an "optimistic" NRC, modest differences in the number of shipments offered by the five strategies. It is also clear that Paths 2, 3 and 4 are not particularly sensitive to the probabilities of approval by the NRC (i.e., little change in respective shipment numbers for three states of NRC approval).

TABLE 13. EXPECTED VALUE FOR SHIPMENTS OF Pu-238 TRU WASTE AFTER REPACKAGING

	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
Optimistic NRC						
In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)	282	244	4	13	1,744	2,287
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	465	383	5	21	2,880	3,755
In Combination With Headspace Gas Sample Tests (Path 3)	465	348	4	17	2,724	3,558
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	465	385	5	22	2,884	3,760
In Combination With Advanced Filters (Path 5)	384	322	4	18	2,448	3,178
Moderate NRC						
In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)	392	328	5	18	2,428	3,171
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	465	384	5	21	2,882	3,757
In Combination With Headspace Gas Sample Tests (Path 3)	465	353	4	17	2,747	3,587
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	465	385	5	22	2,884	3,760
In Combination With Advanced Filters (Path 5)	389	325	5	18	2,471	3,208
Pessimistic NRC						
In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)	428	357	5	20	2,656	3,466
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	465	384	5	21	2,882	3,758
In Combination With Headspace Gas Sample Tests (Path 3)	465	364	5	19	2,793	3,645
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	465	385	5	22	2,884	3,760
In Combination With Advanced Filters (Path 5)	397	332	5	19	2,517	3,270

Of greater import are the implications to shipping resources allotted by *The National TRU Waste Management Plan* (DOE, 1997). Figure 12 is the cumulative distribution function for the percent of allotted resources required to ship Pu-238 TRU waste to the WIPP for an optimistic NRC. Based on the analyses, there is little probability (essentially zero) that the shipping resources allotted by *The National TRU Waste Management Plan* will be sufficient and a high probability that as much as a thousand-fold increase in shipping resources will be needed. It is much more likely that **repackaging even under the best circumstances will produce more volume than can be shipped to the WIPP under current baseline planning assumptions** (DOE, 1997).

FIGURE 12. CUMULATIVE DISTRIBUTION FUNCTION FOR PERCENT (EXPECTED VALUE) OF ALLOTTED SHIPPING RESOURCES TO SHIP Pu-238 TRU WASTE (OPTIMISTIC NRC)



4.2.3 Expected Value – Life-Cycle Cost

Although repackaging Pu-238 TRU waste is the least costly strategy, any waste that can be shipped “as is” (i.e., without repackaging) will help to reduce costs. Table 14 shows the expected values for the life-cycle cost for repackaging Pu-238 TRU waste, including the costs for the ready-to-ship “as is” waste (Paths 2, 3 and 4).

The results are insensitive to the response of the NRC. In all cases, Path 3, headspace gas sampling, has the lowest expected life cycle cost, even for a relatively pessimistic NRC.

TABLE 14. EXPECTED LIFE-CYCLE COSTS (\$ MILLIONS) TO REPACKAGE AND SHIP Pu-238 TRU WASTE TO THE WIPP

	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site	Total
Optimistic NRC						
In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)	21	56	5.93	7	227	317
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	14	46	5.28	6	170	241
In Combination With Headspace Gas Sample Tests (Path 3)	14	39	4.87	4	149	211
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	15	17	5.75	6	177	251
In Combination With Advanced Filters (Path 5)	24	56	5.82	7	252	345
Moderate NRC						
In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)	18	51	5.82	7	198	279
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	15	47	5.52	6	174	247
In Combination With Headspace Gas Sample Tests (Path 3)	14	41	5.00	4	153	217
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	15	47	5.75	6	177	251
In Combination With Advanced Filters (Path 5)	24	56	5.81	7	248	340
Pessimistic NRC						
In Combination With Placing Hydrogen Getters in the Drum Headspace (Path 1)	16	49	5.79	7	189	267
In Combination with Matrix Depletion/Hydrogen Generation Studies (Path 2)	15	47	5.56	6	125	248
In Combination With Headspace Gas Sample Tests (Path 3)	15	43	5.25	5	162	230
In Combination With Placing Hydrogen Getters in the Inner Containment Vessel (Path 4)	15	47	5.75	6	177	251
In Combination With Advanced Filters (Path 5)	23	55	5.81	7	240	331

5. CONCLUSIONS AND RECOMMENDATIONS

None of the strategies under consideration will fully enhance the management and enable efficient transportation of all Pu-238 TRU waste without significant cost and time expenditures. The implementation of any of the five strategies of the decision tree (Figure 2) involves technical uncertainties (will it work?) and uncertainties associated with the approval of the NRC (will the NRC approve?). For these reasons the decision maker is faced with a complex decision that hinges on a fundamental question:

What factors are most important in the selection of a strategy and how much uncertainty is associated with the selection of a strategy?

The following discussion provides insights into addressing this question.

When considering both the technical and regulatory uncertainties (i.e., expected value), drum certification based on headspace gas sample analysis (Path 3) offers the best single strategy (Table 11) to maximize near-term waste disposal (volume disposed by 2006) and minimize total system life-cycle cost (Table 14). If samples of the headspace gas from Pu-238 TRU waste drums in storage show that hydrogen concentrations are indeed within the range projected by the expert panel (Figure 6), around 3,000 drums of the 10,373 drum equivalents in the inventory could be transported and disposed of in the WIPP without treatment or repackaging. The actual outcome of headspace gas sample analysis is uncertain, but by initiating a program to sample the headspace gas on a population of Pu-238 TRU waste drums and seek the NRC's approval for this certification method, the uncertainties will be reduced. Such a program may demonstrate that individual drum testing is a viable strategy that will enable the transportation of a part of the Pu-238 TRU waste inventory.

Most Appropriate Single-Strategy Means to Manage Pu-238 TRU Waste

Performance Measure	Best Strategy for Achievement
Near-term disposal	Headspace hydrogen samples
Volume Reduction	Thermal treatment
Cost Efficiency	Rerecycling

From a volume reduction perspective thermal treatment to remove organic materials and water from the Pu-238 TRU waste is the best single strategy for overall volume reduction of the Pu-238 TRU waste inventory (Tables 7 and 8; Appendix B provides basis for calculations). In the context of this decision analysis treatment has little uncertainty, however, it is also the highest cost option, with a total system life-cycle cost more than double that required for repackaging. If volume reduction is the decision maker's highest priority, the Pu-238 TRU waste inventory should be treated in its entirety.

Repackaging is the lowest cost single strategy. It is also the option that produces the largest volume of Pu-238 TRU waste for disposal (Table 7). Most of the research studies that are being pursued will tend to reduce the volume produced when Pu-238 TRU waste is repackaged. However, because of the limitations on the overall effectiveness of these strategies and the associated technical and regulatory uncertainties, repackaging will produce a shipping need that far exceeds the current baseline planning resources as described in *The National TRU Waste Management Plan* (DOE, 1997) (Figure 11), regardless of the strategy. If cost efficiency is the decision maker's highest priority, the Pu-238 TRU waste inventory should be repackaged.

When considering the probability of technical success of multiple strategies in combination, as much as 3,500 drums of Pu-238 TRU waste could be shipped from all sites by 2006. The remaining inventory could then be repackaged in as few as 11,000

drum equivalents if advanced bag and drum filters are used in conjunction with hydrogen getters in the inner containment vessel of the TRUPACT-II. These estimates, while impressive, must be considered in light of the uncertainties of whether the NRC would approve higher wattage limits because of matrix depletion, use of hydrogen headspace gas sampling to certify waste containers, and the use of hydrogen getters in the TRUPACT-II inner containment vessel

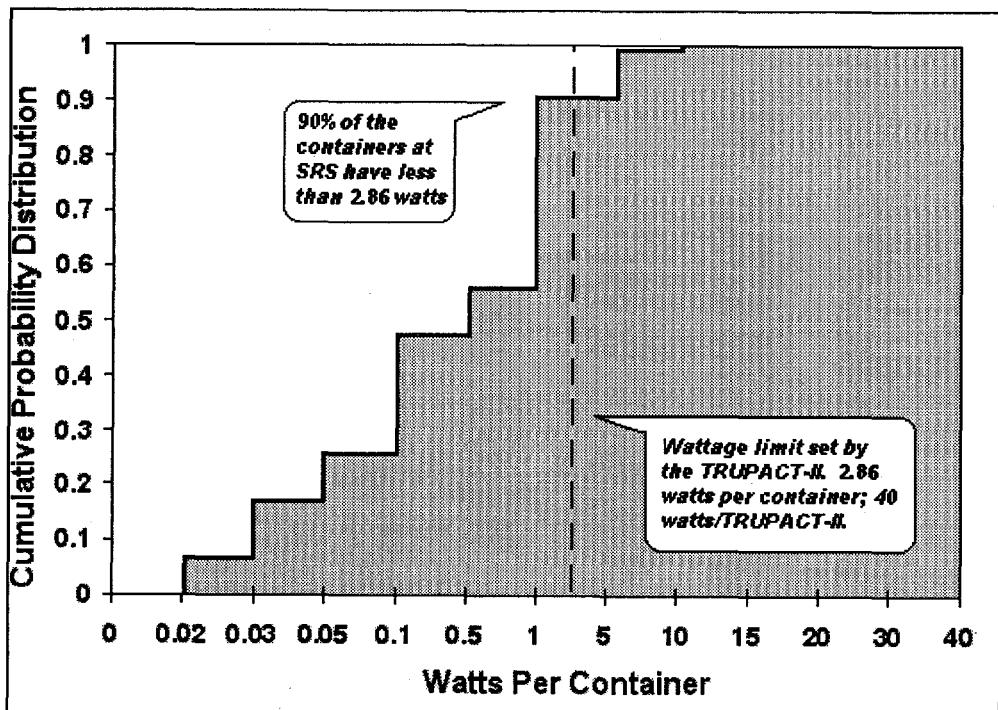
and advanced drum and bag filters when repackaging. These estimates also could be refined, as noted above, by initiating programs to collect the data needed to reduce uncertainties.

In attempting to fully address the fundamental question concerning the decision maker, it should be recognized that the analyses presented herein are strategic in nature. Tactical decisions to implement a selected strategy must be made at the TRU-waste site level. Tactical decisions should target specific portions of the inventory with the appropriate mix of remedial strategies. As an example, consideration should be given to the characteristics of the Pu-238 TRU waste inventory extant at the sites where high wattage waste would unnecessarily produce large volumes for shipment and disposal (Figure 13) under certain strategies. At Hanford there are twelve drums containing more than 100 watts each (Appendix B). Repackaging these drums under current limits could produce close to 16,000 drum equivalents. In this instance, a more cost-effective solution may be to repack these few drums to 40 watts (limit of the TRUPACT-II) using existing facilities and then ship single drums.

This decision analysis was conducted within the context of existing regulations; evaluating possible changes to existing regulations was beyond the scope of this analysis. These regulations result in decay heat limits that ensure that the concentration of hydrogen in any layer of confinement in a payload container does not exceed five percent. Even the best strategy, drum certification by gas generation testing and sampling, or a

combination of strategies, does not allow shipment of all the Pu-238 TRU waste without some repackaging or treatment of the waste. Continued development of technology to mitigate or prevent gas generation and to understand the phenomena is required. The goal is to increase the wattage limits of waste that can be safely and legally transported. Increased knowledge of this waste may also identify additional options.

FIGURE 13. HIGH WATTAGE DRUMS AT SAVANNAH RIVER SITE



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Westinghouse Waste Isolation Division, 1998. *1998 Annual Report: Gas Generation Program*, Carlsbad, NM, October 1998. Prepared for the DOE Carlsbad Area Office. (See Appendix E.)

APPENDIX A

STRATEGIES and PERFORMANCE MEASURES ELIMINATED FROM FURTHER CONSIDERATION

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LIST OF ACRONYMS AND ABBREVIATIONS

ATMX	Atomic Materials Rail Transfer
CFR	Code of Federal Regulations
C of C	Certificate of Compliance
DOE	Department of Energy
eV	electron volt
G- value	hydrogen generation rate due to radiolysis, molecules/100 eV
NRC	Nuclear Regulatory Commission
ppm	parts per million
psia	pounds per square inch absolute
Pu	plutonium
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
STP	Standard Temperature and Pressure
TRU	transuranic
TRUCON	TRUPACT Content Codes
TRUPACT-II	Transuranic Package Transporter, Model II
VOC	Volatile Organic Compound
WIPP	Waste Isolation Pilot Plant

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Appendix A

STRATEGIES AND PERFORMANCE MEASURES ELIMINATED FROM FURTHER CONSIDERATION

The decision analysis process started with a "brainstorming" session to develop a list of relevant strategic decisions that must be made to enhance the management of Pu-238 TRU waste. The strategic decisions analyzed reflect many of the basic strategies that have been considered within the DOE Complex (see Section 2.2.1, Table 3). There have been, however, a few strategies put forth that were initially considered during the development of the decision analysis model, but that were eventually eliminated from detailed study. Appendix A provides additional details on those eliminated strategies.

A-1. Overpack Configuration Strategy

A-1.1 Purpose:

The majority of transuranic (TRU) waste in the Department of Energy (DOE) complex that is expected to be disposed at the Waste Isolation Pilot Plant (WIPP) has plutonium-239 (Pu-239) as the primary TRU isotope. Planning for packaging, characterization, transportation, and disposal has centered on the properties of this isotope. Pu-238 TRU waste has some different characteristics, and a large enough total volume, that it may be possible to effect significant savings in time, money, and resources by developing specific TRU waste handling, packaging, characterization, and shipping methods optimized for Pu-238 TRU waste. The Pu-238 TRU Waste Decision Analysis study is being conducted to examine this possibility.

The major difficulty in shipping current Pu-238 TRU waste to the WIPP in the Transuranic Package Transporter, Model II (TRUPACT-II) is meeting the requirements for ensuring the hydrogen concentration does not exceed the lower explosive limit. The overpack configuration aspect of the Pu-238 TRU Waste Decision Analysis study is to determine if it is feasible to design and use an "explosion proof" overpack for drums transported in the TRUPACT-II. The overpack would allow the hydrogen concentration limit to be eliminated since the overpack would safely contain the energy and any radioactive material released from a waste drum should the hydrogen gas inside ignite or explode.

A-1.2 Background:

The most limiting property of Pu-238 TRU waste preventing it from being shipped to WIPP in its current form is the potential for hydrogen gas generation. The Certificates of Compliance (C of C) (See Section A-4.3.) for many transport packages require that the hydrogen gas concentration in the void volume be limited to ensure the gas will not burn or explode during transport. For many packages this requirement is worded as:

The hydrogen generated must be limited to a molar quantity that would be no more than 5% by volume (or equivalent limits for other inflammable gases) of the secondary container gas void if present at STP [Standard Temperature and

Pressure] (i.e., no more than 0.063 g-moles per cubic foot at 14.7 psia [pounds per square inch absolute] and 70°F);...

[example from C of C No. 9210, Rev. 1].

The amount of hydrogen generated in waste is proportional to the radioactive decay energy deposited in the waste. This is also proportional to the decay heat of the waste. The C of C for the TRUPACT-II (C of C No. 9218) controls the hydrogen concentration by limiting total decay heat; i.e., "Decay heat not to exceed the values given in Tables 6.1 through 6.3 'TRUPACT-II Content Codes' (TRUCON),..." (DOE, 1989). Because Pu-238 TRU waste has a relatively short half-life (87.7 years vs. 24,000 years for Pu-239) much of the Pu-238 TRU waste exceeds the decay heat limits as currently packaged.

If the limit on hydrogen gas concentration were increased or abolished, much of the Pu-238 TRU waste could be shipped to WIPP as currently packaged. The costs, time, and worker radiation dose concerns of treating and/or repackaging the waste are eliminated. The overpack configuration concept involves designing and installing an "explosion proof" overpack for drums carried inside TRUPACT-II packages. The overpack would totally and safely contain the force and any released radioactive material should a drum with a hydrogen concentration above the lower explosive limit ignite or explode. Under this concept, there would be no need for limits on hydrogen concentrations in the waste packages.

Flammable volatile organic compounds in TRUPACT-II shipments are limited by the *Safety Analysis Report for the TRUPACT-II Shipping Package* (DOE, 1998) and C of C 9218 to 500 parts per million (ppm) in the drum headspace. This level is below the lower explosive limit for these compounds. If methane is produced at levels above its lower explosive limit, the overpack would provide the same protection as it does for hydrogen gas.

A-1.3 Analysis:

49 Code of Federal Regulations (CFR) 177.848 "Segregation of hazardous materials" contains a table of requirements for segregation of hazardous materials. The table requires that radioactive materials and flammable gases be segregated. An explanatory instruction for use of the table states "...these materials may not be loaded, transported, or stored together in the same transport vehicle or storage facility during the course of transportation unless separated in a manner that, in the event of leakage from packages under conditions normally incident to transportation, commingling of hazardous materials would not occur." The hydrogen in Pu-238 TRU waste is generated by the radioactive material so the two hazardous materials (radioactive and flammable gas) are commingled from the time the gas is created. As soon as the hydrogen gas concentration reaches the lower explosive limit, the requirements of 49 CFR 177.848 are violated, regardless of whether or not an "explosion proof" overpack is present.

Several people with radioactive materials transportation and packaging experience were interviewed as part of process of gathering information for this paper. All of them felt that even if the 49 CFR 177.848 requirement did not exist, the probability of getting an "explosion proof" overpack licensed and approved for use by the Nuclear Regulatory Commission (NRC) was very low.

A-1.4 Conclusion:

One of the policies of the Pu-238 TRU Waste Decision Analysis project is that changes to laws or regulations would not be sought. 49 CFR 177.848 has requirements that prohibit flammable gases and radioactive material from being shipped together. The overpack concept would violate this requirement by shipping a flammable hydrogen/air mixture in contact with radioactive waste. This alone is sufficient reason to eliminate the overpack concept from further consideration in this work.

A-1.5 References

49 CFR 177.848 Segregation of Hazardous Materials

C of C No. 9210, Rev. 1, expires December 31, 1999, Model No. 10-135B.

C of C No. 9218, Rev. 9, expires June 30, 1999, Model No. TRUPACT-II.

DOE (U.S. Department of Energy), 1989. *TRUPACT-II Content Codes (TRUCON)*, DOE/WIPP 89-004, Revision 10, December 1996, Carlsbad, NM.

DOE (U.S. Department of Energy), 1998. *Safety Analysis Report for the TRUPACT-II Shipping Package*, Revision 17, March. *Appendix 1.3.7 TRUPACT-II Authorized Methods for Payload Control (TRAMPAC)*, Carlsbad, NM.

A-1.6 Other Sources of Information

The following subject matter experts were consulted during preparation of this report:

- Phil Gregory, Westinghouse /Waste Isolation Division, Oct. 29, 1997.
- Paul Drez, Drez Environmental Associates, Nov. and Dec. 1997.
- Mark McAllaster, Sandia National Laboratories, Dept. 6342, Transportation Systems Department, Nov. 18, 1997.
- Jim McClure, Sandia National Laboratories, Dept. 6341, Transportation Systems Analysis Department, Nov. 17, 1997.
- Ross Chappell, NRC, Nov. 18, 1997.

A-2. TRUPACT-II Venting Strategy

A-2.1 Purpose:

Hydrogen gas buildup in the TRUPACT-II is a major constraint on the amount of Pu-238 TRU waste that can be transported in one shipment. Periodically venting the TRUPACT-II inner containment vessel has been proposed as a possible method for controlling hydrogen concentration. One aspect of the Pu-238 TRU Waste Decision Analysis is to examine to what extent periodic venting of the TRUPACT-II inner containment vessel during transit could contribute to shipping Pu-238 TRU waste to the WIPP for disposal.

A-2.2 Background:

The major limitation on shipping Pu-238 TRU waste to the WIPP in the TRUPACT-II is the limit on hydrogen gas concentration in the package void volumes and the inner containment vessel. Hydrogen is produced as a radiolysis product in the waste matrix and the concentration must remain below 5% by volume. If hydrogen gas could be removed from the inner containment vessel, a larger quantity of Pu-238 TRU waste could be loaded in each package and not violate the concentration limit.

One proposed method for controlling hydrogen in the inner containment vessel is to periodically vent the inner containment vessel. In this concept, a valved tube or a vent of some other design would be opened periodically during the shipping period. This allows hydrogen to escape from the inner containment vessel and insure the hydrogen concentration in the inner containment vessel stays below 5% in the innermost layer of confinement. The venting would be done under controlled conditions and with filters and/or other measures to prevent contamination from escaping the package and in compliance with any Resource Conservation and Recovery Act (RCRA) constraints or other regulatory constraints on release of volatile organic compounds (VOCs). For venting to be effective, it might be necessary to supplement hydrogen diffusion with an active purging system. This could involve pumping an inert gas through the inner containment vessel to flush out hydrogen, or a vacuum system to purge the hydrogen.

A-2.3 Analysis:

The Land Withdrawal Act (Public Law 102-579) requires that only NRC-certified packages be used to ship TRU waste to the WIPP. The NRC currently requires double containment on packages used for greater than 20 curies of plutonium. This requirement was recently affirmed in NRC Memo SECY-97-218. Since double containment would be lost during TRUPACT-II venting operations, NRC approval would have to be sought. This approval may involve NRC reexamination of the entire TRUPACT-II C of C. The reexamination could require full scale testing of the modified (i.e., vented) TRUPACT-II, including drop tests with the vent port being the point of impact for the drop.

10 CFR 73.43(h) states "A package may not incorporate a feature intended to allow continuous venting during transport." The NRC has indicated in informal discussions that although the regulation addresses continuous venting, a package that relies on vehicle operators to periodically vent hydrogen would not be acceptable.

A-2.4 Conclusion:

It was concluded that periodic venting of the TRUPACT-II inner containment vessel is not a viable option for shipping Pu-238 TRU waste to the WIPP. The two major reasons for this conclusion are:

- (1) the NRC has indicated periodic TRUPACT-II venting by operators is not acceptable; and
- (2) venting the TRUPACT-II would compromise the NRC requirement for double containment for shipping packages containing more than 20 curies of plutonium; and

A-2.5 References

10 CFR 73.43(h)

NRC C of C No. 9200, Rev. 9, expires April 1, 2001, Model No. 125-B.

NRC C of C No. 9218, Rev. 9, expires Jun. 30, 1999, Model No. TRUPACT-II.

NRC Memo SECY-97-218, from: L. Joseph Callan, Executive Director for Operations, for: "The Commissioners," dated Sept. 29, 1997, Subject: "Special Provisions for Transport of Large Quantities of Plutonium (Response to staff requirements memorandum - SECY-96-215). Printed from internet site <http://www.nrc.gov/NRC/COMMISSION/SECYS/1997-218scy.txt> on Nov. 11, 1997.

Public Law 102-579, *Waste Isolation Pilot Plant Land Withdrawal Act*, 102d Congress, October 30, 1992.

A-2.6 Other Sources of Information

The following subject matter experts were consulted during preparation of this report:

- Steve Best, Nuclear Fuel Services, Oct. 30, 1997.
- Paul Drez, Drez Environmental Associates, multiple conversations, Nov. and Dec. 1997.
- Phil Gregory, Westinghouse/Waste Isolation Division, Oct. 29, 1997.
- Mark McAllaster, Sandia National Laboratories, Dept. 6342, Transportation Systems Department, Nov. 18, 1997.
- Jim McClure, Sandia National Laboratories Dept. 6341, Transportation Systems Analysis Department, Nov. 17, 1997.
- Stacy Rosenberg, NRC, Nov. 18, 1997.
- Ross Chappell, NRC, Nov. 18, 1997.

A-3. Effectiveness of a New Package (All Paths) Strategy

A-3.1 Purpose

The “new package” option of the Pu-238 TRU Waste Decision Analysis program examines the possibility of designing a new package, perhaps an “improved” TRUPACT-II, optimized specifically to transport Pu-238 TRU waste. If such a package can be shown to have significant advantages over the existing TRUPACT-II design for movement of Pu-238 TRU waste, substantial savings in time, cost, and other resources can be realized.

A-3.2 Background

The major limitation in using TRUPACT-IIs for movement of Pu-238 TRU waste is the limit on hydrogen gas production during transport. The NRC C of C for the TRUPACT-II (C of C No. 9218) cites decay heat limits as a means of limiting the hydrogen concentration in void volumes to no more than 5% by volume. Relaxation of this limitation is not considered as an option for management of Pu-238 TRU waste because it is the DOE’s policy not to include seeking regulatory changes as an option for the decision analysis.

The decision analysis scenario for this option is comprised of the research and development of a new package, and transport of a portion of the Pu-238 TRU waste in the new package. The amount of waste to be transported in the new package would be determined by the outcome of previous decisions regarding the pursuit of studies (e.g., development of advanced filters), the outcome of the studies, and approval by the NRC. Waste that remained after accounting for these previous outcomes would be considered for transport in the new package. Any waste that fell within the new wattage limits for the new package would be transported to the WIPP. This waste would not be repackaged for transport. The following assumptions were employed to bound the possible new package solutions:

- The new package will meet all of the current NRC requirements for transportation to the WIPP including hydrogen concentration limits and testing requirements (including drop, puncture, crush thermal exposure and immersion testing) for any new Type B package as given in 10 CFR Part 71. If the new package meets these requirements, it will be approved.
- Any new package will be required to provide double containment (10 CFR 71.63 and NRC Memo SECY-97-218).
- The new package will fit on a standard flatbed trailer.
- The new package will be developed for highway, not rail, transport. Therefore, weight and size restrictions for highway transport will apply to the package.
- Waste will not be repackaged for transport in the new package.

A-3.3 Analysis

The amount of hydrogen gas generated in the waste depends on the number and energy of alpha particles and other high energy radiation emanations absorbed in the waste matrix and on the G-value (hydrogen generation rate due to radiolysis, molecules/100 electron volts [eV]) for hydrogen production for the waste matrix. G-values have been shown to depend on temperature. Thus, the amount of hydrogen gas generated is a function of the waste and the absorbed radiation dose. The type and amount of packaging (layers of confinement) does not directly influence the rate of generation of hydrogen but does impact the buildup of hydrogen in the innermost layers of confinement because each layer of confinement inhibits the release of hydrogen out of the inner layers. In addition, the concentration of hydrogen is dependent on the total volume of the container. A higher rate of hydrogen generation could be tolerated if the container were larger. A larger void volume, and resulting lower hydrogen concentration, would also increase the driving force for diffusion of hydrogen from inner layers of confinement. This would also increase the amount of hydrogen generation that could be tolerated. For a new package to be effective, it would have to address one or more of the characteristics listed above: hydrogen generation rate, layers of confinement, and void volume.

The hydrogen generation rate is primarily a function of the radionuclides and the waste matrix, which are not influenced by the packaging. The maximum activation energy for materials present in TRU waste is about 3 kcal/gmole. Therefore, based on application of the Arrhenius equation for the rate constant of chemical reaction, the maximum reduction in G-values that could be obtained by refrigeration to -20°F (-29°C) would be:

$$G(55^\circ\text{C})/G(-29^\circ\text{C}) = \exp(E_a/R[1/244-1/328]) = 4.87$$

Where: E_a is the activation energy (cal/gmole) [3,000 cal/gmole in this case]
 R is the Gas Law constant (1.99 cal/gmole-K)
 55°C is the maximum temperature considered for normal operating conditions for transportation (328 K)
 -29°C is an example minimum feasible refrigeration temperature (244 K)

Refrigeration of the new package would provide some improvement over the TRUPACT-II. Any refrigeration system incorporated in a new package would have to be robust enough to survive and pass the 10 CFR Part 71 test requirements for a Type B package and satisfy any other NRC concerns about its reliability.

The only way that a new package could address the issue of the layers of confinement for the waste would be to develop a filtered packaging. The effect of adding filters (i.e., filtered vents) to the package would be to reduce the concentration of hydrogen in the outer layers of the container, thus increasing the concentration driving force and reducing the hydrogen buildup in the inner layers of confinement. This option cannot be considered for the decision analysis because the regulations (10 CFR 71.43[h]) specifically prohibit "continuous venting" of the package.

One additional property of a new package proposed by some is an increase in void volume (compared to TRUPACT-II). The argument is that the larger void volume in the inner

containment vessel would allow more total hydrogen to be produced since the hydrogen must fill the larger volume in the inner containment vessel before the concentration exceeds 5% in the innermost layer of confinement. Large increases in void volume decrease shipping efficiency since more of what would be load capacity is replaced by empty space. An increase in void volume can be achieved with the TRUPACT-II by only partially filling the package; for example, by carrying only 7 drums instead of a full load of 14 drums. A factor of 2 or 3 is probably the largest practical increase in void volume with either a new package or with the TRUPACT-II. This increase will have only a small impact (less than 10%) on total Pu-238 TRU waste shippable and will double or triple the number of shipments required.

A-3.4 Conclusions

Any new package must be certified by the NRC, as required by the Land Withdrawal Act (Public Law 102-579). Most C of C's recently issued by the NRC for Type B packages have a 5% hydrogen production limit (e.g., C of C's 9168, 9200, 9210, 9216, and 9228). The C of C for the TRUPACT-II has an equivalent limit expressed in terms of an isotopic decay heat limit. It is unlikely that the NRC would relax any of its requirements for transportation of Pu-238 TRU waste. Therefore, it is assumed the C of C for a new package would have the same limit. The primary issues for this option concern the difficulty of improving upon the performance of the TRUPACT-II while meeting the stringent requirements of the NRC.

Discussions were held with several nuclear waste transport package designers and users. None knew of any new packages in development, or of any concepts for new packages, that would provide an improvement over TRUPACT-II for shipping Pu-238 TRU waste to WIPP. Therefore, development of a new package that would provide significant improvement over the TRUPACT-II is not a viable alternative for management of Pu-238 TRU waste.

A-3.5 References

- 10 CFR Part 71, Packaging and Transportation of Radioactive Materials.
- C of C No. 9168, Rev. 8, expires June 30, 2000, Model No. CNS 8-120B
- C of C No. 9200, Rev. 9, expires April 1, 2001, Model No. 125-B.
- C of C No. 9210, Rev. 1, expires December 31, 1999, Model No. 10-135B.
- C of C No. 9216, Rev. 5, expires December 31, 2002, Model No. CNS 1-13G.
- C of C No. 9218, Rev. 9, expires Jun. 30, 1999, Model No. TRUPACT-II.
- C of C No. 9228, Rev. 12, expires June 30, 1999, Model No. 2000.
- NRC Memo SECY-97-218, from: L. Joseph Callan, Executive Director for Operations, for: "The Commissioners," dated Sept. 29, 1997, Subject: "Special Provisions for Transport of Large Quantities of Plutonium (Response to staff requirements memorandum - SECY-96-215). Printed from internet site <http://www.nrc.gov/NRC/COMMISSION/SECYS/1997-218scy.txt> on Nov. 11, 1997.
- Position Paper on Flammability Concerns Associated with TRU Waste Destined for WIPP, DOE/WIPP 91-018, Rev. 0, April 1991.

Public Law 102-579. *Waste Isolation Pilot Plant Land Withdrawal Act*, 102d Congress, October 30, 1992.

A-3.6 Other Sources of Information

The following subject matter experts were consulted during preparation of this report:

- Steve Best, Nuclear Fuel Services, October 30, 1997.
- Douglas Berry, Savannah River Site, February 19, 1998.
- Paul Drez, Drez Environmental Associates, multiple conversations, November and December 1997.
- Barry Goldstein, Sandia National Laboratories, Dept. 6860, December 18, 1997.
- Phil Gregory, Westinghouse /Waste Isolation Division, October 29, 1997.
- Mark McAllaster, Sandia National Laboratories, Dept. 6342, Transportation Systems Department, November 18, 1997.
- Jim McClure, Sandia National Laboratories, Dept. 6341, Transportation Systems Analysis Department, November 17, 1997.
- Ross Chappell, NRC, November 18, 1997.
- Tom Clements, Idaho National Engineering and Environmental Laboratory, February 26, 1998.

A-4. Alternative Package Strategy

A-4.1 Purpose:

One aspect of the Pu-238 TRU Waste Decision Analysis study is to determine if there are existing alternative shipping packages (other than the TRUPACT-II) that can transport Pu-238-contaminated TRU waste to the WIPP more efficiently and/or less expensively than the TRUPACT-II.

A-4.2 Background:

Under current plans, all TRU waste, including Pu-238 TRU waste, will be transported to the WIPP in the TRUPACT-II for disposal. Pu-238 TRU waste has a narrower range of properties than the full spectrum of all TRU waste slated for disposal in the WIPP. These include a relatively low surface radiation dose rate, low fissile material content, and, due to its relatively short half-life (87.7 years), a high thermal heat production rate. Because the TRUPACT-II was designed to accommodate all contact-handled TRU waste going to WIPP, it was not optimized for the specific properties of Pu-238 TRU waste. There may be other, already existing, radioactive material transporters that can accommodate Pu-238 TRU waste as well, or better, than the TRUPACT-II. The Alternative Package option of the Pu-238 TRU Waste Decision Analysis process involved looking for existing radioactive material transporters, other than the TRUPACT-II, for alternatives that might be used to transport Pu-238 TRU waste to the WIPP. It is recognized that any Pu-238 TRU waste shipped in an alternative package must meet the content requirements of the NRC C of C for the alternative package. If the waste does not already meet the requirements, it must be either repackaged or treated so it does, or the C of C must be amended to allow the additional content form.

Pu-238 TRU waste exists as combustible, inorganic, and inorganic sludge waste forms. Pu-238 (and daughter uranium-234) are typically the dominate radioisotopes present. Since neither of these isotopes decays with the emission of gamma rays or beta particles, the surface radiation dose rate of waste packages is relatively low. This means shipping packages do not have to provide extensive shielding. Pu-238 is essentially non-fissile. If fissile isotopes (e.g., Pu-239 or Pu-241) are present, their activity is always less than that of the Pu-238. The fissile content of Pu-238 TRU waste is not expected to put any restraints on a waste shipping system.

The primary application for Pu-238 has been as a heat source. Pu-238 decays by alpha decay with a half-life of 87.7 years and its radioisotopic power is 0.558 watts per gram of Pu-238. One gram of Pu-238 is 17.1 curies.

The same alpha particle decay process that is responsible for the heat production from Pu-238 also breaks chemical bonds in the waste matrix. When the waste matrix is paper, plastic, or other organic and/or hydrogenous materials, this can lead to the production of gases, including flammable hydrogen. Some package C of C's have limits on the amount of hydrogen or other flammable gases allowed in the void spaces of the package. This hydrogen limit is the major constraint on shipping Pu-238 TRU waste in a TRUPACT-II. Since the amount of hydrogen gas produced is directly proportional to the amount of energy the radioactive decay products deposit

in the matrix materials, hydrogen generation can be quantified in terms of isotopic decay heat or radioisotopic power. Some C of C's control hydrogen concentrations by specifying the concentration limit directly. Others (e.g., TRUPACT-II) control hydrogen concentrations by specifying limits on decay heat.

A-4.3 Analysis:

The WIPP Land Withdrawal Act (Public Law 102-597) requires that waste be shipped to the WIPP in NRC-certified packages. Since the amount of Pu-238 in Pu-238 TRU waste usually exceeds A₁ or A₂ quantities, only Type B packages were considered (see 49 CFR 173.403 for definitions of A₁ and A₂ quantities). Two compilations of NRC C of C's were searched for candidate packages. The first was the *Directory of Certificates of Compliance for Radioactive Materials Packages*, NUREG-0383, Volumes 1 and 2, Revision 18. The second was the C of C search function accessed from the DOE World Wide Web Site for Information Relating to Radioactive Material Packaging (www.rampac.com). Both sources were searched for Type B packages large enough to contain at least one 55-gallon drum of waste, have plutonium as an allowed content, and have a loaded package mass less than about 55,000 pounds (to permit unrestricted over-the-road use). Packages without lead shielding were preferred, but shielded packages were considered if other criteria were met. Packages capable of carrying more than one 55-gallon drum were preferred. Packages (other than the TRUPACT-II) coming closest to meeting the selection criteria are shown in the table below. Some packages that do not strictly meet the search criteria are also included in the table because they are well known in the nuclear waste community and are sometimes mentioned in discussions of possible alternative packages.

The DOE RAMPAC (Radioactive Materials Packaging) World Wide Web site at <http://www.rampac.com> gave instructions on how to reach the DOE Transportation Management Program "FaxBack" system. The "FaxBack" system provides a method for easily obtaining a catalog of C of C's and copies of individual certificates. Copies of C of C's are also available on the World Wide Web at www.emwebwin.com/rampac. Copies of the relevant certificates were obtained.

CofC #	Name or Model Package ID #	Capacity (# of 55 gal drums)	Double Containment? Pu load limit (if stated)	Notes
6058	B-3 USA/6058/B()F	1	No Pu <200 g (fissile limit)	6" lead shielding; content types (i) Pu as solid, dry, nonpowder that will not decompose at 525°F, or (ii) Pu which meets requirements of Special Form; ≤200 grams Pu (if ≥20 curies of Pu, form must be reactor fuel, fuel elements, metal, or metal alloy); ≤400 watts thermal decay.
6400	6400 ("Super Tiger") USA/6400/B()F	16	No Only fissile limits given	No lead shielding. Applicable contents: (2) decontaminated hard waste items such as equipment, metal cans, tools, etc. double bagged in heat-sealed 12-mil polyvinyl chloride (PVC) bags, or (4) soft waste items such as sheeting, gloves, paper, prefilter media, polyethylene bottles, shoe covers, etc. double bagged in heat sealed 12-mil PVC bags with bag size no larger than 22 inches x 16 inches x 10 inches.
6722	BS-33-180 USA/6722/A	14	No Low Specific Activity limits	Generated hydrogen limited to ≤5% by volume of the secondary container gas void, limited to ≤20 watts thermal, content limited to Low Specific Activity waste. This Certificate of Compliance (Rev.11) expired April 30, 1996. There is no current C of C for this package in the RAMPAC database as of 9/30/98.
9070	N-55 USA/9070/B(U)	1	No Pu limit <20 Ci (see notes)	A steel overpack-type container. Allowed content: (i) radioactive material in the form of dewatered, solid, or solidified materials meeting Low Specific Activity requirements, or (ii) radioactive material meeting Special Form requirements, or (iii) radioactive material in the form of solid metal pieces or activated solid metal components. If ≥20 curies of Pu, form must be reactor fuel, fuel elements, metal, or metal alloy.
9089	HN-194S USA/9089/A	14	No Pu≤0.0001 mCi/g waste	Allowed content -- Process solids, either dewatered, solid or solidified, and limited to the following: (i) Materials in which the radioactivity is essentially uniformly distributed and in which the estimated average concentration per gram of contents does not exceed 0.0001 mCi of radionuclides for which the A ₂ quantity in Appendix A of 10 CFR Part 71 is not more than 0.05 Ci (this limit applies to ²³⁸ Pu, other limits given for isotopes with A ₂ values in other ranges); (ii) Objects of nonradioactive material externally contaminated with radioactive material, provided the radioactive material is not readily dispersible and the surface contamination, when averaged over an area of 1 m ² , does not exceed 0.0001 mCi (220,000 dpm) per cm ² of radionuclides for which the A ₂ quantity is not more than 0.05 Ci, or 0.001 mCi) per cm ² for other radionuclides. H ₂ limited to ≤5% by volume of the secondary container gas void, limited to <2 watts thermal.
9094	CNS 14-195-H USA/9094/A	14	No Pu≤0.0001 mCi/g waste	2.18" lead shielding. Allowed content -- Process solids, either dewatered, solid or solidified, and limited to the following: (i) Materials in which the radioactivity is essentially uniformly distributed and in which the estimated average concentration per gram of contents does not exceed 0.0001 mCi of radionuclides for which the A ₂ quantity in Appendix A of 10 CFR Part 71 is not more than 0.05 Ci (this limit applies to ²³⁸ Pu, other limits are given for isotopes with A ₂ values in other ranges); (ii) Objects of nonradioactive material externally contaminated with radioactive material, provided the radioactive material is not readily dispersible and the surface contamination, when averaged over an area of 1 m ² , does not exceed 0.0001 mCi (220,000 dpm) per cm ² of radionuclides for which the A ₂ quantity is not more than 0.05 Ci, or 0.001 mCi (2,200,000 dpm) per cm ² for other radionuclides. Generated hydrogen limited to ≤5% by volume of the secondary container gas void. Gross package weight is 56,500 pounds.

CofC #	Name or Model Package ID #	Capacity (# of 55 gal drums)	Double Containment? Pu load limit (if stated)	Notes
9168	CNS 8-120B USA/9168/B(U)	8	No ≤ 0.63 g Pu-238 (2000 times A ₂)	Has lead shielding. Weighs 74,000 pounds so it does not qualify for highway use, only rail. Contents: (i) Byproduct material in the form of dewatered resins, solids, or solidified waste contained within secondary containers; or (ii) radioactive material in the form of activated reactor components. Maximum quantity of radioactive material allowed: 2,000 times a Type A quantity; no more than 100 thermal watts. Generated hydrogen limited to $\leq 5\%$ by volume of the secondary container gas void.
9200	125-B USA/9200/B(M)F	0	Yes	Lead shielded. Mass of cask, impact limiters, and <i>inner vessel (empty) is 149,299 pounds</i> . Contents: (i) Byproduct and special nuclear material in the form of irradiated fuel particles, partial fuel rods, partial assemblies, and core debris; (ii) Irradiated core structural components, contaminated defueling equipment, and filter-aid materials; (iii) Byproduct and special nuclear material in the form of internal contamination inside the inner vessel. Internal contamination shall not exceed the limits for low specific activity material. Limit of 7 canisters per inner vessel; decay heat load ≤ 100 watts per canister. Inner vessel tubes have 14.5-inch inner diameter, too small to hold 55-gallon drums.
9204	CNS 10-160B USA/9204/B(U)	8 to 14	No ≤ 0.63 g Pu-238 (2000 times A ₂)	Has lead shielding. Weight (empty) 54,000 lbs. Contents: (i) Byproduct material in the form of dewatered resins, solids, or solidified waste contained within secondary containers; or (ii) radioactive material in the form of activated reactor components. Maximum quantity of material per package: Type B quantity not to exceed 2,000 times a Type A quantity, no more than 100 watts decay heat. Generated hydrogen limited to $\leq 5\%$ by volume of the secondary container gas void
9216	CNS 1-13G USA/9216B()F	1	No Pu limit <20 Ci unless in form of metal, metal alloy, or reactor fuel elements	5" lead shielding. Generated hydrogen limited to $\leq 5\%$ by volume of the secondary container gas void. Contents: if Pu >20 curies, form must be metal, metal alloy, or reactor fuel elements and (i) byproduct as solid metal or oxide, ≤ 600 watts, in form of fuel rods, fuel plates, fuel assemblies, or special form, (ii) neutron sources meeting special form requirements, ≤ 50 watts, (iii) irradiated PuO ₂ and UO ₂ fuel rods clad in Zircalloy or stainless steel, ≤ 600 watts; (iv) process solids, either dewatered, solid, or solidified in secondary sealed container meeting Low Specific Activity requirements; (v) solid, nonfissile irradiated metal hardware, reactor control rods, reactor start-up sources, etc.; or (vi) radioactive (Hot Cell) type waste solidified with cement grout to a specific recipe and <100 watts thermal and <500 grams uranium-235 equivalent mass.
9228	2000 USA/9228/B(U)F	1	No Pu limit <20 Ci unless in form of metal, metal alloy, or reactor fuel elements	Generated hydrogen limited to $\leq 5\%$ by volume of the secondary container gas void . Content: (i) irradiated fuel rods, (ii) byproduct, source, or special nuclear material in solid form, (iii) irradiated HFIR fuel assembly, (iv)-(vi) other specified reactor fuel elements or assemblies. For content (ii) ≤ 600 watts and ≤ 500 grams ²³⁵ U equivalent mass fissile. If Pu >20 curies, form must be metal, metal alloy, or reactor fuel elements.

Additional Notes:

1. The Atomic Materials Rail Transfer (ATMX) railcar operates under a Department of Transportation exemption (DOT-E 5948 Rev. 7) to ship up to Highway Route Controlled Quantities (HRCQ) of Pu-containing waste. The HRCQ limit is 3,000 times the A₁ quantity, 3000 times A₂ quantity, or 30,000 curies in a single package, which ever is least. For Pu-238, 3,000 times the A₂ quantity is 16 curies or 0.94 grams. The ATMX is not NRC certified and thus does not meet one of the legal requirements of the WIPP Land Withdrawal Act for packages used to ship TRU waste to WIPP. The DOT exemption cited above expired on April 30, 1998. The DOE/AL office is applying for a further extension of the exemption.
2. Packages with Package ID numbers containing the suffixes "(U)" or "(M)" may be reproduced as long as the fabrication is successfully completed by April 1, 1999. Only packages with Package ID numbers containing the additional suffix "-85" may be reproduced after April 1, 1999. None of the packages in this table have the "-85" suffix.

Several of the above packages have contents limited to Low Specific Activity waste levels, the definition of which can be found in the Code of Federal Regulations, e.g., 10 CFR 71.4. The Low Specific Activity definition pertinent to Pu-238 TRU waste is that the specific activity of the waste must be less than 2×10^{-3} A₂/gram. The A₂ value for Pu-238 is 0.00541 curies. Thus a 55-gallon drum of waste with a waste density of 2 grams per cubic meter would be limited to no more than 4.5 curies or 0.26 grams of Pu-238. Expressed in terms of decay heat, this is equivalent to about 0.14 watts per drum. This limit makes any package limited to Low Specific Activity quantities not practical for transporting Pu-238 TRU waste to WIPP.

Another limitation on the use of many of the packages in the above table is the requirement that hydrogen gas in the void space be $\leq 5\%$ by volume. This limit is the same as the limit for the TRUPACT-II. The hydrogen concentration limit is the most difficult requirement for Pu-238 TRU waste to meet to be eligible for shipment in the TRUPACT-II. Thus any waste that meets this requirement for an alternative package would also be expected to meet the TRUPACT-II requirement, making an alternative package unnecessary.

After eliminating packages limited to Low Specific Activity waste, eliminating those with a 5% hydrogen in void space limit, and eliminating packages that can only carry one 55-gallon drum or less, the package with C of C number 6400 is the only package left for further consideration. This package is known as the Super Tiger and is discussed further below.

A-4.3.1 Super Tiger

The Super Tiger transporter, C of C number 6400, can carry up to 16 55-gallon drums and does not have unnecessary lead shielding. Further information on the Super Tiger was obtained by telephoning Nuclear Fuel Services, who operates Super Tigers.

- Nuclear Fuel Services has obtained from the NRC a new (Rev. 23), 5-year C of C for the Super Tiger. The new C of C is dated July 7, 1997 and expires July 31, 2002.
- Nuclear Fuel Services currently has three Super Tigers.
- Nuclear Fuel Services is currently making shipments of TRU and other radioactive materials in Super Tigers.
- A typical Super Tiger shipment takes about 1 week and the cost is approximately \$20,000. The cost includes the truck and driver, drum bagging equipment, packing material to go between drums, and necessary handling slings.
- The site using the Super Tiger would need to supply suitable cranes or hoists to load and unload the Super Tiger and operators for the cranes and hoists.

The Super Tiger C of C lists a variety of allowed contents. Two of these pertinent to Pu-238 TRU waste are:

- 5.(b)(2) “Decontaminated hard waste items, such as equipment, metal cans, tools, etc., ...double bagged within 12-mil thick PVC with each bag heat sealed.” Total fissile material in the container must not exceed 200 grams.
- 5.(b)(4) “Soft waste items such as sheeting, gloves, paper, prefilter media, polyethylene bottles, shoe covers, etc., ... double bagged in 12-mil thick PVC, with

each bag heat sealed (bag size must not exceed 22" x 16" x 10") and packaged within [Department of Transportation] Specification 17H or 17C steel drums (maximum size 55-gallons)." Each drum is limited to no more than 60 grams of fissile material.

Very little, if any, Pu-238 TRU waste is currently packaged in a manner consistent with these content descriptions. For example, DOE facilities have generally not packaged waste double bagged in heat sealed 12-mil thick PVC bags, and DOE facilities have not limited bag sizes to not exceed 22" x 16" x 10." If a decision is made to repackage Pu-238 TRU waste for shipment, it can be repackaged for the TRUPACT-II, making use of an alternate package unnecessary.

A-4.3.2 RH-72-B TRU Waste Shipping Package

The RH-72-B TRU waste shipping package is designed to transport canisters of remote-handled TRU waste to the WIPP for disposal. The internal volume is sufficient to carry three 55-gallon drums at a time. DOE has applied to the NRC for certification for the package, and the application is currently in the review process.

The *Safety Analysis Report for the RH-72-B Shipping Package* (DOE, 1996) limits hydrogen gas generation in the RH-72B package to 5% by volume in any layer of confinement. This is an equivalent requirement to the hydrogen generation limit for the TRUPACT-II. To make it possible to safely transport remote handled waste, the RH-72B package contains lead shielding. This shielding is not needed to transport Pu-238 TRU waste. Any Pu-238 TRU waste that qualifies for shipment in the RH-72-B cask should also meet requirements for shipment in the TRUPACT-II.

A-4.4 Conclusion:

The only alternative package identified with a C of C that has the potential to allow shipment of multiple 55-gallon drums of TRU waste containing plutonium, and which does not have an hydrogen gas concentration limit similar to the TRUPACT-II, is the Super Tiger (C of C No. 6400). The contents allowed by the Super Tiger C of C do not match the content of the majority of Pu-238 TRU waste drums. In order to ship a significant amount of Pu-238 TRU waste in the Super Tiger without extensive repackaging, it will be necessary to request the NRC to approve an amendment to the C of C to allow additional content types. If the NRC were to approve such an amendment, the NRC would also update the C of C by requiring the contents meet the 5% hydrogen upper limit included in the C of C's for essentially all other packages. Because of these factors, we believe the Super Tiger is not likely to be able to move large amounts of Pu-238 TRU waste to WIPP.

Several people with extensive radioactive waste packaging experience were interviewed to gather information to prepare this paper. All of them had the opinion that any package used for shipping Pu-238 TRU waste will have to meet the same hydrogen gas concentration limits as the TRUPACT-II. If those limits are not currently in the C of C for the package, they would quickly be imposed and added to the C of C when the shipping program is announced. This philosophy is also articulated in the *Standard Review Plan for Transportation Packages for Radioactive Material, Draft Report for Comment* (NUREG-1609) issued by the NRC. [Also, 10 CFR 71.65

is one source of the authority for the NRC to impose additional restrictions. It states "The Commission may, by rule, regulation, or order, impose requirements on any licensee, in addition to those established in this part, as it deems necessary or appropriate to protect public health or to minimize danger to life or property."]

A drum of Pu-238 TRU waste generates the same amount of hydrogen gas whether it is in a TRUPACT-II or any other transport package. All NRC-approved transport packages for plutonium have double containment so all hydrogen gas remains inside the package. Different transport packages have may have different internal void volumes which will result in slightly different final hydrogen concentrations, but no alternative package has been identified that provides any significant advantage over the TRUPACT-II for shipping Pu-238 TRU waste to the WIPP.

It might prove possible and practical to ship an occasional drum or drums of Pu-238 TRU waste to the WIPP in an existing alternative package. The most likely situation would be a small quantity site which could send all of its TRU waste to WIPP in a single shipment.

A-4.5 References:

49 CFR 173.403, Class 7 (Radioactive) Materials, Definitions.

CFR Part 71 - *Packaging and Transportation of Radioactive Material*, 1-1-97 Edition.

C of C No. 6058, Rev. 13, expires Dec. 31, 2000, Model No. B-3.

C of C No. 6400, Rev. 24, expires July 31, 2002, Model No. 6400 (Super Tiger).

C of C No. 6722, Rev. 11, expires April 30, 1996, Model No. BS-33-180.

C of C No. 9010, Rev. 38, expires April 30, 2001, Model NLI-1/2.

C of C No. 9150, Rev. 5, expires July 31, 2001, Model No. PAT-2.

C of C No. 9069, Rev. 11, expires Dec. 31, 2002, Model No. MO-1.

C of C No. 9070, Rev. 13, expires Dec. 31, 1999, Model No. N-55.

C of C No. 9089, Rev. 12, expires Apr. 1, 1999, Model No. HN-194S.

C of C No. 9094, Rev. 14, expires Apr. 1, 1999, Model No. CNS 14-195-H.

C of C No. 9132, Rev. 13, expires Apr. 1, 2001, Model T-3.

C of C No. 9168, Rev. 8, expires Jun. 30, 2000, Model CNS 8-120B.

C of C No. 9200, Rev. 9, expires April 1, 2001, Model No. 125-B.

C of C No. 9204, Rev. 1, expires Oct. 31, 2000, Model No. CNS 10-160B.

C of C No. 9208, Rev. 9, expires Jul. 31, 2001, Model No. 10-142.

C of C No. 9210, Rev. 1, expires Dec. 31, 1999, Model No. 10-135B.

C of C No. 9216, Rev. 5, expires Dec. 31, 2002, Model No. CNS 1-13G.

C of C No. 9218, Rev. 9, expires Jun. 30, 1999, Model No. TRUPACT-II.

C of C No. 9228, Rev. 12, expires Jun. 30, 1999, Model No. 2000.

C of C No. 9904, Rev. 1, expires May 31, 2001, Model No. RTG Package.

DOE, 1996, *Safety Analysis Report for the RH-TRU 72-B Waste Shipping Package*, Rev. 0, Sept. 1996, RH-TRU 72-B Cask SAR.

DOT-E 5948 (Seventh Revision), June 17, 1996. (Department of Transportation Exemption for ATMX 600 rail cars).

NRC Memo SECY-97-218, from: L. Joseph Callan, Executive Director for Operations, for: "The Commissioners," dated Sept. 29, 1997, Subject: "Special Provisions for Transport of Large Quantities of Plutonium" (Response to staff requirements memorandum - SECY-96-215). Printed from internet site <http://www.nrc.gov/NRC/COMMISSION/SECYS/1997-218scy.txt>, on Nov. 11, 1997.

NUREG-0383, *Directory of Certificates of Compliance for Radioactive Materials Packages*, Volumes 1 and 2, Revision 18, 1995.

NUREG-1609, *Standard Review Plan for Transportation Packages for Radioactive Material, Draft Report for Comment*, U.S. Nuclear Regulatory Commission Office of Nuclear Material Safety and Safeguards. Not dated, printed from NRC internet site <http://www.nrc.gov> on 1/27/98.

Public Law 102-579, *Waste Isolation Pilot Plant Land Withdrawal Act*, 102d Congress, October 30, 1992.

A-4.6 Other Sources of Information

DOE Radioactive Materials Packaging (RAMPAC) WWW sites:

<http://www.rampac.com>, RAMPAC Homepage

<http://www.rampac.com/permissions/>, Instructions for use of and searching RAMPAC database

<http://www.rampa.com/Certificates.html>, C of C database search and screening tool

<http://www.emwebwin.com/rampac/>, RAMPAC Document Retrieval System page, a source of current C of C's.

DOE Transportation Management Program "FaxBack" system, 509-373-7259 as a source of current C of C's.

The Radioactive Material Post Notification (RAMPOST) Data Base, SAND95-2611C. Found at WWW URL <http://www.sandia.gov/ttp/flyers/rampost/rampost.htm> on Jan. 19, 1998. (Contains definition of Highway Route Controlled Quantity).

The following subject matter experts were consulted during preparation of this report:

- Steve Best, Nuclear Fuel Services, Oct. 30, 1997.
- Personal communications, R.W. Bild with Paul Drez, Drez Environmental Associates., multiple conversations, Nov. and Dec. 1997.
- Phil Gregory, Westinghouse /Waste Isolation Division, Oct. 29, 1997.
- Mark McAllaster, Sandia National Laboratories, Dept. 6342, Transportation Systems Department, Nov. 18, 1997.
- Jim McClure, Sandia National Laboratories, Dept. 6341, Transportation Systems Analysis Department, Nov. 17, 1997.
- Jim McClure, Sandia National Laboratories, Dept. 6341, Transportation Systems Analysis Department, Jan. 21, 1998.
- Stacy Rosenberg, NRC, Nov. 18, 1997.

- Ross Chappell, NRC, Nov. 18, 1997.
- Mike Wangler, DOE/Headquarters, EM-76, Jan. 22, 1998.
- Marta Jones, DOE/AL, Sept. 24, 1998.

A-5. Performance Measures

The decision analysis process requires the identification of performance measures to quantify the relative merits of each possible outcome of the decision tree. As an aid in the process of identifying performance measures, an objectives hierarchy (Figure A-1) was prepared.

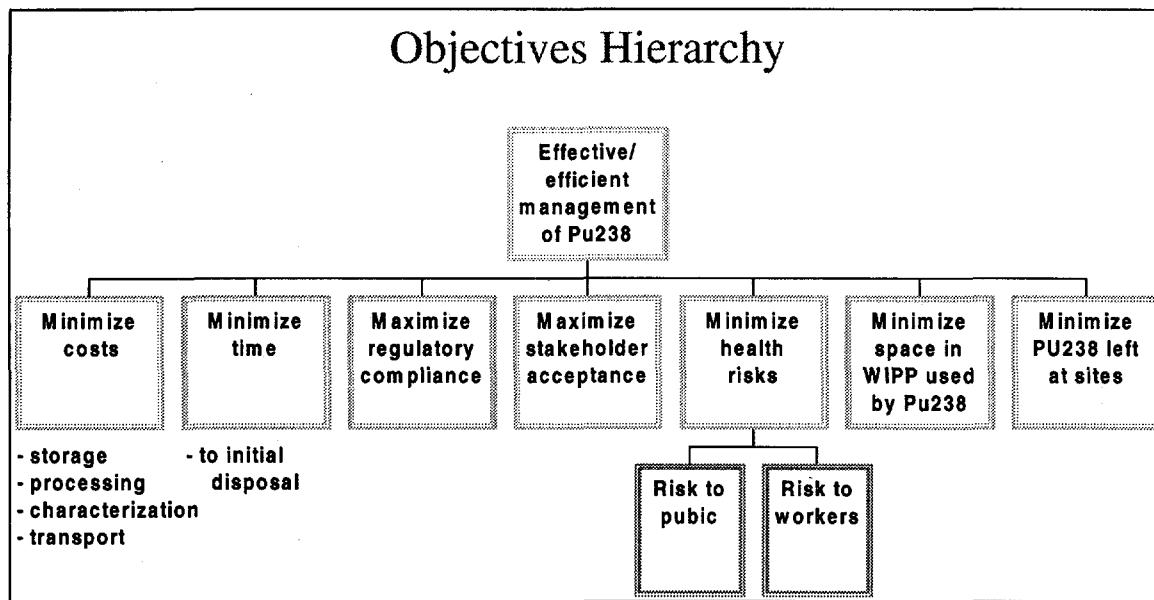


Figure A- 1. Objectives Hierarchy

The objectives hierarchy identifies the potential factors that a decisionmaker is likely to entertain when selecting a strategy(ies) to meet the overall objective of improving upon the packaging and transport of Pu-238 TRU waste (i.e., more effective and efficient management). The objectives were to:

- Minimize costs (storage, processing characterization, transport)
- Maximize the volume disposed of during the time to initial disposal (2006)
- Maximize the ability of strategies to comply with applicable regulations
- Maximize strategy acceptance by stakeholders
- Minimize health risks to workers and the public from strategy implementation
- Minimize the disposal area in the WIPP devoted to Pu-238 TRU waste, and
- Minimize Pu-238 TRU waste that may remain at the sites after disposal operations cease.

To be considered as a performance measure, objectives must be able to be quantified in a manner that will meaningfully allow for the discrimination among strategies. Given this, health risk to workers and the public was rejected from further consideration because it was believed that risk would be difficult to quantify at the strategic level, and in any event exposures (doses) would be very low and in compliance with regulations and DOE orders. Thus, health risk would not enable discrimination between strategies.

Strategy acceptance by stakeholders was disqualified as a performance measure because it is perception-based at the individual or organizational levels. Also, stakeholder acceptance was

likely to vary considerably among the affected sites, and is very difficult to quantify in a meaningful manner.

Regulatory compliance also was eliminated from further consideration. As noted in the text, Section 2.2.1, decisions that have already been made are policies and this decision analysis focused only on strategic decisions within the framework established by policies.

For these reasons, the objectives and therefore the performance measures were limited to cost, and two measures of waste volumes – volumes disposed by 2006 and volumes of waste that exceed current projected shipping rates based on *The National TRU Waste Management Plan* (DOE, 1997). The later measure accounts for the objectives associated with the extent to which the WIPP underground must be devoted to disposal of Pu-238 TRU waste, and the extent to which Pu-238 TRU waste would remain at the sites after disposal operations cease.

A-5.1 References:

DOE (U.S. Department of Energy), 1997. *The National TRU Waste Management Plan*,
DOE/NTP-96-1204, Revision 1, December, DOE Carlsbad Area Office, Carlsbad, NM.

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APPENDIX B

VOLUME CALCULATIONS and PLUTONIUM-238 TRU WASTE INVENTORY

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Acronyms and Abbreviations

eV	electron volt
G-value	hydrogen generation rate due to radiolysis, molecules/100 eV
NRC	Nuclear Regulatory Commission
Pu	plutonium
TRU	transuranic
TRAMPAC	TRUPACT-II Authorized Methods for Payload Control
TRUPACT-II	Transuranic Package Transporter, Model II

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Appendix B

VOLUME CALCULATIONS

Sections B-1 through B-5 provide the analytical basis used to determine the change in wattage limits that could be achieved by applying the benefits of each path (strategy) in the decision tree. Sections B-6 and B-7 discuss the basis used to change the wattage limits as a result of thermal treatment and repackaging, respectively. The "modified" wattage limits were then applied on a container-by-container basis using the waste model volume described in the body of the report. Section B-9 includes the container-by-container inventory provided by the TRU waste sites.

B-1. Calculations for Path 1

B-1.1 Theory

Path 1 involves repackaging the plutonium-238 (Pu-238) transuranic (TRU) waste and placing hydrogen getters in the headspace of the drum. The expectation is that with the new configuration, the Pu-238 TRU waste drums can accommodate higher wattage waste without violating the restriction on hydrogen accumulation currently set for the Transuranic Package Transporter, Model II (TRUPACT-II). A new wattage limit for Pu-238 TRU waste drums repackaged with hydrogen getters can be derived as follows:

1. The rate of hydrogen accumulation in the innermost layer of confinement is equal to the difference between the hydrogen generation rate from the waste (due to radiolysis) and the release rate from the innermost layer of confinement to the drum headspace.

$$R_{\text{headspace}} = \frac{1}{r_{\text{plastic}}} (X_i - X_h)$$
$$\frac{dX_i}{dt} = R_{\text{actual}} - R_{\text{headspace}}$$

X_i	= volume fraction of hydrogen in the innermost layer of confinement
X_h	= volume fraction of hydrogen in the headspace of the drum
R_{actual}	= hydrogen generation rate from radiolysis in the waste
$R_{\text{headspace}}$	= hydrogen release rate to the drum headspace
r_{plastic}	= effective resistance of plastic layers of confinement

2. The rate of hydrogen accumulation in the headspace is the sum of three contributors: the getter reaction rate (a negative contributor), release from the inner layers of confinement (a positive contributor), and release from the headspace to the inner containment vessel of the TRUPACT-II (a negative contributor).

$$R_{\text{ICV}} = \frac{1}{r_{\text{df}}} (X_h - X_{\text{ICV}})$$

$$\frac{dX_h}{dt} = -R_{getter} + R_{headspace} - R_{ICV}$$

X_{ICV}	= volume fraction of hydrogen in the inner containment vessel
R_{getter}	= hydrogen getter reaction rate
r_{df}	= resistance of the drum filter
R_{ICV}	= hydrogen release rate to the TRUPACT-II ICV

3. Since hydrogen is not released from the inner containment vessel, the concentration of hydrogen in the inner containment vessel is:

$$X_{ICV} = R_{ICV} \frac{t \cdot n_{gen}}{N_{tg}}$$

R_{ICV}	= the per drum hydrogen release rate to the inner containment vessel
t	= the time that the inner containment vessel has been sealed
n_{gen}	= the number of drums in the inner containment vessel
N_{tg}	= the total moles of gas in the inner containment vessel

4. At steady state,

$$\frac{dX_i}{dt} = 0$$

$$\frac{dX_h}{dt} = 0$$

$$R_{actual} = R_{headspace}$$

$$R_{ICV} = R_{headspace} - R_{getter}$$

$$R_{ICV} = R_{actual} - R_{getter}$$

and

$$X_{ICV} = (R_{actual} - R_{getter}) \cdot \frac{t \cdot n_{gen}}{N_{tg}} \quad (1)$$

$$0 = R_{actual} - \frac{1}{r_{plastic}}(X_i - X_h) \quad (2)$$

$$0 = -R_{getter} + \frac{1}{r_{plastic}}(X_i - X_h) - \frac{1}{r_{df}}(X_h - X_{ICV}) \quad (3)$$

5. Solving Equations (1), (2), and (3) for R_{actual} gives

$$R_{actual} = \frac{X_i}{r_{eff} + \frac{t \cdot n_{gen}}{N_{tg}}} + R_{getter} \left(\frac{\frac{t \cdot n_{gen}}{N_{tg}}}{r_{df} + \frac{t \cdot n_{gen}}{N_{tg}}} \right)$$

where

$$I_{eff} = I_{plastic} + I_{df}$$

6. If the gas getter rate is greater than or equal to the gas generation rate,

$$X_h = 0$$

$$R_{actual} = \frac{X_i}{I_{plastic}} \quad (\text{from Equation 2})$$

7. The watts allowed can be calculated from the hydrogen generation rate

$$W_{allowed} = R_{actual} \cdot \frac{N_a \cdot k}{G_{eff}}$$

N_a = Avogadros Number

k = units conversion constant

G_{eff} = effective G-Value

B-1.2 Example Calculation

The following is an example calculation for Path 1 using the first data point from the Hanford inventory (2 drum equivalents of Pu-238 TRU waste each containing 295 watts; Shipping Category III.1A4). The data for the calculation are given in Table B-1.

$$R_{actual} = \frac{0.05}{162,086 \text{ sec/mole}}$$

$$R_{actual} = 3.08E - 7 \text{ moles/sec}$$

$$\begin{aligned} \frac{k \cdot N_a}{G_{eff}} &= \frac{(1.60E - 19 \text{ watt sec/eV}) (6.023 \times 10^{23} \text{ molecules/g mole})}{(3.4 \text{ molecules/100 eV})} \\ &= 2.84E + 06 \text{ watts \cdot sec/mole} \end{aligned}$$

$$W_{allowed} = 3.08E - 7 \text{ moles/sec} \cdot [2.84E + 06 \text{ watts sec/mole}]$$

$$W_{allowed} = 0.87 \text{ watts}$$

For two drums each with 295 watts, repackaging would produce:

$$N_{\text{drums}} = 2 \text{ drum equivalents} \frac{295 \text{ watts}}{0.87 \text{ watts}} = 678 \text{ repackaged drums}$$

B-2. Calculations for Path 2

B-2.1 Theory

Path 2 involves changing the effective G-value used to calculate wattage limits and shipping some of the Pu-238 TRU waste "as-is." A new wattage limit for Pu-238 TRU waste drums can be derived as follows:

1. The watts allowed can be calculated from the hydrogen generation rate

$$W_{\text{allowed}} = R_{\text{actual}} \cdot \frac{N_a \cdot k}{G_{\text{eff}}}$$

N_a	= Avogadro's Number
k	= units conversion constant
G_{eff}	= effective G-Value
R_{actual}	= hydrogen generation rate from radiolysis in the waste

2. Since R_{actual} , N_a , and k remain the same, the new wattage can be calculated from the ratio:

$$(W_{\text{allowed}})_{\text{new}} = \frac{(G_{\text{eff}})_{\text{old}}}{(G_{\text{eff}})_{\text{new}}} (W_{\text{allowed}})_{\text{old}}$$

B-2.2 Example Calculation

The following is an example calculation for Path 2 using the first data point from the Hanford inventory (2 drum equivalents of Pu-238 TRU waste each containing 295 watts; Shipping Category III.1A4). The data for the calculation are given in Table 2.

$$(W_{\text{allowed}})_{\text{new}} = \left(\frac{3.4}{0.13} \right) \cdot 0.0207 \text{ watts} = 0.541 \text{ watts}$$

Both drums have 295 watts each. Therefore, neither one of the drums can be shipped "as-is" even if the wattage limit were changed to 0.541 watts.

Table B- 1. Parameter Values for Path 1 Sample Calculations

Parameter	Value	Parameter	Value
$r_{plastic}$	^(a) 162,086 sec/mole	X_i	^(e) 0.05
r_{df}	^(b) 10,811 sec/mole	t^*n_{gen}/N_{tg}	^(f) 612,525 sec/mole
r_{eff}	^(c) 172,897 sec/mole	R_{getter}	^(g) 2.50E-02 mole/sec
G_{eff}	^(d) 3.4 molecules/100 eV	N_a	6.023×10^{23} molecules/g mole
k	1.60E-19 watt sec/eV	drums per TRUPACT-II	^(h) 12 drums

^(a)waste is repackaged into one filtered inner bag (93,023 sec/mole), one filtered liner bag (67,295 sec/mole), and one drum liner with a one-inch hole (1,768 sec/mole)

^(b)advanced drum filter assumed for repackaging scenario (10,811 sec/mole);

^(c)effective resistance is the sum of the plastic resistance and the drum filter resistance

^(d)G-value is for Waste Type III

^(e)volume fraction of hydrogen in innermost bag; corresponds to 5% limit

^(f)The Nuclear Regulatory Commission (NRC) requires an assumed shipping time of 60 days

^(g)This is the getter reaction rate given by the experts for the high case

^(h)from *The National TRU Waste Management Plan* (DOE, 1997)

⁽ⁱ⁾ Note that the gas getter rate is greater than the gas generation rate.

Table B- 2. Parameter Values for Path 2 Sample Calculation

Parameter	Value	Parameter	Value	Parameter	Value
Old G_{eff}	^(a) 3.4 molecules/100 eV	New G_{eff}	^(b) 0.13 molecules/100 eV	Old $W_{allowed}$	^(c) 0.0207 watts

^(a)For Waste Type III

^(b)This is the new effective G-value given by the expert panel for Waste Type III, the high case;

^(c)from *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC) (DOE, 1998)

B-3. Calculations for Path 3

B-3.1 Theory

Path 3 involves testing the Pu-238 TRU waste drums for hydrogen in the headspace and determining if the drum is shippable with a back calculation of the concentration of hydrogen in the innermost layer of confinement. One can determine if the drum is shippable as follows:

1. The rate of hydrogen accumulation in the innermost layer of confinement is equal to the difference between the hydrogen generation rate from the waste (due to radiolysis) and the release rate from the innermost layer of confinement to the drum headspace.

$$\frac{dX_i}{dt} = R_{actual} - \frac{1}{r_{plastic}}(X_i - X_h)$$

X_i = volume fraction of hydrogen in the innermost layer of confinement
 X_h = volume fraction of hydrogen in the drum headspace
 R_{actual} = hydrogen generation rate from radiolysis in the waste
 $r_{plastic}$ = effective resistance of plastic layers of confinement

2. The rate of hydrogen accumulation in the drum headspace is the sum of two contributors, release from the inner layers of confinement (a positive contributor), and release from the headspace to the inner containment vessel of the TRUPACT-II (a negative contributor).

$$R_{\text{headspace}} = \frac{1}{r_{\text{plastic}}} (X_i - X_h)$$

$$R_{\text{ICV}} = \frac{1}{r_{\text{df}}} (X_h - X_{\text{ICV}})$$

$$\frac{dX_h}{dt} = R_{\text{headspace}} - R_{\text{ICV}}$$

X_{ICV} = volume fraction of hydrogen in the inner containment vessel

r_{df} = resistance of the drum filter

$R_{\text{headspace}}$ = hydrogen release rate to the drum headspace

R_{ICV} = the per drum hydrogen release rate to the inner containment vessel

3. Since hydrogen is not released from the inner containment vessel, the concentration of hydrogen in the inner containment vessel is:

$$X_{\text{ICV}} = R_{\text{ICV}} \frac{t \cdot n_{\text{gen}}}{N_{\text{tg}}}$$

t = the time that the inner containment vessel has been sealed

n_{gen} = the number of drums in the inner containment vessel

N_{tg} = the total moles of gas in the inner containment vessel

4. At steady state,

$$\frac{dX_i}{dt} = 0$$

$$\frac{dX_h}{dt} = 0$$

$$R_{\text{actual}} = R_{\text{headspace}}$$

$$R_{\text{ICV}} = R_{\text{headspace}}$$

$$R_{\text{ICV}} = R_{\text{actual}}$$

and

$$X_{\text{ICV}} = (R_{\text{actual}}) \cdot \frac{t \cdot n_{\text{gen}}}{N_{\text{tg}}} \quad (1)$$

$$0 = R_{\text{actual}} - \frac{1}{r_{\text{plastic}}} (X_i - X_h) \quad (2)$$

$$0 = \frac{1}{r_{\text{plastic}}} (X_i - X_h) - \frac{1}{r_{\text{df}}} (X_h - X_{\text{ICV}}) \quad (3)$$

5. Solving Equations (1), (2), and (3) for X_h gives

$$X_h = \frac{X_i}{1 + \frac{r_{\text{plastic}}}{r_{\text{df}} + \frac{t \cdot n_{\text{gen}}}{N_{\text{tg}}}}}$$

B-3.2 Example Calculation

The following is an example calculation for Path 3 using the Hanford inventory as an example. The data for the calculation are given in Table B-3.

$$X_h = \frac{0.05}{1 + \frac{5,610,124 \text{ sec/mole}}{526,316 \text{ sec/mole} + 612,525 \text{ sec/mole}}} = 0.0084 \text{ moles hydrogen per total moles}$$

This is the maximum concentration of hydrogen that would be allowed in the headspace of a drum to be shipped "as-is." Using the distribution given by the experts, the probability that a drum has less than or equal to 0.8% hydrogen in the headspace is 0.99 (Appendix D). Hanford has 51 drums of III.1A4 waste. Therefore, of the III.1A4 waste at Hanford, 50 drums should be shippable based on headspace gas sample results.

$$0.99 \cdot 51 \text{ drums} = 50 \text{ drums}$$

However, twelve of the III.1A4 drums have over 100 watts each. The authors believe that even with a positive result from the headspace gas sampling, these twelve drums cannot be shipped "as-is" to WIPP. One reason is that each of the drums violates the 40 watt limit set for the TRUPACT-II. Therefore, the number of III.1A4 drums that can be shipped from Hanford based on headspace gas sampling results is:

$$50 - 12 = 38 \text{ drums}$$

Table B- 3. Parameter Values for Path 3 Sample Calculations

Parameter	Value	Parameter	Value
$r_{plastic}$	^(a) 5,610,124 sec/mole	X_i	^(e) 0.05
r_{df}	^(b) 526,316 sec/mole	t^*n_{gen}/N_{tg}	^(f) 612,525 sec/mole
r_{eff}	^(c) 6,136,440 sec/mole	N_a	6.023×10^{23} molecules/ g mole
G_{eff}	^(d) 3.4 molecules/100 eV	Distribution for Volume Percent of Hydrogen	^(g) Lognormal
k	1.60E-19 watt sec/eV	Mean Value for Volume Percent Hydrogen	^(g) 0.075
N_a	6.023×10^{23} molecules/ g mole	Standard Deviation for Volume Percent Hydrogen	^(g) 0.5

^(a)three inner bags (1,792,115 sec/mole), one liner bag (214,133 sec/mole), and one drum liner with a 0.3 inch hole (19,646 sec/mole)

^(b)current drum filter

^(c)effective resistance is the sum of the plastic resistance and the drum filter resistance

^(d)G-value is for Waste Type III; ^(e)5% hydrogen limit in innermost bag

^(e)volume fraction of hydrogen in innermost bag; corresponds to 5% limit

^(f)The NRC requires an assumed shipping time of 60 days

^(g)This is the distribution for hydrogen concentration in the headspace given by the experts for the high case

B-4. Calculations for Path 4

B-4.1 Theory

Path 4 involves placing Pu-238 TRU waste drums in the TRUPACT-II and adding hydrogen getters to the inner containment vessel. The expectation is that with the new configuration, some of the Pu-238 TRU waste drums can be shipped "as-is." A new wattage limit for Pu-238 TRU waste drums with hydrogen getters placed in the inner containment vessel can be derived as follows:

1. The rate of hydrogen accumulation in the innermost layer of confinement is equal to the difference between the hydrogen generation rate from the waste (due to radiolysis) and the release rate from the innermost layer of confinement.

$$R_{headspace} = \frac{1}{r_{plastic}} (X_i - X_h)$$

$$\frac{dX_i}{dt} = R_{actual} - R_{headspace}$$

X_i = volume fraction of hydrogen in the innermost layer of confinement
 X_h = volume fraction of hydrogen in the drum headspace
 R_{actual} = hydrogen generation rate from radiolysis in the waste
 $r_{plastic}$ = effective resistance of plastic layers of confinement
 $R_{headspace}$ = hydrogen release rate to the drum headspace

2. The rate of hydrogen accumulation in the headspace is the sum of two contributors, release from the inner layers of confinement (a positive contributor), and release from the headspace to the inner containment vessel of the TRUPACT-II (a negative contributor).

$$\frac{dX_h}{dt} = \frac{1}{r_{\text{plastic}}} (X_i - X_h) - \frac{1}{r_{\text{df}}} (X_h - X_{\text{ICV}})$$

X_{ICV} = volume fraction of hydrogen in the inner containment vessel

R_{getter} = hydrogen getter reaction rate

r_{df} = resistance of the drum filter

3. Since getters are placed in the inner containment vessel:

$$X_{\text{ICV}} = 0$$

4. At steady state,

$$\frac{dX_i}{dt} = 0$$

$$\frac{dX_h}{dt} = 0$$

$$R_{\text{actual}} = R_{\text{headspace}}$$

$$R_{\text{ICV}} = R_{\text{headspace}} - R_{\text{getter}}$$

$$R_{\text{ICV}} = R_{\text{actual}} - R_{\text{getter}}$$

and

$$0 = R_{\text{actual}} - \frac{1}{r_{\text{plastic}}} (X_i - X_h) \quad (1)$$

$$0 = \frac{1}{r_{\text{plastic}}} (X_i - X_h) - \frac{1}{r_{\text{df}}} (X_h) \quad (2)$$

5. Solving Equations (1), and (2), for R_{actual} gives

$$R_{\text{actual}} = \frac{X_i}{r_{\text{eff}}}$$

where

$$r_{\text{eff}} = r_{\text{plastic}} + r_{\text{df}}$$

6. The watts allowed can be calculated from the hydrogen generation rate

$$W_{\text{allowed}} = R_{\text{actual}} \cdot \frac{N_a \cdot k}{G_{\text{eff}}}$$

N_a = Avogadro's Number

k = units conversion constant

G_{eff} = effective G-Value

B-4.2 Example Calculation

The following is an example calculation for Path 4 using the first data point from the Hanford inventory (2 drum equivalents of Pu-238 TRU waste each containing 295 watts; Shipping Category III.1A4). The data for the calculation are given in Table B-4.

$$R_{actual} = \frac{0.05}{6,136,440 \text{ sec / mole}}$$

$$R_{actual} = 8.15E - 09 \text{ moles / sec}$$

$$\frac{k \cdot N_a}{G_{eff}} = \frac{(1.60E - 19 \text{ watt sec/eV}) (6.023 \times 10^{23} \text{ molecules/g mole})}{(3.4 \text{ molecules/100 eV})}$$

$$= 2.84E + 06 \text{ watts \cdot sec/mole}$$

$$W_{allowed} = 8.15E - 09 \text{ moles/sec} \cdot \left(2.84E + 06 \text{ watts \cdot sec/mole} \right)$$

$$W_{allowed} = 0.023 \text{ watts}$$

For two drums each with 295 watts, neither would meet the new wattage restriction, and neither would be shipped "as-is."

Table B- 4. Parameter Values for Path 4 Sample Calculations

Parameter	Value	Parameter	Value
$r_{plastic}$	^(a) 5,610,124 sec/mole	X_j	^(e) 0.05
r_{df}	^(b) 526,316 sec/mole	t^*n_{gen}/N_{tg}	^(f) 612,525 sec/mole
r_{eff}	^(c) 6,136,440 sec/mole	R_{getter}	^(g) 2.50E-05 mole/sec
G_{eff}	^(d) 3.4 molecules/100 eV	N_a	6.023×10^{23} molecules/g mole
k	1.60E-19 watt sec/eV	Number Drums/TRUPACT-II	12 drums

^(a)three inner bags (1,792,115 sec/mole), one liner bag (214,133 sec/mole), and one drum liner with a 3/8 inch hole (19,646 sec/mole)

^(b)current drum filter

^(c)effective resistance is the sum of the plastic resistance and the drum filter resistance

^(d)G-value is for Waste Type III

^(e) volume fraction of hydrogen in innermost bag; corresponds to 5% limit

^(f)The NRC requires an assumed shipping time of 60 days

^(g)This is the getter reaction rate given by the experts for the high case

^(h)from *The National TRU Waste Management Plan* (DOE, 1997)

B-5. Calculations for Path 5

B-5.1 Theory

Path 5 involves repackaging the Pu-238 TRU waste with advanced bag, liner, and drum filters. The expectation is that with the new configuration, the Pu-238 TRU waste drums can accommodate higher wattage waste without violating the restriction on hydrogen accumulation currently set for the TRUPACT-II. A new wattage limit for Pu-238 TRU waste drums repackaged with advanced filters can be derived as follows:

1. The rate of hydrogen accumulation in the innermost layer of confinement is equal to the difference between the hydrogen generation rate from the waste (due to radiolysis) and the release rate from the innermost layer of confinement.

$$\frac{dX_i}{dt} = R_{actual} - \frac{1}{r_{plastic}}(X_i - X_h)$$

X_i = volume fraction of hydrogen in the innermost layer of confinement
 X_h = volume fraction of hydrogen in the headspace
 R_{actual} = hydrogen generation rate from radiolysis in the waste
 $r_{plastic}$ = effective resistance of plastic layers of confinement

2. The rate of hydrogen accumulation in the headspace is the sum of two contributors, release from the inner layers of confinement (a positive contributor), and release from the headspace to the inner containment vessel of the TRUPACT-II (a negative contributor).

$$\frac{dX_h}{dt} = \frac{1}{r_{plastic}}(X_i - X_h) - \frac{1}{r_{df}}(X_h - X_{ICV})$$

X_{ICV} = volume fraction of hydrogen in the inner containment vessel
 r_{df} = resistance of the drum filter

3. Since hydrogen is not released from the inner containment vessel, the concentration of hydrogen in the inner containment vessel is:

$$X_{ICV} = R_{ICV} \frac{t \cdot n_{gen}}{N_{tg}}$$

R_{ICV} = the per drum hydrogen release rate to the inner containment vessel
 t = the time that the inner containment vessel has been sealed
 n_{gen} = the number of drums in the inner containment vessel
 N_{tg} = the total moles of gas in the inner containment vessel

4. At steady state,

$$\frac{dX_i}{dt} = 0$$

$$\frac{dX_h}{dt} = 0$$

$$R_{actual} = R_{headspace}$$

$$R_{ICV} = R_{headspace}$$

$$R_{ICV} = R_{actual}$$

and

$$X_{ICV} = (R_{actual}) \cdot \frac{t \cdot n_{gen}}{N_{tg}} \quad (1)$$

$$0 = R_{actual} - \frac{1}{r_{plastic}} (X_i - X_h) \quad (2)$$

$$0 = \frac{1}{r_{plastic}} (X_i - X_h) - \frac{1}{r_{df}} (X_h - X_{ICV}) \quad (3)$$

5. Solving Equations (1), (2), and (3) for R_{actual} gives

$$R_{actual} = \frac{X_i}{r_{eff} + \frac{t \cdot n_{gen}}{N_{tg}}}$$

where

$$r_{eff} = r_{plastic} + r_{df}$$

6. The watts allowed can be calculated from the hydrogen generation rate

$$W_{allowed} = R_{actual} \cdot \frac{N_a \cdot k}{G_{eff}}$$

N_a = Avogadros Number

k = units conversion constant

G_{eff} = effective G-Value

B-5.2 Example Calculation

The following is an example calculation for Path 5 using the first data point from the Hanford inventory (2 drum equivalents of Pu-238 TRU waste each containing 295 watts; Shipping Category III.1A4). The data for the calculation are given in Table B-5.

$$R_{actual} = \frac{0.05}{28,610 \text{ sec/mole} + 612,525 \text{ sec/mol}} = 7.79E - 08 \text{ mole/sec}$$

$$\frac{k \cdot N_a}{G_{\text{eff}}} = \frac{(1.60E-19 \text{ watt sec/eV}) (6.023 \times 10^{23} \text{ molecules/g mole})}{(3.4 \text{ molecules/100 eV})} \\ = 2.84E+06 \text{ watts} \cdot \text{sec/mole}$$

$$W_{\text{allowed}} = 7.79E-08 \text{ moles/sec} \cdot \left(2.84E+06 \text{ watts} \cdot \text{sec/mole} \right) \\ W_{\text{allowed}} = 0.22 \text{ watts}$$

For two drums each with 295 watts, repackaging would produce:

$$N_{\text{drums}} = 2 \text{ drum equivalents} \frac{295 \text{ watts}}{0.22 \text{ watts}} = 2,682 \text{ repackaged drums}$$

Table B- 5. Parameter Values for Path 5 Sample Calculation

Parameter	Value	Parameter	Value
r_{plastic}	^(a) 17,800 sec/mole	k	1.60E-19 watt sec/eV
r_{df}	^(b) 10,811 sec/mole	X_i	^(e) 0.05
r_{eff}	^(c) 28,611 sec/mole	$t^* n_{\text{gen}} / N_{\text{tg}}$	^(f) 612,525 sec/mole
G_{eff}	^(d) 3.4 molecules/100 eV	N_a	$6.023 \times 10^{23} \text{ molecules/g mole}$

^(a)waste is repackaged into one advanced filtered inner bag (9,302 sec/mole), one advanced filtered liner bag (6,729 sec/mole), and one advanced drum liner with a one inch hole (1,768 sec/mole)

^(b)advanced drum filter assumed for repackaging scenario

^(c)effective resistance is the sum of the plastic resistance and the drum filter resistance

^(d)G-value is for Waste Type III

^(e)volume fraction of hydrogen in innermost bag; corresponds to 5% limit

^(f)The NRC requires an assumed shipping time of 60 days

B-6. Calculations for Treated Waste

B-6.1 Theory

Paths 2, 3, and 4 involve treating the Pu-238 TRU waste that cannot be shipped "as-is." Treated waste will be packaged in the "Half-pact" which will probably be approved by the NRC (Nuclear Regulatory Commission) for 30 watts per "Half-pact" (DOE, 1998)¹. Therefore, the watts allowed in each drum are:

$$W_{\text{allowed}} = \frac{30 \text{ watts per "Half - pact"}}{N_{\text{drums}}}$$

¹ The Safety Analysis Report for the "Half-pact" is currently under review by the NRC.

B-6.2 Example Calculation

The following is an example calculation for treatment using the first data point from the Hanford inventory (2 drum equivalents of Pu-238 TRU waste each containing 295 watts; Shipping Category III.1A4). The data for the calculation are given in Table B-6.

$$W_{\text{allowed}} = \frac{30_{\text{watts}}}{7_{\text{drums}}} = 4.28 \text{ watts}$$

For two drums each with 295 watts, treatment would produce:

$$N_{\text{drums}} = \frac{2 \text{ drum equivalents}}{4.28 \text{ watts}} = 138 \text{ treated drums}$$

Table B- 6. Parameter Values for Treatment Sample Calculations

Parameter	Value
Watts Allowed	30
Number of drums	7

The reader should note that a 60 percent maximum volume reduction was assumed. This is consistent with assumptions used in *The National TRU Waste Management Plan* (DOE, 1997) for the Advanced Mixed Waste Treatment Facility and accounts for the fact that there is a limit on compaction of bulky materials. For example, 1 drum of Pu-238 TRU waste containing 0.1 watts could be reduced to:

$$1 \text{ drum} \left(\frac{0.1 \text{ watts}}{4.28 \text{ watts}} \right) = 0.02 \text{ drums}$$

But this exceeds the maximum 60% volume reduction assumption. As a result, it is assumed that after treatment a drum containing 0.1 watts becomes

$$1 \text{ drum (0.40)} = 0.40 \text{ drums}$$

B-7. Calculations for Repackaged Waste

B-7.1 Theory

Paths 2, 3, and 4 involve repackaging the Pu-238 TRU waste that cannot be shipped "as-is" with the best practices currently available. A new wattage limit for Pu-238 TRU waste drums repackaged with the best current practice can be derived as follows:

1. The rate of hydrogen accumulation in the innermost layer of confinement is equal to the difference between the hydrogen generation rate from the waste (due to radiolysis) and the release rate from the innermost layer of confinement.

$$\frac{dX_i}{dt} = R_{actual} - \frac{1}{r_{plastic}}(X_i - X_h)$$

X_i = volume fraction of hydrogen in the innermost layer of confinement
 X_h = volume fraction of hydrogen in the drum headspace
 R_{actual} = hydrogen generation rate from radiolysis in the waste
 $r_{plastic}$ = effective resistance of plastic layers of confinement

2. The rate of hydrogen accumulation in the headspace is the sum of two contributors, release from the inner layers of confinement (a positive contributor), and release from the headspace to the inner containment vessel of the TRUPACT-II (a negative contributor).

$$\frac{dX_h}{dt} = \frac{1}{r_{plastic}}(X_i - X_h) - \frac{1}{r_{df}}(X_h - X_{ICV})$$

X_{ICV} = volume fraction of hydrogen in the inner containment vessel
 r_{df} = resistance of the drum filter

3. Since hydrogen is not released from the inner containment vessel, the concentration of hydrogen in the inner containment vessel is:

$$X_{ICV} = R_{ICV} \frac{t \cdot n_{gen}}{N_{tg}}$$

R_{ICV} = the per drum hydrogen release rate to the inner containment vessel
 t = the time that the inner containment vessel has been sealed
 n_{gen} = the number of drums in the inner containment vessel
 N_{tg} = the total moles of gas in the inner containment vessel

4. At steady state,

$$\frac{dX_i}{dt} = 0$$

$$\frac{dX_h}{dt} = 0$$

$$R_{actual} = R_{headspace}$$

$$R_{ICV} = R_{headspace}$$

$$R_{ICV} = R_{actual}$$

and

$$X_{ICV} = (R_{actual}) \cdot \frac{t \cdot n_{gen}}{N_{tg}} \quad (1)$$

$$0 = R_{actual} - \frac{1}{r_{plastic}} (X_i - X_h) \quad (2)$$

$$0 = \frac{1}{r_{plastic}} (X_i - X_h) - \frac{1}{r_{df}} (X_h - X_{ICV}) \quad (3)$$

5. Solving Equations (1), (2), and (3) for R_{actual} gives

$$R_{actual} = \frac{X_i}{r_{eff} + \frac{t \cdot n_{gen}}{N_{tg}}} \quad (4)$$

where

$$r_{eff} = r_{plastic} + r_{df}$$

6. The watts allowed can be calculated from the hydrogen generation rate

$$W_{allowed} = R_{actual} \cdot \frac{N_a \cdot k}{G_{eff}} \quad (5)$$

N_a = Avogadro's Number
 k = units conversion constant
 G_{eff} = Effective G-Value

B-7.2 Example Calculation

The following is an example calculation for repackaged waste using the first data point from the Hanford inventory (2 drum equivalents of Pu-238 TRU waste each containing 295 watts; Shipping Category III.1A4). The data for the calculation are given in Table B-7.

$$R_{actual} = \frac{0.05}{172,897 \text{ sec/mole} + 612,525 \text{ sec/mole}} = 6.37E-08 \text{ moles/sec}$$

$$\begin{aligned}
 \frac{k \cdot N_a}{G_{eff}} &= \frac{(1.60E-19 \text{ watt sec/eV}) (6.023 \times 10^{23} \text{ molecules/g mole})}{(3.4 \text{ molecules/100 eV})} \\
 &= 2.84E+06 \text{ watts} \cdot \text{sec/mole}
 \end{aligned}$$

$$W_{\text{allowed}} = 6.37E - 08 \text{ moles/sec} \cdot \left(2.84E + 06 \text{ watts} \cdot \text{sec/mole} \right)$$

$$W_{\text{allowed}} = 0.18 \text{ watts}$$

For two drums each with 295 watts, repackaging would produce:

$$N_{\text{drums}} = 2 \text{ drum equivalents} \frac{295 \text{ watts}}{0.18 \text{ watts}} = 3,278 \text{ repackaged drums}$$

Table B- 7. Parameter Values for Repackaging Sample Calculation

Parameter	Value	Parameter	Value
r_{plastic}	^(a) 162,086 sec/mole	k	1.60E-19 watt sec/eV
r_{df}	^(b) 10,811 sec/mole	$t^* n_{\text{gen}} / N_{\text{tg}}$	^(f) 612,525 s/mol
r_{eff}	^(c) 172,897 sec/mole	N_a	6.023×10^{23} molecules/g mole
G_{eff}	^(d) 3.4 molecules/100 eV	X_i	^(e) 0.05

^(a)waste is repackaged into one filtered inner bag (93,023 sec/mole), one filtered liner bag (67,295 sec/mole), and one drum liner with a one inch hole (1,768 sec/mole)

^(b)advanced drum filter assumed for repackaging scenario (10,811 sec/mole)

^(c)effective resistance is the sum of the plastic resistance and the drum filter resistance

^(d)G-value is for Waste Type III

^(e)volume fraction of hydrogen in innermost bag; corresponds to 5% limit

^(f)The NRC requires an assumed shipping time of 60 days

B-8. References

DOE (U.S. Department of Energy), 1997. *The National TRU Waste Management Plan*, DOE/NTP-96-1204, Revision 1, December, DOE Carlsbad Area Office, Carlsbad, NM.

DOE (U.S. Department of Energy), 1998. *Safety Analysis Report for the TRUPACT-II Shipping Package*, Revision 17, March. *Appendix 1.3.7 TRUPACT-II Authorized Methods for Payload Control (TRAMPAC)*, Carlsbad, NM.

B-9. Pu-238 TRU WASTE INVENTORY

B-9.1 Hanford Reservation Inventory

Table B- 8. Hanford Inventory of Pu-238 TRU Waste that Exceeds Expected Wattage Limits

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected ^a Shipping Category	Wattage Limit
Drum	2	295	III.1A4	0.0207
Drum	2	294	III.1A4	0.0207
Drum	1	293	III.1A4	0.0207
Drum	1	287	III.1A4	0.0207
Drum	1	284	III.1A4	0.0207
Drum	1	277	III.1A4	0.0207
Drum	1	228	III.1A4	0.0207
Drum	1	180	III.1A4	0.0207
Drum	1	144	III.1A4	0.0207
Drum	1	127	III.1A4	0.0207
Drum	3	1	III.1A4	0.0207
Drum	1	0.23	III.1A4	0.0207
Drum	1	0.18	III.1A4	0.0207
Drum	1	0.12	III.1A4	0.0207
Drum	2	0.09	III.1A4	0.0207
Drum	1	0.08	III.1A4	0.0207
Drum	4	0.07	III.1A4	0.0207
Drum	5	0.06	III.1A4	0.0207
Drum	6	0.05	III.1A4	0.0207
Drum	5	0.04	III.1A4	0.0207
Drum	7	0.03	III.1A4	0.0207
Drum	3	0.02	III.1A4	0.0207
Box	16	0.04	III.1A4	0.0207
Box	16	0.04	III.1A4	0.0207
Box	16	0.04	III.1A4	0.0207
Box	16	0.04	III.1A4	0.0207
Box	16	0.04	III.1A4	0.0207

^a In some cases the shipping category for the waste was known. In other cases, the shipping category was predicted by the authors based on information about the packaging and waste material.

B-9.2 Los Alamos National Laboratory Inventory

Table B- 9. Los Alamos National Laboratory Inventory of PU-238 TRU Waste that Exceeds Expected Wattage Limits

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	5	23	III.1A4	0.0207
Drum	4	22	III.1A4	0.0207
Drum	8	21	III.1A4	0.0207
Drum	6	20	III.1A4	0.0207
Drum	2	19	III.1A4	0.0207
Drum	2	18	III.1A4	0.0207
Drum	1	16	III.1A4	0.0207
Drum	4	14	III.1A4	0.0207
Drum	6	13	III.1A4	0.0207
Drum	11	12	III.1A4	0.0207
Drum	12	11	III.1A4	0.0207
Drum	19	10	III.1A4	0.0207
Drum	8	9	III.1A4	0.0207
Drum	15	8	III.1A4	0.0207
Drum	18	7	III.1A4	0.0207
Drum	26	6	III.1A4	0.0207
Drum	11	5	III.1A4	0.0207
Drum	14	4	III.1A4	0.0207
Drum	37	3	III.1A4	0.0207
Drum	39	2	III.1A4	0.0207
Drum	130	1	III.1A4	0.0207
Drum	1	0.48	III.1A4	0.0207
Drum	1	0.47	III.1A4	0.0207
Drum	7	0.45	III.1A4	0.0207
Drum	3	0.43	III.1A4	0.0207
Drum	1	0.42	III.1A4	0.0207
Drum	6	0.40	III.1A4	0.0207
Drum	1	0.38	III.1A4	0.0207
Drum	6	0.37	III.1A4	0.0207
Drum	1	0.35	III.1A4	0.0207
Drum	1	0.34	III.1A4	0.0207
Drum	1	0.32	III.1A4	0.0207
Drum	6	0.31	III.1A4	0.0207
Drum	6	0.28	III.1A4	0.0207
Drum	2	0.26	III.1A4	0.0207
Drum	1	0.25	III.1A4	0.0207

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	2	0.24	III.1A4	0.0207
Drum	6	0.23	III.1A4	0.0207
Drum	4	0.22	III.1A4	0.0207
Drum	1	0.21	III.1A4	0.0207
Drum	3	0.20	III.1A4	0.0207
Drum	1	0.19	III.1A4	0.0207
Drum	8	0.17	III.1A4	0.0207
Drum	3	0.15	III.1A4	0.0207
Drum	5	0.14	III.1A4	0.0207
Drum	2	0.13	III.1A4	0.0207
Drum	5	0.12	III.1A4	0.0207
Drum	10	0.11	III.1A4	0.0207
Drum	2	0.10	III.1A4	0.0207
Drum	3	0.09	III.1A4	0.0207
Drum	5	0.08	III.1A4	0.0207
Drum	7	0.07	III.1A4	0.0207
Drum	17	0.06	III.1A4	0.0207
Drum	3	0.05	III.1A4	0.0207
Drum	3	0.04	III.1A4	0.0207
Drum	7	0.03	III.1A4	0.0207
Drum	4	0.02	III.1A4	0.0207
Drum	2	22	II.1A4	0.0414
Drum	2	21	II.1A4	0.0414
Drum	4	20	II.1A4	0.0414
Drum	2	19	II.1A4	0.0414
Drum	4	12	II.1A4	0.0414
Drum	4	10	II.1A4	0.0414
Drum	2	8	II.1A4	0.0414
Drum	1	6	II.1A4	0.0414
Drum	6	5	II.1A4	0.0414
Drum	2	4	II.1A4	0.0414
Drum	10	3	II.1A4	0.0414
Drum	14	2	II.1A4	0.0414
Drum	42	1	II.1A4	0.0414
Drum	3	0.48	II.1A4	0.0414
Drum	7	0.45	II.1A4	0.0414
Drum	2	0.34	II.1A4	0.0414
Drum	4	0.28	II.1A4	0.0414
Drum	2	0.26	II.1A4	0.0414
Drum	3	0.23	II.1A4	0.0414
Drum	1	0.17	II.1A4	0.0414

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	4	0.11	II.1A4	0.0414
Drum	1	0.10	II.1A4	0.0414
Drum	1	0.09	II.1A4	0.0414
Drum	8	0.06	II.1A4	0.0414
Drum	2	1	I.2A0	0.2536
Drum	23	0.32	I.2A0	0.2536
Box	4	3.53	III.1A4	0.0207
Box	20	0.23	II.1A4	0.0414
Box	68	0.17	II.1A4	0.0414
Box	68	0.15	II.1A4	0.0414
Box	65	0.13	II.1A4	0.0414
Box	68	0.09	II.1A4	0.0414
Box	57	0.08	II.1A4	0.0414
Box	68	0.06	II.1A4	0.0414
Box	78	0.06	II.1A4	0.0414
Box	78	0.06	II.1A4	0.0414
Box	78	0.06	II.1A4	0.0414
Box	149	0.05	II.1A4	0.0414

B-9.3 Mound Plant Inventory

Table B- 10. Mound Plant Inventory of Pu-238 TRU Waste that Exceeds Expected Wattage Limits

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	1	3	III.1A3	0.028
Drum	2	2	III.1A3	0.028
Drum	2	1	III.1A3	0.028
Drum	1	0.49	III.1A3	0.028
Drum	1	0.44	III.1A3	0.028
Drum	1	0.41	III.1A3	0.028
Drum	1	0.31	III.1A3	0.028
Drum	1	0.30	III.1A3	0.028
Drum	2	0.29	III.1A3	0.028
Drum	1	0.25	III.1A3	0.028
Drum	1	0.22	III.1A3	0.028
Drum	2	0.21	III.1A3	0.028
Drum	1	0.19	III.1A3	0.028
Drum	1	0.18	III.1A3	0.028
Drum	1	0.17	III.1A3	0.028
Drum	1	0.11	III.1A3	0.028
Drum	1	0.08	III.1A3	0.028
Drum	1	0.07	III.1A3	0.028
Drum	2	0.06	III.1A3	0.028
Drum	1	0.05	III.1A3	0.028
Drum	1	0.04	III.1A3	0.028
Drum	1	4	II.1A3	0.0561
Drum	2	1	II.1A3	0.0561
Drum	1	0.08	II.1A3	0.0561
Box	13.61	0.063	IV	NA
Box	0.09	0.011	IV	NA
Box	20.24	0.288	III.1A3	0.028
Box	20.24	0.107	III.1A3	0.028

B-9.4 Oak Ridge National Laboratory Inventory

Table B- 11. Oak Ridge National Laboratory Inventory of Pu-238 TRU Waste that Exceeds Expected Wattage Limits

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	1	11	III.1A2	0.0434
Drum	4	10	III.1A2	0.0434
Drum	1	8	III.1A2	0.0434
Drum	1	7	III.1A2	0.0434
Drum	2	6	III.1A2	0.0434
Drum	3	3	III.1A2	0.0434
Drum	20	2	III.1A2	0.0434
Drum	11	1	III.1A2	0.0434
Drum	1	0.46	III.1A2	0.0434
Drum	3	0.36	III.1A2	0.0434
Drum	1	0.29	III.1A2	0.0434
Drum	1	0.28	III.1A2	0.0434
Drum	1	0.23	III.1A2	0.0434
Drum	2	0.17	III.1A2	0.0434
Drum	1	0.15	III.1A2	0.0434
Drum	1	0.14	III.1A2	0.0434
Drum	1	0.10	III.1A2	0.0434
Drum	2	0.09	III.1A2	0.0434
Drum	2	0.08	III.1A2	0.0434
Drum	1	0.06	III.1A2	0.0434
Drum	1	0.05	III.1A2	0.0434
Box	9	0.10	III.1A2	0.0434

B-9.5 Savannah River Site Inventory

Table B- 12. Savannah River Site Inventory of Pu-238 TRU Waste that Exceeds Expected Wattage Limits

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	1	34	III.1A4	0.0207
Drum	1	31	III.1A4	0.0207
Drum	2	29	III.1A4	0.0207
Drum	1	27	III.1A4	0.0207
Drum	1	21	III.1A4	0.0207
Drum	1	20	III.1A4	0.0207
Drum	1	19	III.1A4	0.0207
Drum	3	17	III.1A4	0.0207
Drum	7	16	III.1A4	0.0207
Drum	17	15	III.1A4	0.0207
Drum	31	14	III.1A4	0.0207
Drum	25	13	III.1A4	0.0207
Drum	25	12	III.1A4	0.0207
Drum	56	11	III.1A4	0.0207
Drum	77	10	III.1A4	0.0207
Drum	108	9	III.1A4	0.0207
Drum	124	8	III.1A4	0.0207
Drum	129	7	III.1A4	0.0207
Drum	140	6	III.1A4	0.0207
Drum	137	5	III.1A4	0.0207
Drum	170	4	III.1A4	0.0207
Drum	402	3	III.1A4	0.0207
Drum	761	2	III.1A4	0.0207
Drum	925	1	III.1A4	0.0207
Drum	7	0.50	III.1A4	0.0207
Drum	15	0.49	III.1A4	0.0207
Drum	17	0.48	III.1A4	0.0207
Drum	14	0.47	III.1A4	0.0207
Drum	44	0.46	III.1A4	0.0207
Drum	20	0.45	III.1A4	0.0207
Drum	25	0.44	III.1A4	0.0207
Drum	16	0.43	III.1A4	0.0207
Drum	33	0.42	III.1A4	0.0207
Drum	11	0.41	III.1A4	0.0207
Drum	23	0.40	III.1A4	0.0207
Drum	63	0.39	III.1A4	0.0207

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Drum	10	0.38	III.1A4	0.0207
Drum	20	0.37	III.1A4	0.0207
Drum	7	0.36	III.1A4	0.0207
Drum	11	0.35	III.1A4	0.0207
Drum	12	0.34	III.1A4	0.0207
Drum	14	0.33	III.1A4	0.0207
Drum	24	0.32	III.1A4	0.0207
Drum	15	0.31	III.1A4	0.0207
Drum	7	0.30	III.1A4	0.0207
Drum	15	0.29	III.1A4	0.0207
Drum	34	0.28	III.1A4	0.0207
Drum	10	0.27	III.1A4	0.0207
Drum	32	0.26	III.1A4	0.0207
Drum	17	0.25	III.1A4	0.0207
Drum	16	0.24	III.1A4	0.0207
Drum	44	0.23	III.1A4	0.0207
Drum	16	0.22	III.1A4	0.0207
Drum	14	0.21	III.1A4	0.0207
Drum	13	0.20	III.1A4	0.0207
Drum	24	0.19	III.1A4	0.0207
Drum	14	0.18	III.1A4	0.0207
Drum	11	0.17	III.1A4	0.0207
Drum	19	0.16	III.1A4	0.0207
Drum	18	0.15	III.1A4	0.0207
Drum	25	0.14	III.1A4	0.0207
Drum	20	0.13	III.1A4	0.0207
Drum	34	0.12	III.1A4	0.0207
Drum	24	0.11	III.1A4	0.0207
Drum	22	0.10	III.1A4	0.0207
Drum	44	0.09	III.1A4	0.0207
Drum	34	0.08	III.1A4	0.0207
Drum	54	0.07	III.1A4	0.0207
Drum	219	0.06	III.1A4	0.0207
Drum	90	0.05	III.1A4	0.0207
Drum	106	0.04	III.1A5	0.0207
Drum	205	0.03	III.1A4	0.0207
Drum	81	0.02	III.1A4	0.0207
Box	15	17	III.1A4	0.0207
Box	28	16	III.1A4	0.0207
Box	29	15	III.1A4	0.0207
Box	58	14	III.1A4	0.0207

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Box	57	13	III.1A4	0.0207
Box	61	12	III.1A4	0.0207
Box	29	11	III.1A4	0.0207
Box	92	10	III.1A4	0.0207
Box	15	9	III.1A4	0.0207
Box	26	8	III.1A4	0.0207
Box	28	6	III.1A4	0.0207
Box	31	5	III.1A4	0.0207
Box	27	4	III.1A4	0.0207
Box	192	3	III.1A4	0.0207
Box	294	2	III.1A4	0.0207
Box	303	1	III.1A4	0.0207
Box	46	0.50	III.1A4	0.0207
Box	2	0.43	III.1A4	0.0207
Box	8	0.42	III.1A4	0.0207
Box	1	0.41	III.1A4	0.0207
Box	10	0.40	III.1A4	0.0207
Box	13	0.36	III.1A4	0.0207
Box	4	0.35	III.1A4	0.0207
Box	2	0.31	III.1A4	0.0207
Box	2	0.30	III.1A4	0.0207
Box	1	0.29	III.1A4	0.0207
Box	3	0.28	III.1A4	0.0207
Box	40	0.26	III.1A4	0.0207
Box	3	0.25	III.1A4	0.0207
Box	218	0.24	III.1A4	0.0207
Box	217	0.23	III.1A4	0.0207
Box	6	0.22	III.1A4	0.0207
Box	2	0.20	III.1A4	0.0207
Box	42	0.19	III.1A4	0.0207
Box	228	0.18	III.1A4	0.0207
Box	3	0.17	III.1A4	0.0207
Box	220	0.16	III.1A4	0.0207
Box	2	0.14	III.1A4	0.0207
Box	2	0.13	III.1A4	0.0207
Box	1	0.11	III.1A4	0.0207
Box	1	0.10	III.1A4	0.0207
Box	1	0.09	III.1A4	0.0207
Box	6	0.08	III.1A4	0.0207
Box	226	0.07	III.1A4	0.0207
Box	40	0.06	III.1A4	0.0207

Container Type	Drum Equivalents	Watts/Drum Equivalent	Expected Shipping Category	Wattage Limit
Box	1	0.05	III.1A4	0.0207
Box	672	0.04	III.1A4	0.0207
Box	222	0.03	III.1A4	0.0207
Box	2	0.02	III.1A4	0.0207

B-10. Quality Assurance

The equations in Sections B-1 through B-8 were derived with the assistance of Sinisia Djordjevic (at that time with Benchmark, Inc.). The equations were reviewed independently by Darlene Steward (Stoller, Inc.), Murthy Devarakonda (IT Corporation), and Gene Mroz (Los Alamos National Laboratory).

Once the equations were reviewed, they were implemented in a series of spreadsheets. Darlene Steward reviewed the spreadsheets, verifying that the equations were implemented correctly and consistently.

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APPENDIX C

PU-238 DECISION ANALYSIS COST MODEL

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Acronym List

C of C	Certificate of Compliance
CH	Contact-handled
DOE	Department of Energy
NRC	Nuclear Regulatory Commission
Pu	plutonium
TRU	transuranic
TRUPACT-II	Transuranic Package Transporter, Model II
WIPP	Waste Isolation Pilot Plant

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Appendix C

PU-238 DECISION ANALYSIS COST MODEL

C-1. Cost Model Description

Costs for the plutonium (Pu)-238 transuranic (TRU) waste treatment/transportation options for the Pu-238 TRU Waste Decision Analysis are calculated in a Cost Model. The Cost Model consists of two parts: fixed costs and volume-dependent costs. The fixed costs include costs for performing studies and seeking approval by the Nuclear Regulatory Commission (NRC) for changes in the Transuranic Package Transporter, Model II (TRUPACT-II) Certificate of Compliance (C of C). Costs for building and/or operating treatment or repackaging facilities, transportation costs, and other associated costs that depend on the amount of waste to be processed/transported, are calculated in an ExcelTM Workbook. The Cost Model output is the total cost for facilities and transportation for each decision analysis option.

It has been assumed for the decision analysis model that all shipments will be made in the TRUPACT-II and that the existing fleet of these containers will be used for transporting Pu-238 TRU waste.

The cost information is derived primarily from; (1) United States Department of Energy (DOE) Carlsbad Area Office, "CH [Contact-Handled] Waste Packaging Optimization Report Revision 1," (DOE, 1995a); (2) DOE Idaho Operations Office, *Evaluation of Feasibility Studies for Private Sector Treatment of Alpha and TRU Mixed Wastes*, DOE, 1995b); (3) *The National TRU Waste Management Plan Revision 1* (DOE, 1997a) and September 9, 1997 *National TRU Waste Management Plan Cost Model* (DOE, 1997b) and (4) various personal communications with subject matter experts.

C-2. Fixed Costs

Fixed costs for the Pu-238 decision analysis are:

- Costs for performing studies to develop a methodology for calculating hydrogen concentration in the innermost layer of confinement based on headspace gas measurements.
- Costs for performing studies to determine the effectiveness of adding getters to the inner containment vessel.
- Costs for performing studies to determine the effectiveness of advanced filters.

Costs for performing studies to determine the effectiveness of adding getters to drums (Path 1) and performing studies to determine the effect of matrix depletion and measurement of more realistic G-values (Path 2) were set at zero because these costs have already been incurred or the studies are already funded.

Interactions with the NRC, including the cost for developing the application to the NRC for approval of changes to transportation requirements based on the results of studies and working with the NRC during the review period, have also been funded. Therefore, no costs for NRC applications have been included in the cost model for the Pu-238 decision analysis.

C-3. Volume-Dependent Costs

Volume-dependent costs are costs associated with disposition of waste after the outcome of studies and NRC decisions has been determined. If the NRC approves the DOE's petition for Path 2 (Matrix Depletion), Path 3 (Drum Testing), or Path 4 (Getters in the inner containment vessel), some of the waste may be transportable "as is" without repackaging. Costs for this waste would include any fixed costs (discussed in Section C-1.1), costs for loading and unloading the waste, and in the case of Path 4 adding getters to the inner containment vessel), and costs for transporting the waste. Regardless of the NRC decision, some or all of the waste from each site will be either repackaged or treated and the resulting Waste Isolation Pilot Plant (WIPP)/TRUPACT-II compliant waste will be transported to the WIPP.

C-3.1 Treatment Costs

Treatment of the Pu-238 TRU waste would involve thermal treatment to remove residual moisture and destroy organic materials in the waste that are sources for hydrogen generation. Treated waste would be packaged using two layers of confinement and the best currently-approved bag and drum filters. The treated waste would be transported to WIPP in TRUPACT-II containers. None of the facilities in the Pu-238 decision analysis study are currently planning any treatment of TRU waste. Therefore, if the treatment option were implemented, facilities would have to be constructed for treatment of Pu-238 TRU waste. For the purposes of the decision analysis, it was assumed that a treatment facility would include open-dump-and-sort, thermal treatment/vitrification, treatment for special wastes (e.g., size reduction), and packaging/loading capabilities. A facility, sized based on the amount of waste to be treated, would be built at each of the five sites. Costs for the treatment facilities account for the waste types and amounts to be treated and are scaled from the conceptual costs developed for a waste treatment facility at the Savannah River Site (see Section C-1.2.1.1). The facility capital expenditures were scaled by waste volume using the correlation given by Peters and Timmerhaus (Peters and Timmerhaus, 1968). Operating costs were based on information provided by Dale Ormond at the Savannah River Site. Operating costs for a thermal treatment facility for Pu-238 waste are high because Pu-238 is very difficult to handle giving rise to containment issues for incineration.

A treatment system development program would face serious technical challenges including control of emissions in the offgas system, which would push current technology. Engineers have estimated \$500 million to construct a thermal treatment facility at the Savannah River Site plus \$60 million per year operating expenses. It is important to note that these estimates are not based on design and are higher than cost estimates from Shropshire (Shropshire et al., 1995) and costs for the Advanced Mixed

Waste Treatment Facility being built at Idaho National Engineering and Environmental Laboratory. However, these costs are consistent with the increased difficulties associated with treatment of Pu-238 waste and have, therefore, been used in the Pu-238 decision analysis model.

C-3.1.1 Treatment Cost Calculations

Assumptions:

1. A treatment facility would be built at each site.
2. Treatment facility costs include preconstruction (design, permitting, administration), construction, and decontamination and decommissioning activities. The facility includes characterization and packaging areas.
3. Operations costs include packaging activities.
4. The treatment method consists of thermal destruction of organic materials and drying.
5. The baseline inventory of waste to be treated at the Savannah River Site is 19,231 drum equivalents. The facility costs provided by Dale Ormond are based on treating 19,231 drum equivalents of waste. The inventory of Pu-238 TRU waste at the Savannah River Site is 8,556 drum equivalents. Therefore, costs for treating Pu-238 waste at the Savannah River Site facility are obtained by scaling from the baseline costs in the same way as for the other sites (i.e., the cost of the Savannah River Site treatment facility is less than \$500 million).

Basis:

Baseline treatment facility:	\$500 million
Baseline capacity:	4,000 cubic meters (19,231 drum equivalents)
Baseline operating costs:	\$60 million per year, 5 years of operations

Example cost calculation for the Savannah River Site facility:

$$\begin{aligned}\text{New facility cost} &= (\text{Baseline treatment facility cost}) \times (\text{new facility capacity} \div \text{baseline capacity})^{0.6} \\ &= \$500 \text{ million} \times (8,556 \text{ drum equivalents} \div 19,231 \text{ drum equivalents})^{0.6} \\ &= \$308 \text{ million}\end{aligned}$$

Operations costs are scaled linearly on a per-drum-equivalent-basis from the Savannah River Site baseline number ($(\$60 \text{ million/year} \times 5 \text{ years}) \div 19,231 \text{ drum equivalents} = \$15,600 \text{ per drum equivalent}$).

C-3.2 Repackaging Costs

The repackaging option involves repackaging all of the waste that could not be transported to WIPP through implementation of the studies and NRC decisions (e.g. through headspace gas testing). The waste would be repackaged to meet current wattage

limits using the best currently-approved packaging materials. For the purposes of the decision analysis, it was assumed that a facility sized based on the amount of waste to be repackaged would be built at each of the five sites. Costs for the repackaging facilities account for the waste types and amounts to be treated and are scaled from the conceptual costs developed for a repackaging facility at the Savannah River Site. However, per-drum-equivalent-operational costs were included. These costs were based on the expected repackaging operating costs for the repackaging facilities as outlined in *The National TRU Waste Management Plan* Revision 1 (DOE, 1997a, DOE, 1997b). As in the case of treatment, increased costs are expected for repackaging of the Pu-238 waste. Therefore, the operational costs given in the TRU Waste Management Plan were doubled for repackaging of the Pu-238 in the existing facilities.

Engineers have estimated \$250 million to construct a repackaging facility at the Savannah River Site plus \$60 million per year operating expenses. It is important to note that these estimates are not based on design and are higher than cost estimates from Shropshire (Shropshire et al., 1995). However, these costs are consistent with the increased difficulties associated with repackaging of Pu-238 waste and have, therefore, been used in the Pu-238 decision analysis model.

For Path 1 Getters in Drums, an additional cost is included for the addition of getter material to the repackaged drums. The cost for the getter material was based on information provided by Allied Signal Corp., the manufacturer of the getter. Costs for addition of getter to the inner containment vessel are included for Path 4. The amount of getter to be added was based on the amount of getter needed for Path 1; 1000 grams of getter per drum multiplied by the number of drums in the TRUPACT-II container. An additional per drum cost is also included for repackaging for Path 5 (Advanced Filters). This is the additional cost for purchasing and installing the advanced filters, which might include, for example, installing more than one filter in the inner bag or a more complex installation procedure than the one now used.

C-3.3 Transportation Costs

The transportation costs shown in Table C-1 include costs for preparing waste for transport, loading waste, transporting waste, unloading of waste, and maintenance costs for the trucks and TRUPACT-II containers. It was assumed that the current fleet of TRUPACT-IIs would be used for all shipments. The assumptions outlined in the *CH-TRU Waste Packaging Optimization Report*, Revision 1 (DOE, 1995a) were used to determine cost per mile and maintenance costs (allocated per shipment). The methodology and data used to estimate the transportation costs is outlined in Section C-3.3.1.

C-3.3.1 Transportation Cost Calculations:

Assumptions:

1. All waste will be transported in TRUPACT-II containers. The existing fleet of containers will be used (i.e., no new TRUPACT-IIs will be built).

2. All waste will be packaged in drums. There will be a maximum of 14 drums per TRUPACT-II and a maximum of 42 drums per shipment.
3. Loading and unloading facilities will not have to be built. Loading and unloading activities are included in the costs.
4. Larger sites (Hanford, Los Alamos National Laboratory, and Savannah River Site) have trailers in reserve.

Basis:

Values are from the *CH-TRU Waste Packaging Optimization Report*, Revision 1 (DOE, 1995a) unless otherwise noted.

Table C- 1. Transportation Costs

Site	Hanford Reservation	Los Alamos National Laboratory	Mound Plant	Oak Ridge National Laboratory	Savannah River Site
Distance from Site to WIPP (one way) - miles	1820	357	1547	1517	1522
Shipping Cost (\$/shipment) ^a	\$10,920	\$2,142	\$9,282	\$9,102	\$9,132
Total Turnaround Time (hours) ^b	16	16	80	80	16
Operations Cost (\$/shipment) ^c	\$800	\$800	\$4,000	\$4,000	\$800
Maintenance Costs (\$/shipment)	\$1,028	\$1,028	\$1,028	\$1,028	\$1,028
Escalation Cost 1995 to 1997 (4.46 percent) ^e	\$569	\$177	\$638	\$630	\$489
Total Transportation Cost per Shipment	\$13,317	\$4,147	\$14,948	\$14,760	\$11,449

- a Per-shipment shipping cost = (distance x 2) x cost-per-mile. Per-mile cost includes cost of driver and fuel.
- b Reserve trailer at larger sites decreases turnaround time.
- c Operations costs are costs for loading waste at the sites and unloading waste at the WIPP. Costs are calculated as turnaround time in hours x cost per hour.
- d Maintenance costs are given in the *CH-TRU Waste Packaging Optimization Report* (DOE, 1995a) on a per-trailer basis. Maintenance costs were calculated on a per-shipment basis by dividing the total cost of maintenance for the *CH-TRU Waste Packaging Optimization Report Option 1* (all shipments in TRUPACT-IIs) by the total number of shipments predicted for Option 1.
- e Escalation rates were obtained from the standard rate of inflation (based on Gross Domestic Product) from the Environmental Protection Agency's Resource Conservation and Recovery Act/Emergency Planning Community Right to Know Act Hotline 1-800-535-0202.

C-4. References

DOE, 1995a. *CH-TRU Waste Packaging Optimization Report* Revision 1, DOE Carlsbad Area Office, Carlsbad, NM. December 1995.

DOE, 1995b. *Evaluation of Feasibility Studies for Private Sector Treatment of Alpha and TRU Mixed Wastes*, DOE/ID-10512, Department of Energy Idaho Operations Office, May 1995.

DOE, 1997a. *The National TRU Waste Management Plan* Revision 1, DOE/NTP -96-1204, DOE Carlsbad Area Office, Carlsbad, NM. December 1997.

DOE, 1997b. *The National TRU Waste Management Plan Cost Model*, DOE Carlsbad Area Office, Carlsbad, NM, September 8, 1997.

Peters and Timmerhaus, 1968. Peters, Max S. and Klaus D. Timmerhaus. *Plant Design and Economics for Chemical Engineers*, Second Edition. McGraw-Hill Book Company, New York, 1968.

Shropshire et al., 1995. Shropshire, David; Michael Sherick, and Chuck Biagi, Waste Management Facilities Cost Information for Transuranic Waste, INEL-95/0015, Revision 1. Lockheed Idaho Technologies Company, June 1995.

C-5. Other Sources of Information

The following subject matter experts were consulted during the preparation of this report.

Sinisia Djordjevic, Benchmark Environmental. Subject: Costs for performing studies.

Paul Drez, Drez Environmental Associates. Subject: Calculation basis for amount of getter added to drums.

Expert Panel, (See Appendix D.) Subject: 100 percent excess capacity assumption.

John Koltz, INEEL. Subject: Advanced Mixed Waste Treatment Facility costs.

Dale Ormond, SRS. Subject: Conceptual treatment costs for facility at SRS.

Phil Gregory, Westinghouse. Subject: Costs and status for development of applications to the NRC; Costs for performing studies for advanced filters; Costs of advanced filters.

Alan Updike, Allied Signal Kansas City. Subject: Cost of DEB getter material.

APPENDIX D

PU-238 UNCERTAINTY VARIABLE ELICITATION WORKSHOP

**Meeting Minutes of
MARCH 16-19, 1998**

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List of Acronyms and Abbreviations

CAO	Carlsbad Area Office
cc atm/g sec	cubic centimeters - atmosphere/(gram-second) <i>units for getter reaction rate</i>
DEB	1,4-bis(phenylethynyl)benzene
DOE	Department of Energy
EPA	Environmental Protection Agency
eV	electron volt
G-value	hydrogen generation rate due to radiolysis, molecules/100 eV
ICV	Inner Containment Vessel
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
NRC	Nuclear Regulatory Commission
psia	pounds per square inch absolute
Pu	plutonium
RFETS	Rocky Flats Environmental Technology Site
SARP	<i>Safety Analysis Report for the TRUPACT-II Shipping Package</i>
SRS	Savannah River Site
STP	Standard Temperature and Pressure
TRU	transuranic
TRUPACT-II	Transuranic Package Transporter, Model II
VOC	volatile organic compound
WIPP	Waste Isolation Pilot Plant

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Pu-238 Uncertainty Variable Elicitation Workshop

March 16 - 19, 1998

Meeting Notes

D-1. Introduction

Members of the Pu-238 decision analysis team met with a panel of experts the week of March 16, 1998. The purpose of the meeting was to perform an expert elicitation of values for uncertainty variables for the Pu-238 decision analysis. The meeting lasted four days and covered both technical and regulatory uncertainties. The Pu-238 decision analysis is being funded by The Department of Energy's (DOE's) Carlsbad Area Office (CAO) which was represented at the meeting by Mike Brown. The Pu-238 decision analysis team was represented by:

Christi Leigh	Sandia National Laboratories	(Sandia)
Dick Bild	Sandia National Laboratories	(Sandia)
Dave Lechel	Lechel Inc.	
Paul Drez	Drez Environmental	
Darlene Steward	S.M. Stoller Corp.	(Stoller)
Rebecca Grohler	S.M. Stoller Corp.	(Stoller)

The panel of experts included:

Sinisia Djordevic	Benchmark Inc.	
Gene Mroz	Los Alamos National Laboratory	(LANL)
Bruce LeBrun	Los Alamos National Laboratory	(LANL)
Mike Connolly	Idaho National Engineering & Environmental Laboratory	(INEEL)
John Schierloh	Rocky Flats Environmental Technology Site	(RFETS)
Gerry O'Leary	Rocky Flats Environmental Technology Site	(RFETS)
Doug Berry	Savannah River Site	(SRS)
Ruth Weiner	Sandia National Laboratories	(SNL)
Marilyn Warrant	Sandia National Laboratories	(SNL)
Murthy Devarakonda	International Technology	

The agenda was as follows:

Pu-238 Uncertainty Variable Elicitation Workshop
Schedule of Events

Monday March 16, 1998

Dave Lechel	Introduction to Elicitation Workshop	1:00 PM
Christi Leigh	Introduction to Path 1	2:00 PM
Participants	Background Discussion	2:30 PM
	- Break -	
Darlene Steward	Bounding Value Elicitation	3:30 PM
Participants	Individual Assessment	
	Exercise 1 (15 minutes)	
	Exercise 2 (15 minutes)	
	Exercise 3(15 minutes)	
Darlene Steward	Direct Assessment	4:30 PM
Christi Leigh	Ranking Assessment	
Christi Leigh	Distribution Shapes	
	- Break -	
Dave Lechel	Resolution	6:00 PM

Tuesday March 17, 1998

Dave Lechel	Resolution for Path 1	8:00 AM
Darlene Steward	Introduction to Path 4	9:00 AM
Participants	Background Discussion	9:30 AM
	- Break -	
Christi Leigh	Bounding Value Elicitation	10:30 AM
Participants	Individual Assessment	
	Exercise 1 (15 minutes)	
	Exercise 2 (15 minutes)	
	Exercise 3(15 minutes)	
Christi Leigh	Direct Assessment	11:30 AM
Darlene Steward	Ranking Assessment	
Darlene Steward	Distribution Shapes	
	- Lunch -	
Dave Lechel	Resolution	1:00 PM
Christi Leigh	Introduction to Path 2	2:00 PM
Participants	Background Discussion	2:30 PM
	- Break -	
Darlene Steward	Bounding Value Elicitation	3:30 PM
Participants	Individual Assessment	
	Exercise 1 (15 minutes)	
	Exercise 2 (15 minutes)	
	Exercise 3(15 minutes)	
Darlene Steward	Direct Assessment	4:30 PM
Christi Leigh	Ranking Assessment	
Christi Leigh	Distribution Shapes	
	- Break -	
Dave Lechel	Resolution	6:00 PM

Wednesday March 18, 1998

Dave Lechel	Introduction to Elicitation Workshop	9:00 AM
Christi Leigh	Introduction to Path 3	10:00 AM
Participants	Background Discussion	10:30 AM
Darlene Steward	Discussion of Distribution Shape	11:30AM
	- Lunch -	
Darlene Steward	Bounding Value Elicitation - 1 st Characteristic	1:00 PM
Participants	Individual Assessment	
	Exercise 1 (15 minutes)	
	Exercise 2 (15 minutes)	
	Exercise 3(15 minutes)	
Darlene Steward	Direct Assessment	2:00 PM
Christi Leigh	Ranking Assessment	
Darlene Steward	Bounding Value Elicitation - 2 nd Characteristic	2:30 PM
Participants	Individual Assessment	
	Exercise 1 (15 minutes)	
	Exercise 2 (15 minutes)	
	Exercise 3(15 minutes)	
Darlene Steward	Direct Assessment	3:30 PM
Christi Leigh	Ranking Assessment	
	- Break -	
Dave Lechel	Resolution	5:00 PM

Thursday March 19, 1998

	Introduction to Elicitation Workshop	8:00 AM
	Introduction to Decision Tree Paths	9:00 AM
	Background Discussion	9:30 AM
	- Break -	
	Assessment Exercises	10:30 AM
	- Lunch-	
	Assessment Exercises	1:00 PM
	- Break -	
	Resolution	2:00 PM

D-2. Research Hydrogen Getters in Drums

The use of hydrogen getters in Pu-238 transuranic (TRU) waste drums to control the build up of hydrogen gas during transportation was the elicitation topic on Monday March 16, 1998 starting at 1:00 PM. Gene Mroz, Sinisia Djordevic, and Mike Connolly formed the expert panel for this session. Dave Lechel began with a presentation of background information for the expert panel. The background material included a review of the decision analysis task, a discussion of the role of expert judgment, and a review of uncertainty, probability, and elicitation concepts.

The following issues were discussed in relation to the background information presented:

1. Gene Mroz questioned the team about the possibility of a vented Transuranic Package Transporter, Model II (TRUPACT-II). His question was two-fold. Did we consider it and wouldn't a vented TRUPACT-II represent the best approximation to an infinite sink for hydrogen? In answer to the first question, yes, the Pu-238 team did consider the idea of a vented TRUPACT-II and determined that the vented TRUPACT-II violates federal law (Attachment 2). In answer to the second question, the participants agreed that, in theory, a vented TRUPACT-II represents the best case for an infinite hydrogen sink. Sinisia Djordevic mentioned that there would be a two-fold increase in wattage limit for a vented TRUPACT-II. Mike Brown mentioned that a zero hydrogen concentration in the inner containment vessel (ICV) or even in the drum headspace is not enough. The real issue is the hydrogen concentration in the innermost bag, and that depends on the resistance offered by the packaging configuration, not just the hydrogen concentration in the "sink." All participants agreed with this statement.
2. As part of the background discussion Mike Brown emphasized that the Pu-238 decision analysis is being done because we want to ship as much Pu-238 TRU waste as possible without repackaging or treating.
3. The expert panel was asked if they had any general questions about the decision tree and background material. Mike Connolly questioned the team about the assumption used in the deterministic model for treatment (i.e., a thermal process). He wanted to know if this was based on information from the Savannah River Site stating that they would perform thermal treatment. The answer was no. The Advanced Mixed Waste Treatment Facility at INEEL is used as a model for treatment in the decision analysis. The Savannah River Site has not indicated that they will treat Pu-238 TRU waste thermally or otherwise. It was believed that thermal treatment would be an adequate representative of a treatment option for the decision analysis.
4. Gene Mroz asked for clarification about one of the performance measures: time to initial disposal. He wanted to know why it was included instead of time to final disposal. The answer was that the time to initial disposal performance measure was included to capture the recent emphasis on cleanup by 2006. Christi Leigh explained that the four performance measures are designed to show how fast a solution can be put in place, how long it will take

to finish the job, how much of the waste will be addressed, and how much will the solution cost. All of these attributes were deemed important by the CAO.

5. Mike Connolly asked the team about the definition of stakeholder evaluation. Dave Lechel answered saying that stakeholders for this analysis means the DOE and sites that have Pu-238 TRU waste. Mike Brown emphasized that the purpose of the analysis is to assure there is coordination between sites and to look at issues at all of the sites.

Once the background material was covered, Christi Leigh began a discussion of Path 1 (Research Hydrogen Getters in Drums). The path was defined as:

Studies show that adding hydrogen getter materials to the headspace of the drums can reduce the number of drums produced when Pu-238 TRU waste is repackaged for shipment to the Waste Isolation Pilot Plant (WIPP). The DOE petitions the Nuclear Regulatory Commission (NRC) to allow the use of hydrogen getter materials in TRU waste drums. The NRC either approves or denies the petition. Waste is either repackaged with getters, or treated, or repackaged without getters and shipped to WIPP in the TRUPACT-II.

The elicitation variable was defined as:

the expected reaction rate for hydrogen getter materials in Pu-238 TRU waste drums under testing conditions required by the NRC.

The following issues were discussed in relation to the path description and the elicitation variable definition:

1. There was a discussion of the "NRC conditions" clause in the variable definition. It was noted that this means over a temperature range dictated by the NRC (-20°F to 146°F). The experts were asked if there are any other conditions for consideration that would be required by the NRC. Gene Mroz mentioned that the reaction rate will be a function of the partial pressure of hydrogen. He said that pressure changes would, at most, produce a 25% change in the reaction rate. Sinisia Djordevic said that the packaging configuration would have a greater effect than the pressure. The experts agreed that pressure fluctuations would not be considered during the elicitation. Mike Brown asked if accident conditions would have to be considered when a reaction rate for getters was presented to the NRC. Dave Lechel mentioned that we are assuming that the DOE will take mitigating measures given an accident. Dave's supposition was that the NRC may not ask DOE to justify getter reaction rates under accident conditions. Mike Brown mentioned that given an accident, hydrogen becomes a smaller concern and the real concern is potential dose rates. Paul Drez thought that interactions with the waste during an accident might be a worry, but loss of containment is the real worry under accident conditions. Gene Mroz wondered if the getters would still be effective if they were in contact with the waste or would that aggravate the problem. It was the consensus of the group that the getter would not aggravate any accident conditions. The

conclusion was that accident conditions should not have a bearing on the reaction rate elicitation.

2. There was a discussion of the placement of getters in the drum. The team explained that the configuration being modeled was placement of the getters outside the drum liner (between the liner and the lid of the drum). The waste is repackaged in two layers of filtered bags, and there is a one-inch hole in the drum liner.
3. There was a discussion of the units (cubic centimeters atmosphere/gram-second [cc atm/g sec]) for the elicitation variable. The panel noted that the units are not universal constants. If the reaction rate is expressed in cc atm/g sec, the rate will change as a function of time because the getter is used up. Mike Brown noted that the panel might have to consider depletion of the getter with time. Gene Mroz wanted a reaction rate independent of getter mass.
4. There was discussion about the correct equation to use to convert getter reaction rate to wattage.
5. Sinisia Djordevic noted that the equation that Christi had was correct if the getters are placed in the ICV but not correct if the getters are placed in the drum headspace. Christi wondered if it was just a change in the resistance, to which Sinisia replied that it was more than that. He gave Christi a handout with the derivation of the correct equation. This new equation will be implemented in the decision analysis.

Once the elicitation variable was agreed upon, each of the panel members was given the opportunity to describe the status of their work in the area of hydrogen getters. Gene Mroz discussed ongoing experiments at LANL on getter reaction rates and the effects of poisons. They have developed a mathematical model for their experimental setup. The setup is a column of getter material with a hydrogen gas flow from the bottom of the column. There is an analyzer at the top of the column. They have looked at temperatures from 10°C to 60°C. None of their tests so far are for subfreezing conditions. The getter material that they are considering is 1,4-bis(phenylethynyl)benzene (DEB), which has been used in the weapons community. The melting point for DEB is 179°C. Saturation is at about 85% reacted. He noted that DEB does not decompose; it is a very stable compound. He also noted that pressure effects are not significant (25% maximum effect from sea level to 7,000 feet).

After Gene's presentation the panel and team members discussed a series of background questions and developed a set of working assumptions for the elicitation. The background discussion is summarized as follows:

1. **Capacity:** The theoretical capacity of DEB is 240 cc hydrogen/gram. Gene notes that the duration of effectiveness for the getter depends on the amount of material placed in the drum and the hydrogen gas generation rate. If the time that the getter needs to work in the drum and the maximum hydrogen generation rate are known, one can calculate the amount of getter material that is needed. Gene noted that there is a physical limitation of space between the

drum liner and the drum lid. The panel concluded that about 1 kilogram of getter would be needed for a 3 watt drum assuming the DEB capacity is 120 cc/gram.

2. **Recombination reaction** (hydrogen with oxygen to make water): The palladium catalyst will promote this reaction. The recombination reaction is faster than the DEB - hydrogen reaction, but requires the presence of oxygen. There was some discussion of purging the oxygen, but this idea was rejected. Gene Mroz noted that some experiments were performed at 70% relative humidity, and the presence of water had no effect on the reaction rate. Christi Leigh asked about the potential for water freezing on the surface of the getter. Gene said he wasn't sure how much water would be generated. Dave Lechel wondered if conditions during transportation would be below the dew point in winter. Gene Mroz noted that the work in Kansas City showed that getter in water does not work because of the physical barrier. He concluded that a liquid water film would have the same effect. Sinisia noted that the Kansas City application included putting desiccant in with the getter to remove water. He also wondered if the heat of reaction with the palladium might be enough to keep water from condensing on the DEB.
3. **Heat of reaction:** The DEB heat of reaction is 30 kcal /mole.
4. **Physical form:** Gene Mroz noted that the reaction rate is dependent on physical form.
5. **Poisons:** Gene Mroz noted that they held an expert elicitation workshop to determine the gases that might be present in the headspace of TRU waste drums. The experts included people from LANL, Kansas City, and Paul Nigrey from Sandia. They considered headspace gas results from 1,000 drums at INEEL and drums at RFETS. The RFETS drums were from the bin program (80 drums), where they found an average carbon monoxide concentration of 230 parts per million (ppm); about one half of the drums were below the carbon monoxide detection limit, and the highest concentration (in an unvented drum) was 0.2 volume percent carbon monoxide. The compounds observed were grouped by class:

inorganic gases: carbon monoxide, hydrogen chloride, hydrogen sulfide

halogenated olefins: tetrachloroethylene, dichloroethylene

halogenated alkanes: carbon tetrachloride

alcohols: methanol

ketones: acetone

aromatics: toluene

The experts agreed that alcohols, ketones, and aromatics were not poisons for DEB, but inorganic gases (especially carbon monoxide) and halogenated compounds are poisons for DEB. Gene noted that the getter reaction rate decreases by a factor of ten in the presence of carbon monoxide. The reaction rate with carbon monoxide is reversible, but the carbon monoxide competes with the hydrogen for DEB reaction sites. Gene's conclusion was that the getter will not work in the presence of carbon monoxide.

D-2.1 WORKING ASSUMPTIONS

1. The system can be engineered so that there will be enough getter capacity. Getter will have 100% excess capacity - Minimum rate will be at 50% of capacity used.
2. The getter is pelletized (75% DEB, 25% palladium).
3. The getter is contained and container will not affect reaction rate.
4. There will be an engineering solution to mitigate poisons.
5. There are no chemical compatibility issues for the getters.
6. Formation of water and free water in drums will not impede getter reaction (there will be mitigation of water).
7. The temperature range to consider will be -20°F to 146°F.
8. The drums are vented and at steady state.

D-2.2 REACTION RATE ELICITATION

The panel preferred to work as a group rather than individually. The first elicitation was for the minimum reaction rate. This was defined as the lowest reaction rate that would be considered during the elicitation. The panel agreed on the following assumptions for the minimum rate:

1. Assume minimum rate will occur at -20°F with 50% capacity filled.
2. Assume physical configuration has no effect.
3. Assume that the reaction rate decreases by a factor of 3 for every 10°C decrease in temperature.
4. Assume conversion factor of 20,000 cc atm/mole hydrogen.

The panel started with two known values:

reaction rate = 3E-2 cc atm/g sec	reaction rate = 8E-3 cc atm/g sec
20°C	20°C
5% hydrogen	5% hydrogen
95% nitrogen	95% nitrogen
0.2 g DEB	0.2 g DEB
100% capacity available	50% capacity available

From 20°C to -20°F (-29°C) is an approximate temperature change of -50°C which means the low reaction rate (8E⁻³ cc atm/g sec) should be divided by (3)⁵ or 243. This gives:

$$(\text{reaction rate})_{-20°F, 50\% \text{ capacity}} = 8E^{-3} \text{ cc atm/g sec} / 243 = 3.3E^{-5} \text{ cc atm/g sec}$$

The panel agreed to lower this value by a factor of ten to account for possible errors in the starting value (8E⁻³ cc atm/g sec) which they obtained from their experimental results. As a result, the minimum value assigned by the panel was 3E⁻⁶ cc atm/g sec or 1.5E⁻¹⁰ moles hydrogen/g sec. The panel agreed that there is a zero probability that the reaction rate would be less than or equal to 1.5E⁻¹⁰ mole hydrogen/g sec.

The panel agreed on the following assumptions for the maximum rate:

1. Assume maximum rate will occur at 63°C with 100% capacity available.

2. Assume physical configuration has no effect.
3. Assume that the reaction rate increases by a factor of 3 for every 10°C decrease in temperature.
4. Assume conversion factor of 20,000 cc atm/mole hydrogen.

From 20°C to 63°C is an approximate temperature change of +43°C which means the reaction rate should be multiplied by $(3)^{4.3}$ or 112.6. This gives:

$$(\text{reaction rate})_{63^\circ\text{C}, 100\% \text{ capacity}} = 3\text{E-2 cc atm/g sec} \times 112.6 = 3.4 \text{ cc atm/g sec}$$

The panel agreed to raise this value by a factor of ten to account for possible errors in the starting value (3E-2 cc atm/g sec) which they obtained from experimental results. As a result, the maximum value assigned by the panel was 3.7E-1 cc atm/g sec or 1.7E-3 moles hydrogen/g sec. The panel agreed that there is a zero probability that the reaction rate would be greater than or equal to 1.5E-3 mole hydrogen/g sec. They did note, however, that there is evidence that the reaction rate temperature dependence levels off at around 50°C.

To get their 1% and 99% values, the panel decided to take the lowest calculated number and divide by 2. The lowest calculated number obtained by the panel was 1.5E-9 moles hydrogen/g sec (ten times faster than the minimum value they chose). Dividing by 2 gives 0.75E-9 moles hydrogen/g sec. The panel agreed that there is a 1 in 100 chance (1% probability) that the reaction rate would be lower than or equal to 7.5E-10 mole hydrogen/g sec. Using the same logic for their 99% value, the panel noted that their highest calculated number was 3E-4 moles hydrogen/g sec. Increasing this by a factor of 2, they chose 7.5E-4 moles hydrogen/g sec for their 99% value. The panel agreed that there is a 1 in 100 chance (1% probability) that the reaction rate would be greater than or equal to 7.5E-4 mole hydrogen/g sec.

The panel agreed that the midpoint value should be the reaction rate evaluated at what they believe to be the most likely conditions during transport. These conditions are:

1. 10-day shipping period (TRUPACT-II is sealed at room temperature and sits for 10 days)
2. 40 watts/TRUPACT-II
3. An ambient temperature of 20°C plus a heat load from the wattage that results in a 7°C temperature rise (27°C in the drum)
4. Assume 8% (1/6 of the 50% number) of the getter capacity has been used (92% remaining). Note: the difference between the rate at 100% capacity and the rate at 92% capacity is minimal. Therefore, the 100% capacity numbers were used.

From 20°C to 27°C is a temperature change of +7°C, which means the reaction rate should be multiplied by $(3)^7$ or 2.15. This gives:

$$(\text{reaction rate})_{27^\circ\text{C}, 100\% \text{ capacity}} = 3\text{E-2 cc atm/g sec} \times 2.15 = 6.5\text{E-2 cc atm/g sec} \\ = 3.2\text{E-6 moles hydrogen/g sec}$$

The panel settled on a midpoint value of 2.7E-6 moles hydrogen/g sec.

The panel agreed on the following assumptions for calculation of their 33% and 67% values:

1. Assume volume of unshippable Pu-238 TRU waste at SRS is 1,693 cubic meters, at LANL is 313 cubic meters, and at Mound is 17 cubic meters.
2. Assume the SRS mean temperature is at or below 18°C 33 percent of the time, between 18° and 32°C 33% of the time, and at or above 32°C 33% of the time.
3. Assume LANL mean temperature is at or below 7°C 33% of the time, between 7 and 20°C 33% of the time, and at or above 20°C 33% of the time.

The numbers used were calculated as follows:

$$\begin{aligned}
 (\text{reaction rate})_{18^\circ\text{C}, 100\% \text{ capacity}} &= 3\text{E-2 cc atm/g sec} / 1.24 = 2.4\text{E-2 cc atm/g sec} \\
 &= 1.2\text{E-6 moles hydrogen/g sec}
 \end{aligned}$$

$$\begin{aligned}
 (\text{reaction rate})_{32^\circ\text{C}, 100\% \text{ capacity}} &= 3\text{E-2 cc atm/g sec} \times 3.73 = 1.1\text{E-1 cc atm/g sec} \\
 &= 5.6\text{E-6 moles hydrogen/g sec}
 \end{aligned}$$

$$\begin{aligned}
 (\text{reaction rate})_{7^\circ\text{C}, 100\% \text{ capacity}} &= 3\text{E-2 cc atm/g sec} / 4.17 = 7.2\text{E-3 cc atm/g sec} \\
 &= 3.6\text{E-7 moles hydrogen/g sec}
 \end{aligned}$$

The panel agreed that the 33% value for SRS would be 9E-7 moles hydrogen/g sec and the 67% value would be 4.1E-6 moles hydrogen/g sec. The 33% value for LANL would be 3E-7 moles hydrogen/g sec and the 67% value would be 1.4E-6 moles hydrogen/g sec. Taking a weighted average, based on the volume of Pu-238 at SRS, the 33% value they chose was 7.8E-7 moles hydrogen/g sec and the 67% value they chose was 3.6E-6 moles hydrogen/g sec. The elicitation results are summarized in Table D-1. The results have been plotted in Figure D-1 and fit with a lognormal distribution with a mean value of 1.4E-6 moles hydrogen/g sec and a standard deviation of 1.1E-5 moles hydrogen/g sec. Note that the curve in Figure D-1 looks like a cumulative distribution function for a normal distribution because the x-axis is logarithmic. The probability mass function (on a logarithmic scale) is shown in Figure D-2. Figure D-3 shows the representative percentile values that will be used for the decision tree. Three states will be modeled: 1) a state with a reaction rate of 2.5E-5 moles hydrogen/g sec and a probability of 25%, 2) a state with a reaction rate of 1.4E-6 moles hydrogen/g sec and a probability of 50%, and 3) a state with a reaction rate of 8.2E-8 moles hydrogen/g sec and a probability of 25%.

Table D- 1. Getters in Drums - Path 1

Probability	Reaction Rate (moles/g sec)	Notes
0	1.5E-10	at -20°F (-29°C)
0.01	0.75E-9	lowest calculated number decreased by a factor of 2
0.33	7.8E-7	see calculations
0.5	2.7E-6	initial measured rate at 20°C scaled up for 7°C temperature change due to wattage heat load
0.67	3.6E-6	see calculations
.99	7.5E-4	highest calculated number increased by a factor of 2

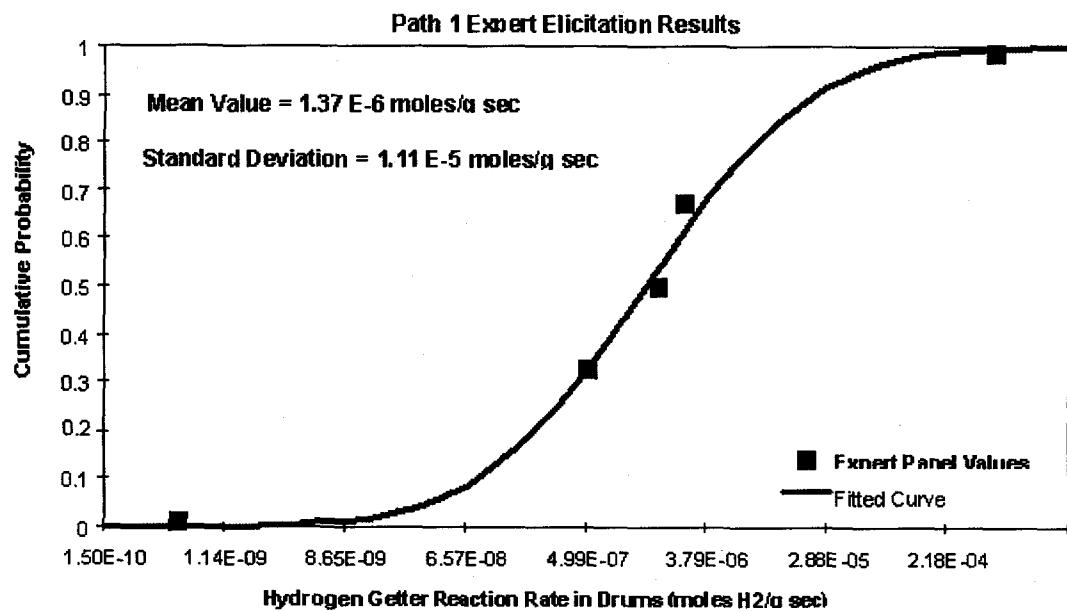


Figure D- 1. Cumulative Probability Distribution for Getter Reaction Rate

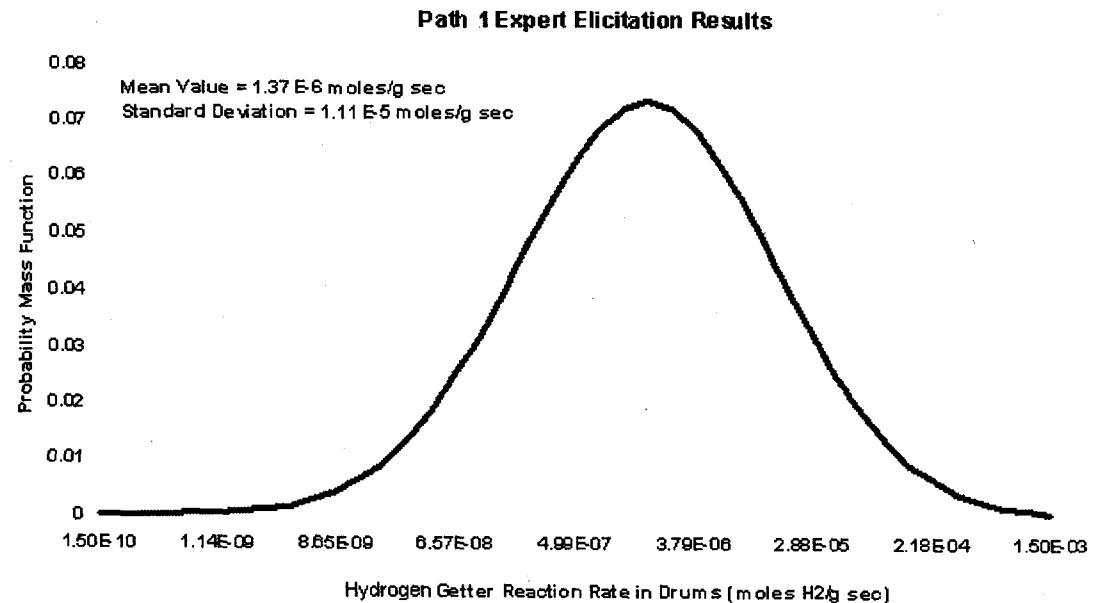


Figure D- 2. Probability Mass Function for Getter Reaction Rate

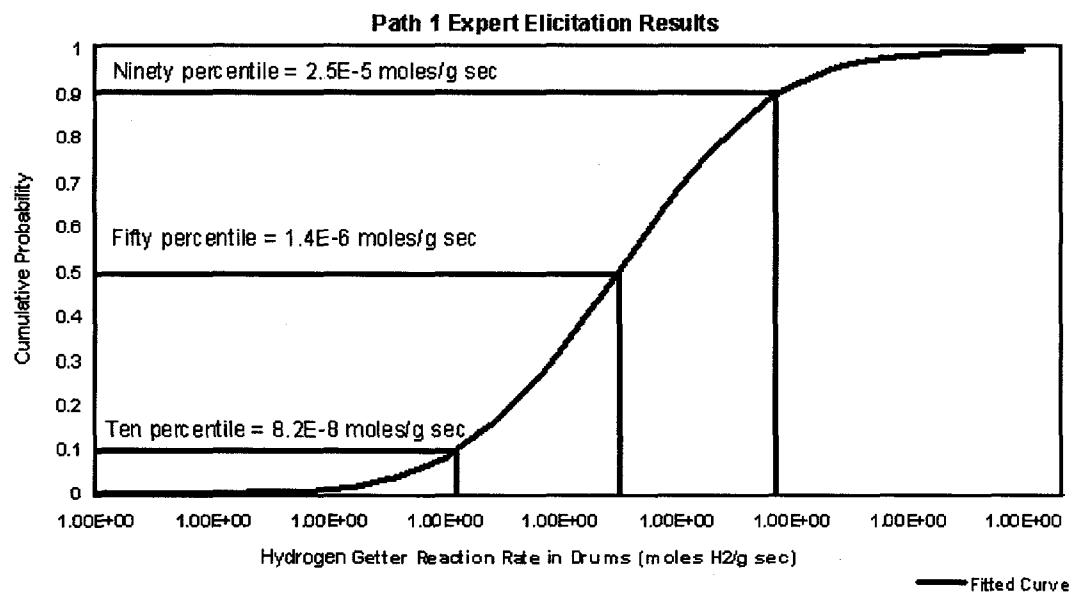


Figure D- 3. Representative Percentile Values for the Decision Tree

D-3. Research Hydrogen Getters in the Inner Containment Vessel

The use of hydrogen getters in the TRUPACT-II ICV to control the buildup of hydrogen gas during transportation was the elicitation topic on Tuesday, March 17 starting at 8 AM. The expert panel was made up of Gene Mroz, Sinisia Djordevic, and Mike Connolly. This panel had participated in the elicitation for the reaction rate of getters in drums that had been conducted the previous day. Therefore, the background material was not reviewed. A discussion of the background material is presented in Section 2 "Research Hydrogen Getters in Drums."

Christi Leigh facilitated the discussion of Path 4 (Research Hydrogen Getters in the ICV). The path was defined as:

Studies show that adding hydrogen getter materials to the ICV of the TRUPACT-II increases the allowable wattage of drums that can be included in each shipment to WIPP. The DOE petitions the NRC to allow the use of hydrogen getter materials in the ICV. The NRC either approves or denies the petition. Waste is either transported in the TRUPACT-II with getters in the ICV or treated or repackaged and transported to WIPP in the TRUPACT-II without getters in the ICV.

The elicitation variable was defined as:

the expected reaction rate for hydrogen getter materials in the ICV of the TRUPACT-II under testing conditions required by the NRC.

The following issues were discussed in relation to the path description and the elicitation variable definition:

1. There was some discussion of possible methods for preventing carbon monoxide, water, and poisons from contacting the getter material, and potentially interfering with the reaction between the getter and hydrogen. Confining the getter material in a bag that would be permeable to hydrogen but not to carbon monoxide, water, or poisons was discussed. The consensus of the group was that it is technically feasible to design such a confinement layer (membrane bag). A materials scientist would have to be consulted to reach a definitive conclusion on this question. However, the bag material might slow the reaction rate between the getter and hydrogen. For the purpose of the elicitation, it was assumed that a selectively permeable bag material could be found, and that the bag would not slow the getter reaction rate (see assumptions 3 and 4).
2. There was a discussion of possible strategies for mitigating the effects of temperature variations on the getter reaction rate. One suggestion was that temperature-dependent shipping schedules could be employed to ensure that the reaction rate was maintained at a high level (i.e., waste could not be shipped if the ambient temperature fell below a threshold temperature). Both Mike Brown and Dave Lechel questioned the use of administrative controls (changing shipping schedules) to address a technical issue (the decrease in getter

reaction rate at lower temperatures). It was decided that such administrative controls would not be considered. However, it was agreed that the technical discussion of the temperature dependence of the reaction rate would be very important.

3. Mike Connolly said that the scenario, as presented, would give only a five percent increase in the wattage limit. He said that the reduced effectiveness is due to the inability of hydrogen to escape from the inner layers of confinement. Without repackaging, the effectiveness is reduced even though the reaction rate of the getters is unchanged from the Path 1 scenario. In light of this, he questioned whether the path should be evaluated. Paul Drez felt that the evaluation was necessary to document that the scenario is not effective. Dave Lechel concurred, stating that the decision analysis would show any lack of effectiveness. Christi Leigh said that the distribution for the reaction rate was still needed. Sinisia Djordevic said that the rate equation used for the "Getters in Drums" elicitation is valid for this elicitation. It was agreed that the scenario would be evaluated "as is."

The status of experiments with getters had been previously discussed (see Section 2 - Getters in Drums). There was no further discussion of experimental plans or results.

The panel and team members then discussed a series of background questions and developed a set of working assumptions for the elicitation. The background discussion is summarized as follows:

1. Gene Mroz asked whether there would be any thermal lag between the drums and the ICV (i.e., any temperature difference between the ICV and the drums). The panel decided that the thermal mass of the drums would dictate the temperature. Therefore, the temperature within the ICV would be the same as the temperature of the drums. It was decided that the 7°C temperature increase during a ten-day shipping period used for the Path 1 elicitation would also be valid for this elicitation.
2. The diffusion of hydrogen to the getter in the ICV cavity was discussed. It was decided that the mixing within the ICV cavity and diffusion would ensure that hydrogen reached the getter. Therefore, diffusion of hydrogen to the getter in the ICV would not be significantly different from diffusion of hydrogen in the drum.
3. Doug Berry commented that the "Getters in the ICV" scenario is equivalent to placing the drums in the open air. He noted that storage of drums in the open has been approved as safe in the SRS Baseline, but transport using getters in the ICV might not be deemed safe.

D-3.1 WORKING ASSUMPTIONS

1. The system can be engineered so that there will be enough getter capacity. Getter will have 100% excess capacity - Minimum rate will be at 50% of capacity used.
2. The getter is pelletized (75% DEB, 25% palladium).
3. The getter is contained and container will not affect reaction rate.
4. There will be an engineering solution to mitigate poisons.
5. There are no chemical compatibility issues for the getters.

6. Formation of water and free water in drums will not impede getter reaction (there will be mitigation of water).
7. The temperature range to consider will be -20°F to 146°F.
8. The drums are vented and at steady state.
9. Getter is added to the ICV in a honeycomb section.
10. Waste is not repackaged.
11. Mixing within all void spaces is complete.

D-3.2 REACTION RATE ELICITATION

The panel's consensus was that the reaction rate would not be affected by differences between the configuration of placing getters in the ICV versus placement of getters in drums. Therefore, it was decided that the elicitation for adding getters in the ICV would be exactly the same as for adding getters to drums. Refer to Section 2 for the reaction rate data, distribution, and discussion.

D-4. RESEARCH HYDROGEN GENERATION IN ACTUAL WASTE

Matrix depletion and hydrogen generation studies were the elicitation topic on Tuesday March 17, 1998 starting at 1:00 PM. Gene Mroz, Sinisia Djordevic, Mike Connolly, and John Schierloh formed the expert panel for this session. Since the background material was covered with this panel on Monday, it was not repeated on Tuesday. Christi Leigh began a discussion of Path 2. The path was defined as:

Matrix depletion and hydrogen generation studies show that the effective G-values for actual TRU waste are lower than the G-values currently used to calculate wattage limits. The DOE petitions the NRC for a change in wattage limits for TRU waste based on the study results. The NRC either approves or denies the petition. Containers that qualify based on approved wattage limits are shipped in the TRUPACT-II without treatment or repackaging. The remaining Pu-238 TRU waste is either treated or repackaged and shipped to WIPP in the TRUPACT-II.

The elicitation variables were defined as:

The effective G-value that the DOE would use in a petition to the NRC for Type I TRU waste.

The effective G-value that the DOE would use in a petition to the NRC for Type II TRU waste.

The effective G-value that the DOE would use in a petition to the NRC for Type III TRU waste.

The following issues were discussed in relation to the path description and elicitation variable definition:

1. John Schierloh asked for clarification about how repackaging fits in with matrix depletion. It was explained that repackaging is a decision that would be made after the matrix depletion

studies were performed and the results of the NRC petition are known. For Path 2, the DOE ships some of the waste "as is," based on the results of matrix depletion work. Then a decision to either treat or repackage the remaining waste is made.

2. The panel decided that they could not provide information about what G-value the DOE would use in a petition to the NRC. They could only provide information about the G-value that they believe is representative of the waste. It was decided that the clause "that the DOE would use in a petition" would be deleted from the definition for the elicitation variable.
3. There was a lengthy discussion about the meaning of "effective" G-value. Sinisia Djordevic noted that the G-value is an inherent value of a material. He suggested that we have to choose the most conservative material because we don't know exactly what is in our waste. They have been studying matrix depletion in polyethylene as a pure material for this reason. Their work is being done on polyethylene, not real waste drums. He believes that the polyethylene results provide bounding effective G-values. Christi Leigh asked about whether the gas generation tests that are being performed at RFETS show effective values since the tests are for a composite of actual waste materials, not just a pure component. Other things discussed about the definition of effective: 1) not at time of initial exposure, 2) based on energy emitted (not energy absorbed) - some energy internally absorbed.
4. There was discussion of the misconception that hydrogen generation falls off with time. Gene Mroz made it clear that the hydrogen generation rate is really a function of the accumulated dose, which is both the time and the activity.
5. There was discussion of the initial values (time = 0). Values based on the *Safety Analysis Report for the TRUPACT-II Shipping Package* (SARP) (DOE, 1998) are as follows:

TYPE 1 WASTE

G-value = 1.2

water

experiments based on water, EnvirostoneTM

TYPE II WASTE

G-value = 2.0

50% polyethylene

G-value = 50% of G-value for TYPE III

TYPE III

G-value = 4.0

pure polyethylene

Once the elicitation variable was agreed upon, each of the panel members was given the opportunity to describe the status of their work in the area of matrix depletion and hydrogen generation. Gene Mroz talked about the experiments being conducted at LANL. He discussed the experimental set up and presented results. The experiments show that matrix depletion is a

process that happens very fast (within weeks). They believe the initial time period is about 60 days. They do not have measurements within the 60-day period, but are planning experiments to show that the gas generation rate drops rapidly from the SARP value during this time. They will complete these experiments within a few months (e.g., control experiments, replication of SARP experiments). They expect the gas generation rate to drop within the first two weeks (based on their data from previous experiments). So far the measured values (at greater than 60 days) are much lower than the values used in the SARP.

They have looked at the effects of temperature, pressure, and isotopic mix. They found that temperature and pressure have no effect. They also found that the isotopic mix has no effect as long as the accumulated dose is equal. This is one of Gene's most important points. It is the accumulated dose (activity and time combined) that drives the rate of matrix depletion. The x-axis on his graphs was in watt-years. The experiments have been run biweekly for two years.

Gene was asked about the agitation issue. They have experiments designed specifically to address this. They are not complete yet; however, he reported that some earlier work conducted by John Cappis showed no increase in gas generation with agitation. Everyone wondered why agitation would not increase the gas generation rate. Gene talked about the possibility that the Pu-238 particles become imbedded in the waste or adhere due to electrostatic forces. Another possibility discussed is that the Pu-238 particles are continuously moving throughout the waste because of surface charges and alpha recoil (affecting smaller particles). If this were the case, there would be no measurable effect from additional movement due to agitation. Gene concluded that his work will show a G-value of about 3 for polyethylene.

There was a discussion of the particle size distribution. Gene noted that the current assumption is that 82% of the alpha radiation escapes the particle and impacts waste material. This assumption accounts for the particle size distribution.

Paul Drez wanted to know if they saw any carbon dioxide in their analysis. Gene says they don't look for it in every sample because it is hard to analyze. Every 19th run they do an analysis for carbon dioxide, methane, and others.

Sinisia Djordevic talked about the theoretical model (in radial coordinates) that shows the loss of energy with distance from the point of emission. This energy is compared to the bond energy for carbon-carbon, carbon-oxygen, and carbon-hydrogen bonds. Combined with the probability of hitting a particular bond, they can calculate a theoretical gas generation rate.

John Schierloh talked about work conducted at RFETS. In the RFETS study they are testing waste drums and calculating an effective G-value based on the gas generation rate. This is to confirm the laboratory G-values. The panel noted that G-values derived from the RFETS experiments should always be lower than the laboratory G-values because actual drums do not contain pure polyethylene. John Schierloh mentioned that they are looking at categories (by Item Description Code) of waste and other groups of waste (e.g., waste type). They are looking both at the time dependence of the hydrogen generation rate and variations in the initial rate. John stated that RFETS does not know much about the distribution of waste materials in their drums.

The RFETS experimental set up is a bell jar with sampling ports at the top. The samples are analyzed by a mass spectrometer. John's highest G-value was 1.1, which was for a combustible waste. His mean value was 0.32 with a standard deviation of 0.26. For Type II.1 waste, John has a mean of 0.039 with a standard deviation of 0.057. For Type III waste, John has a mean of 0.324 with a standard deviation of 0.260. His waste varies from 150 to 180 grams of plutonium. John stated that they did calculate some negative values which he believes resulted from insufficient purging of the measurement apparatus between drums. This is a problem that they have now corrected.

John Scheirloh gave a presentation on modeling of the belljar experiments using LabView software. The following assumptions were used for the modeling:

- Two layers of confinement using filtered bags
- Resistance values used were from the SARP
- The void volume of the drum was assumed to be one-half of the drum volume; 3.03 moles (90 liters). This value will be measured in future experiments.

The headspace concentration of hydrogen was modeled as a function of time. The generation rate was derived from the hydrogen concentration and time. The generation rate could then be used in combination with the drum wattage to calculate the G-value for the drum. He noted that the resistances for filtered bags presented in the SARP were higher than those measured by Terry Wickland (Ed. note; Terry Wickland is with Nuclear Filter Technology Corp.). If the actual resistance of the filtered bags were lower than assumed, the G-value calculated by the model would be higher than the actual G-value. Therefore, use of the SARP values for the resistance of filtered bags is a conservative assumption.

Mike Connolly described the experiments at INEEL. He said that the INEEL experiments are designed to be consistent with TRUPACT-II methods (laboratory values for individual materials) given in the SARP.

After Gene and John's presentations, the panel and team members discussed a series of background questions and developed a set of working assumptions for the elicitation. The background discussion is summarized as follows:

1. Are the effects of matrix depletion measurable in a meaningful time frame? Christi Leigh asked if matrix depletion is complete after a two-week period. The answer was no because it is based on the dose as well (watt-year). Gene stated that the cutoff for polyethylene appears to be 0.02 watt years. This would apply to Waste Types II and III. After discussion, the panel agreed that Pu-238 TRU waste would easily be beyond the 0.02 watt-year window, so full matrix depletion would be in effect.
2. LANL reported on their work in the area of cemented materials. Plutonium was dissolved and mixed in Envirostone™ to form a cement. They observed very low measured values. Gene supposes this is because the all of the hydrogen generated within the cement matrix does not escape. Previous work at SRS and Argonne National Laboratory-West looked at hydrogen generation as a function of free water. The results are very linear. If free water is

not controlled, the G-values are not affected. The panel decided that the G-value for Type I would be 1.3 (the current G-value), so an elicitation would not be done on the G-value for Waste Type I.

3. The effect of drum movement (from loading and transport) on gas generation was discussed. LANL's new experiments will produce a more accurate simulation of over-the-road vibration, but previous studies did not show any effect. The only reason that the LANL experiments are being done is that people keep bringing up the issue. Again the panel discussed possible reasons that agitation would have no effect. Doug Berry from SRS (who was observing on Tuesday) noted that Pu-238 is highly mobile. SRS has cleaned rooms one day and found Pu-238 on the opposite wall in the room the next day, as if it had moved over to the other wall. He wondered if, because of the high Pu-238 activity, smaller quantities can be detected. The panel also discussed surface charges, alpha recoil for smaller particles, and other theories that support the idea that the Pu-238 is moving throughout the waste matrix continuously. Whatever the reason, the panel agreed that agitation should have no effect on the G-value. Mike Brown noted that we may have to restart the clock for any intrusion of the drum (e.g., sampling, puncture of bags, etc.), but the time until matrix depletion has occurred appears to be so short, it probably doesn't matter.
4. The importance of the range of temperatures during shipping was discussed. The panel noted that the G-value dependence on temperature is slight. G-values are about 20% higher at 60°C than at 20°C.
5. The difference between G-values for Pu-238 and Pu-239 TRU wastes was discussed. The panel agreed, based on previous discussion, that there is no difference. What really matters is the accumulated dose. If the accumulated dose is the same, the G-value will be the same.
6. The panel discussed the issue of particle size distribution. Doug Berry noted that SRS has a very small particle size distribution (like face powder). Mike Connolly suggested an average particle size of 0.8 micron. This reduces the amount of self-absorption. The smaller the particle size, the more mobile the particle, which gives a higher dose. A higher dose rate will lead to faster matrix depletion. On the other hand, the initial G-value decreases with increasing particle size. The panel decided it was a wash.
7. The issue of assay accuracy was brought up. Gene Mroz's experiments have very good assay accuracy. He noted that bias in wattage toward high values will bias G-values toward low values.

D-4.1 WORKING ASSUMPTIONS

1. The elicitation will determine the asymptotic G-values. This is defined as the average G-value after the cutoff value of 0.02 watt-years for Waste Types II and III.
2. Agitation does not affect matrix depletion (e.g., the G-value).
3. The effect of temperature is negligible.
4. The fact that experimental results are based on emitted energy rather than absorbed energy accounts for effects of particle size.

D-4.2 G-VALUE ELICITATION

The panel preferred to work as a group. Even though they felt that the values for polyethylene (LANL experiments) were the bounding values, the elicitation focused more on the experimental

data from RFETS, which is for actual waste. The first elicitation was for the minimum and maximum G-values. These were defined as the lowest and highest G-values that would be considered for Type III waste during the elicitation. The panel agreed on the following assumptions for the maximum G-value:

1. The minimum G-value is 0.
2. The maximum G-value is 4.1, the literature value for Type III (polyethylene).

For a median value, the panel looked to John Schierloh's results. His median value for Type III waste was 0.329 with 30 drums below and 30 drums above that value. This is the 50% value for their curve. The panel felt that the RFETS data would best represent the SRS waste.

There was some discussion about Type II waste. There are only 13 drums in John Schierloh's sample for Type II waste. Mike Connolly said that the data set from Idaho has Type II waste (12 measurements). The highest G-value found for Type II waste was 1.33. This was for a metal waste stream. The panel felt that the population distribution for Type II waste is too small to make a determination. Therefore, they decided to assign Type II based on Type III (Type II = 0.5 times Type III).

The results for waste Type II have been plotted in Figure 4 and fit with a lognormal distribution with a mean value of .15 and a standard deviation of .18. Note that the curve in Figure D-4 looks like a cumulative distribution function for a normal distribution because the x-axis is logarithmic. The probability mass function (on a logarithmic scale) is shown in Figure D-5. Figure D-6 shows the representative percentile values that will be used for the decision tree. Three states will be modeled: 1) a state with a G-value for waste Type II of 0.05 and a probability of 25%, 2) a state with a G-value for waste Type II of 0.15 and a probability of 50%, and 3) a state with a G-value for waste Type II of 0.42 and a probability of 25%.

Table D- 2. Matrix Depletion - Path 2

Waste Type I		Waste Type II		Waste Type III	
Probability	G-value (molecules/100 eV)	Probability	G-value (molecules/100 eV)	Probability	G-value (molecules/100 eV)
1	1.3*	0	0	0	0
		.01	.004	.01	.008
		.33	.088	.33	.176
		.5	.165	.5	.329
		.67	.202	.67	.403
		.99	.09	.99	1.6
		1	2.05	1	4.1

*Free water is not controlled, therefore, matrix depletion is not expected to affect Waste Type I

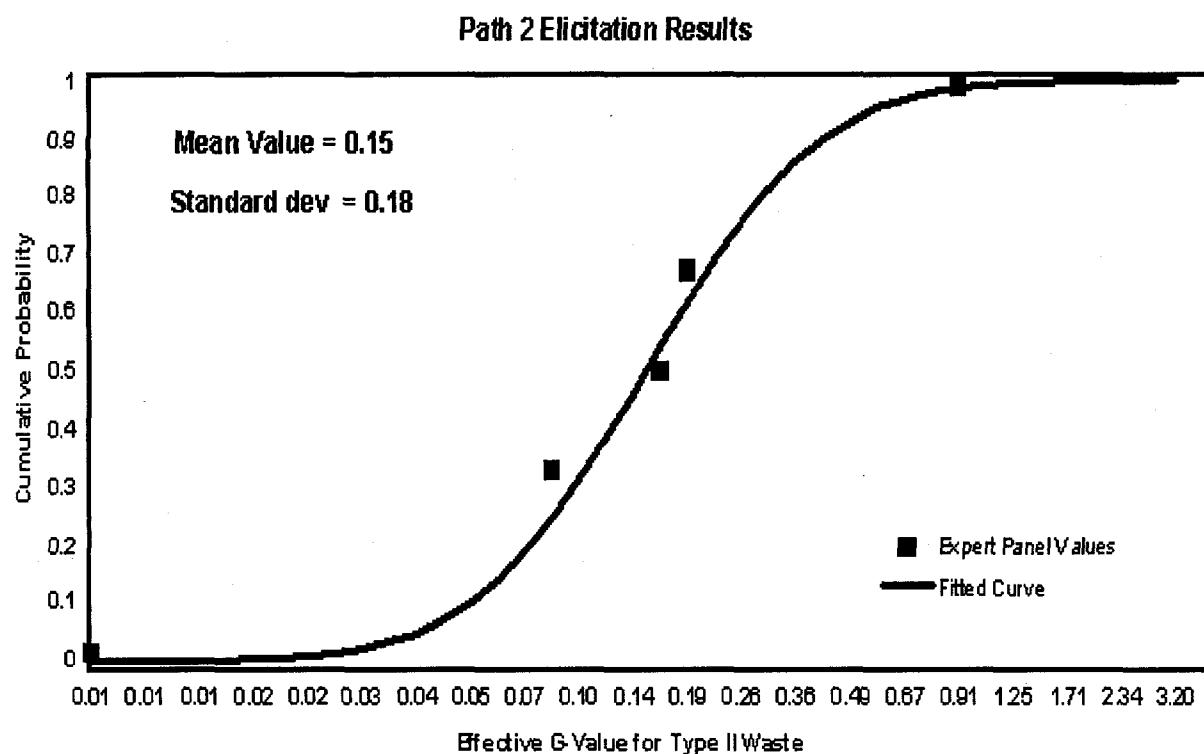


Figure D- 4. Cumulative Probability Distribution for Type II Waste G-Value

Figure D- 5. Probability Mass Function for Type II Waste G-Value

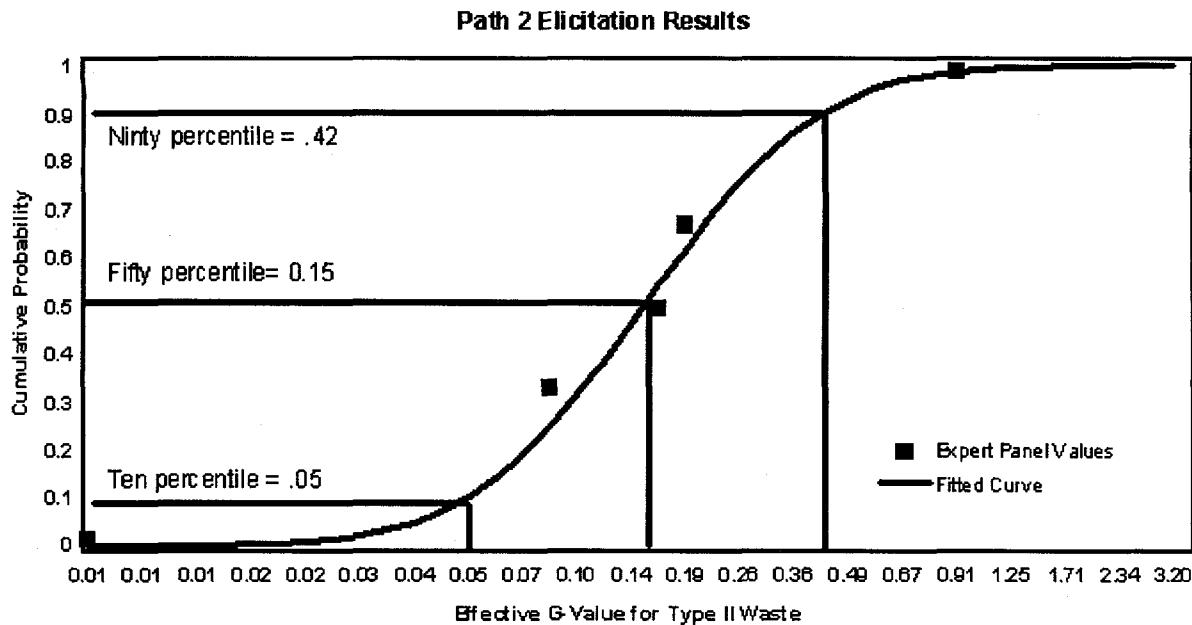


Figure D- 6. Representative Percentile Values for the Decision Tree

The results for waste Type III have been plotted in Figure D-7 and fit with a lognormal distribution with a mean value of .30 and a standard deviation of .49. Note that the curve in Figure D-7 looks like a cumulative distribution function for a normal distribution because the x-axis is logarithmic. The probability mass function (on a logarithmic scale) is shown in Figure D-8. Figure D-9 shows the representative percentile values that will be used for the decision tree. Three states will be modeled: 1) a state with a G-value for waste Type III of 0.13 and a probability of 25%, 2) a state with a G-value for waste Type III of 0.30 and a probability of 50%, and 3) a state with a G-value for waste Type III of 0.75 and a probability of 25%.

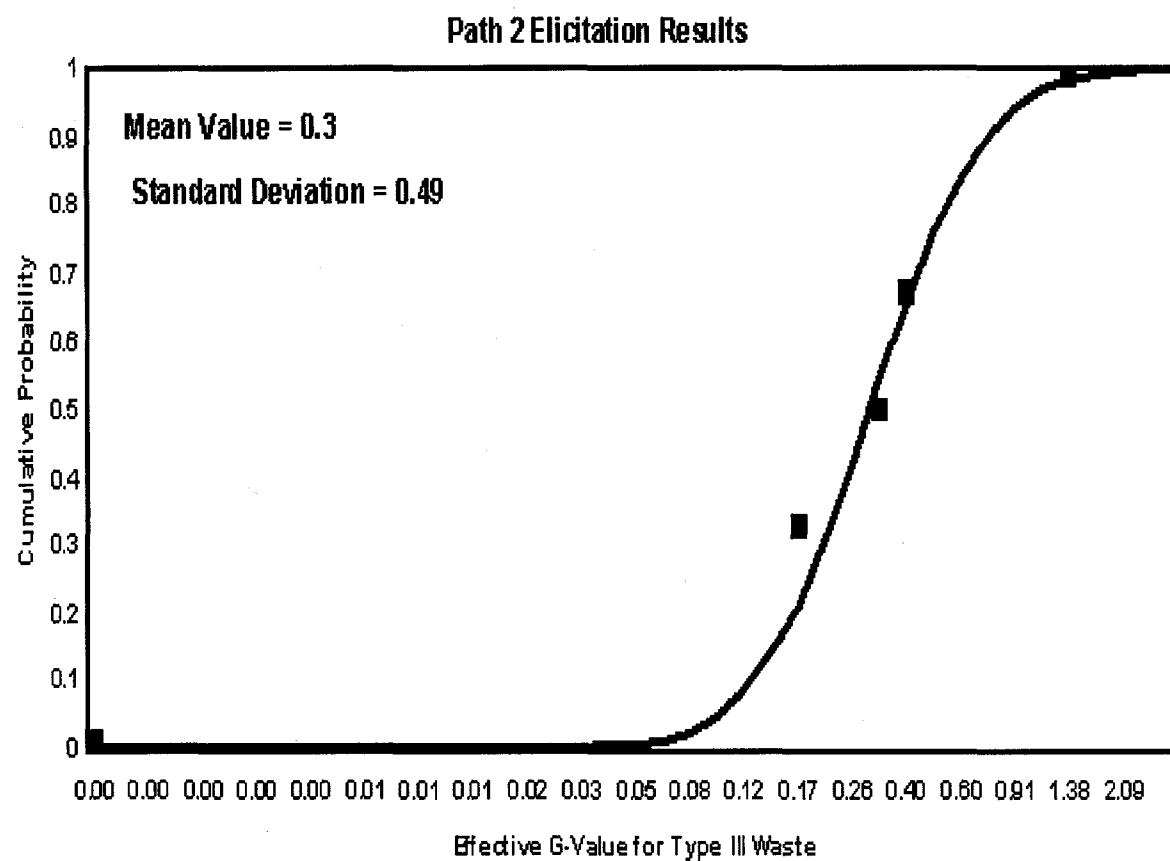


Figure D- 7. Cumulative Probability Distribution for Type III Waste G-Value

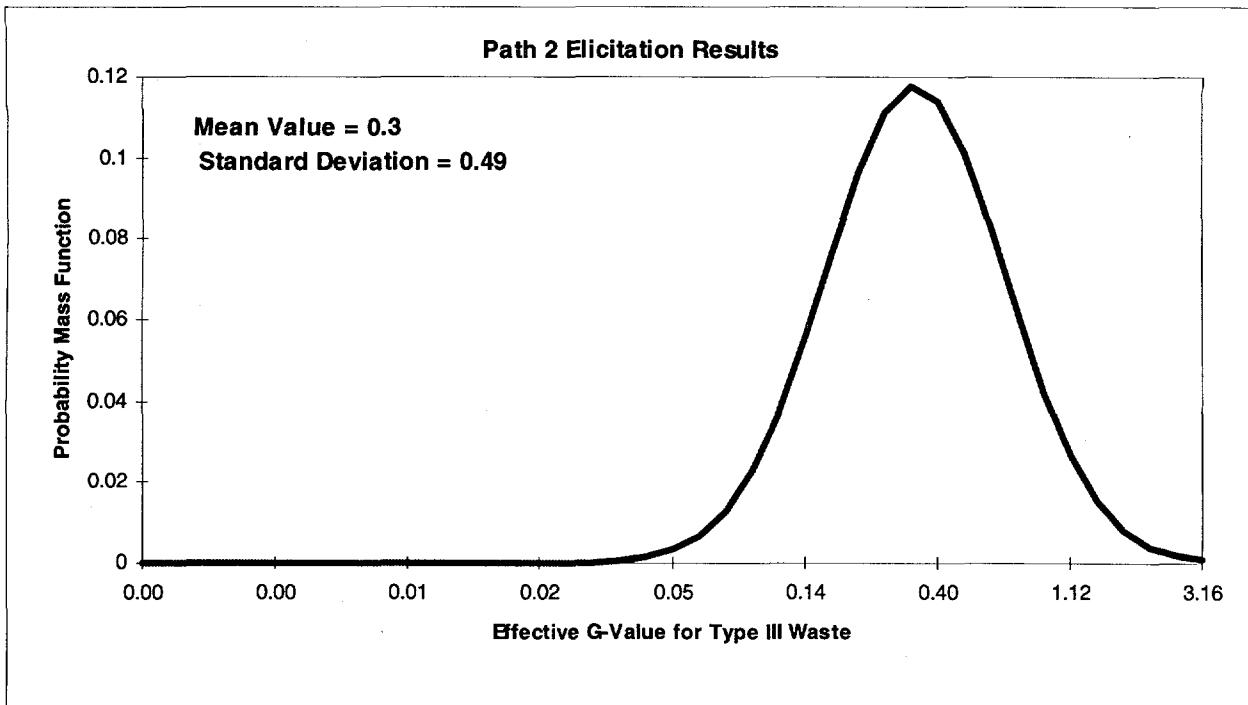


Figure D- 8. Probability Mass Function for Type III Waste G-Value

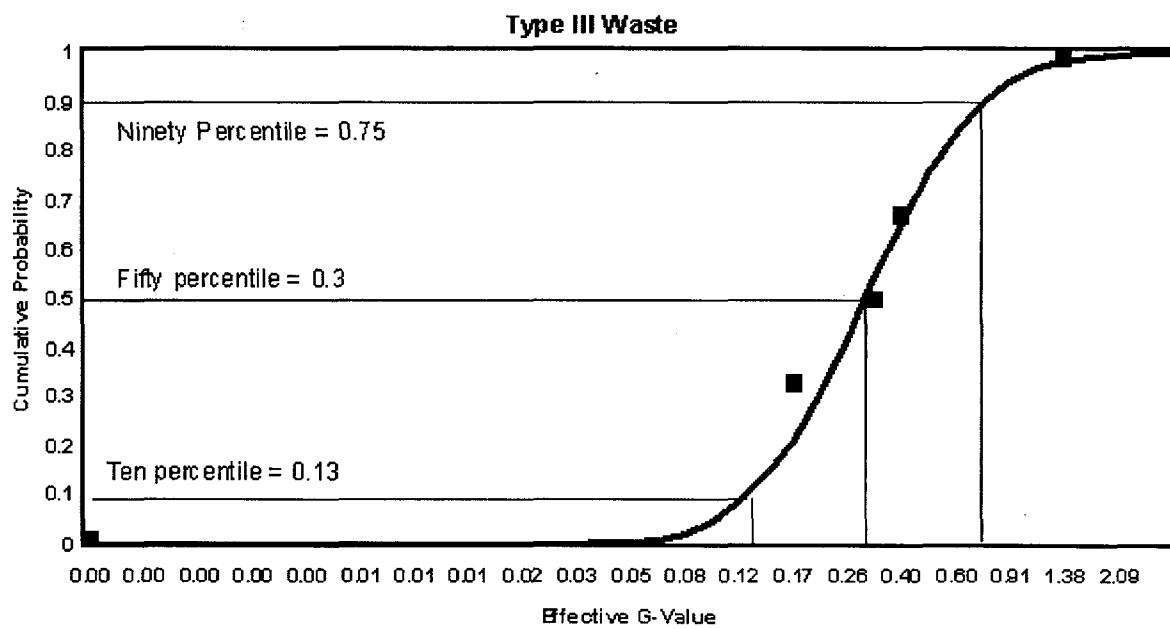


Figure D- 9. Representative Percentile Values for the Decision Tree

D-5. TEST INDIVIDUAL DRUMS FOR HYDROGEN IN THE HEADSPACE

The use of headspace gas sample results to certify containers for shipping was the elicitation topic on Wednesday March 18, 1998 starting at 8:00 AM. Dave Lechel began with a presentation of background information for the experts. The background material included a review of the decision analysis task, a discussion of the role of expert judgment, and a review of uncertainty, probability, and elicitation concepts. Doug Berry, Gerry O'Leary, Bruce LeBrun and Chuck Edinborough formed the expert panel for this session.

The following issues were discussed in relation to the background information presented:

Once the background material was covered, Christi Leigh began a discussion of Path 3. The path was defined as:

The DOE has demonstrated that the hydrogen gas concentration in the headspace of the drum is related mathematically to the hydrogen gas concentration in the innermost layer of confinement. If the NRC approves the use of headspace gas sample results to certify containers for shipping to WIPP, sampled containers that show less than 5 percent hydrogen gas concentration in the innermost layer (back calculated from the headspace sampling results) will be shipped to WIPP in the TRUPACT-II without treatment or repackaging. The remaining Pu-238 waste is either treated or repackaged and shipped to WIPP in the TRUPACT-II.

The elicitation variable was defined as:

expected distribution of steady-state headspace hydrogen gas concentrations by waste type.

The following issues were discussed in relation to the path description and the elicitation variable definition:

1. What's the difference between the matrix depletion path and the drum testing path? The underlying values are the same (generation rate).
2. Dave Lechel noted that G-values from matrix depletion are bounding values, where drum testing looks at the individual drums. Distribution may be the same, similar but shifted, or different. The decision analysis team has not thought seriously about the issue.

Once the elicitation variable was agreed upon, each of the panel members was given the opportunity to describe headspace gas sample results for drums at their site. Doug Berry lead the discussion with information from SRS. SRS tested 14 Pu-238 TRU waste drums (from a culvert) in the late 1980s. They monitored the drums for hydrogen concentration versus time. They also monitored Pu-239 TRU waste drums that were packaged in the early 1980s. These drums were not vented (either liner or lid). They were a mix of low level waste and TRU waste. SRS used a device to insert a filter and simultaneously measure the concentration of gases in the headspace.

They tested about 4,000 drums in this category. All of the drums were the same age. When questioned further about the drums that were sampled, he mentioned the following:

1. There was no noticeable pressure buildup in any of the drums (i.e., bulging or distended drums).
2. SRS did not measure the void volume.
3. The drums were from two covered storage pads.

10% of the drums from the first storage pad were over the 5% limit in the innermost bag (based on the headspace concentration). This was about 3,500 drums. 66% of the drums from the second storage pad had greater than 5% hydrogen in the innermost bag based on the headspace hydrogen concentration. This was about 400 drums. The highest hydrogen concentration values found were between 40 and 60%.

They also found a small number of drums which exceeded the limits for volatile organic compounds. Doug noted that this may be due to the presence of aerosol cans in some of the drums. He also noted that all of the drums had less than 0.5 curies. He noted that the assay was very difficult and the original assay may not be accurate. The drums did, however, contain weapons grade plutonium (Pu-239).

Doug did not know the distribution between low level waste and TRU waste for these drums. SRS will not know until the drums are re-assayed. He thought that there was a generally high percentage of low level waste because of the history (generation location) of drums stored on those waste pads. Also, the storage condition (e.g., water) was not completely known.

With regard to the drums showing very high hydrogen concentrations, there was speculation among the panel regarding the mechanism for production of the hydrogen. Most agreed that it had to come from a chemical reaction (like corrosion), not from radiolysis.

Bruce LeBrun talked about the headspace hydrogen sample results they have from LANL drums. They did a study to confirm the computer model used to estimate hydrogen in the drums. They tested 90 Pu-238 TRU waste drums. 50 of the drums were newly generated and sampled within the first two weeks at TA 55. They sampled 38 to 40 Waste Type II and III drums. These drums were vented and only a couple of years old. They found hydrogen concentrations between 0 and 1%.

LANL has tested 3,000 drums of Pu-239 (weapons grade) TRU waste. These drums were about 20 years old. Most of these drums had less than 1% hydrogen in the headspace. The few that had greater than 5% were mostly waste Type I. Waste Type I is cemented waste and could contain water. The results also show the result of galvanic corrosion, not so much radiolysis.

Gerry O'Leary presented information about hydrogen concentrations in RFETS drums. They tested 450 drums, mostly of Waste Type III and some II. All were of the age criteria for WIPP and met the packaging criteria for WIPP (rigid liner vented). All of them had less than five

grams Pu-239. The drums were from the late 1970s. Analysis of Gerry's results showed no correlation between hydrogen concentration and wattage.

RFETS also tested 600 drums of residues which are TRU waste. They had both vented and unvented drums in their population. They had all three waste types (Types I, II, and III). The samples were taken from the headspace and within the rigid liner (unvented). There was no difference between the two sampling routines. Again there was no correlation between hydrogen concentration and the wattage for vented drums. One major observation was that the hydrogen concentration in unvented drums is much greater than the hydrogen concentration in vented drums. This is to be expected.

Christi Leigh showed Gerry an analysis of his data that she had performed. She plotted the frequency of occurrence versus the hydrogen concentration for Type I, Type II, and Type III waste drums. Each of the mass density functions looked lognormal. The mass density function for Type III waste had the largest standard deviation, followed by Type I and Type II wastes. This made intuitive sense to the panel since higher hydrogen concentrations are expected for Type III, then Type II, then Type I wastes. For unvented drums, the distributions look uniform. This is an indication that the measurements are close to the detection limit for the population of vented drums at RFETS.

Chuck Edinborough noted that INEEL has sampled over 1,000 unvented drums and they did not see many drums (2 or 3) over the limit. INEEL did not measure wattage on very many of the drums they sampled.

After this discussion of the hydrogen sample results available to the panel, there was a discussion of the background questions. The panel developed a set of working assumptions for the elicitation. The background discussion is summarized as follows:

1. **Layers of confinement:** The panel noted that at SRS there are many layers of confinement (usually five layers). Also, SRS has all Type III waste. The RFETS waste is similar to the LANL waste but with fewer layers of confinement (four to six layers sealed in older drums for all Waste Types). However, the panel agreed that the layers of confinement should have no effect on the measured hydrogen concentration in the headspace at steady state. It will, however, affect the hydrogen concentration in the innermost layer of confinement and will be reflected in our calculations.
2. **Age of the waste:** Gerry O'Leary noted that RFETS saw no difference in the hydrogen concentration between the early 90s and the 80s waste. Doug Berry mentioned that since the measurement is at steady state there should be no difference. The panel wondered if matrix depletion was changing the steady state concentration over time. Gene Mroz from LANL (who was observing that day) noted that the hydrogen generation rate seems to be constant after an initial drop, which takes place in weeks to months.
3. **Waste type:** The panel agreed that the waste type would make a difference.
4. **Isotopic mix:** The panel agreed that the amount of Pu-238 would make a difference

5. **Particle size effects:** The panel decided that smaller particles would accelerate generation rate, but there would be compensating effects.
6. **Other mechanisms for hydrogen generation:** The panel concluded that corrosion of low carbon steel produces hydrogen. Doug Berry also noted there is corrosion due to the presence of aerosol cans. The panel thought that corrosion of the drum and liner is significant only in a very small percentage of the waste. In these cases, volatile organic compounds react with water to produce hydrogen chloride, which corrodes the drums. It was mentioned that in the SARP the only viable mechanism of hydrogen generation is radiolysis. Other sources of hydrogen may artificially elevate the headspace concentration, giving high estimates of the concentration in the innermost bag. So the question was discussed of whether the panel wanted to unbias the experimental data by subtracting out other sources for hydrogen generation. The answer was no.

D-5.1 WORKING ASSUMPTIONS

1. Layers of confinement do not affect headspace hydrogen concentration at steady state.
2. Age does not affect headspace hydrogen concentration at steady state.
3. All drum filters have the same diffusivity characteristic (within the accuracy of this elicitation).
4. Pu-238 TRU waste will exhibit higher wattage, higher hydrogen generation rates, and higher headspace hydrogen concentration.
5. The standard minimum diffusivity characteristic of the drum filter will be used for the drum diffusivity.
6. All sources of hydrogen will be considered.

D-5.2 HEADSPACE HYDROGEN CONCENTRATION ELICITATION

The first elicitation was for the shape of the distribution of hydrogen sample values in Pu-238 TRU waste drums. Based on the following arguments, the panel agreed on a lognormal distribution.

1. SRS has observed that the watt values for their drums are normally distributed. This is because the operating procedures at SRS have produced very similar waste and packaging. SRS believes that hydrogen concentration and wattage are correlated. However, because many of the hydrogen concentration values fall near the detection limit of the equipment being used, the shape of the hydrogen concentration distribution is lognormal.
2. At LANL they have measured 90 Pu-238 TRU waste drums with fairly high wattage and their distribution looks lognormal.

Once the distribution was decided, the panel was queried (individually) about the maximum, minimum, median, and intermediate values for the mean and standard deviation for a distribution of hydrogen in Pu-238 TRU waste drums. When the panel was reassembled and results were compared, there was a large discrepancy in the results. The panel worked effectively to understand and resolve their differences. The consensus cumulative probability values are shown in Figure D-10. A curve has been fitted to the consensus values. The fitted curve does not,

however, represent any standard distribution, it is just a curve fitted to the data points. From the curve, the ten, fifty, and ninety percentile values were inferred. These are shown in Figure D-11.

Once the 10, 50, and 90 percentile values were determined, Christi plotted lognormal curves using these values for the mean. She then varied the standard deviation and discussed the results with the panel. By exploring the outlying points of each curve, the panel decided on the three lognormal curves shown in Figure D-12. The three states that will be used in the decision tree are:

1. a lognormal distribution of hydrogen concentration in Pu-238 drums with a mean of 0.075 and a standard deviation of 0.5. This state will be given a probability of 25%.
2. a lognormal distribution of hydrogen concentration in Pu-238 drums with a mean of 0.3 and a standard deviation of 0.5. This state will be given a probability of 50%.
3. a lognormal distribution of hydrogen concentration in Pu-238 drums with a mean of 0.75 and a standard deviation of 0.5. This state will be given a probability of 25%.

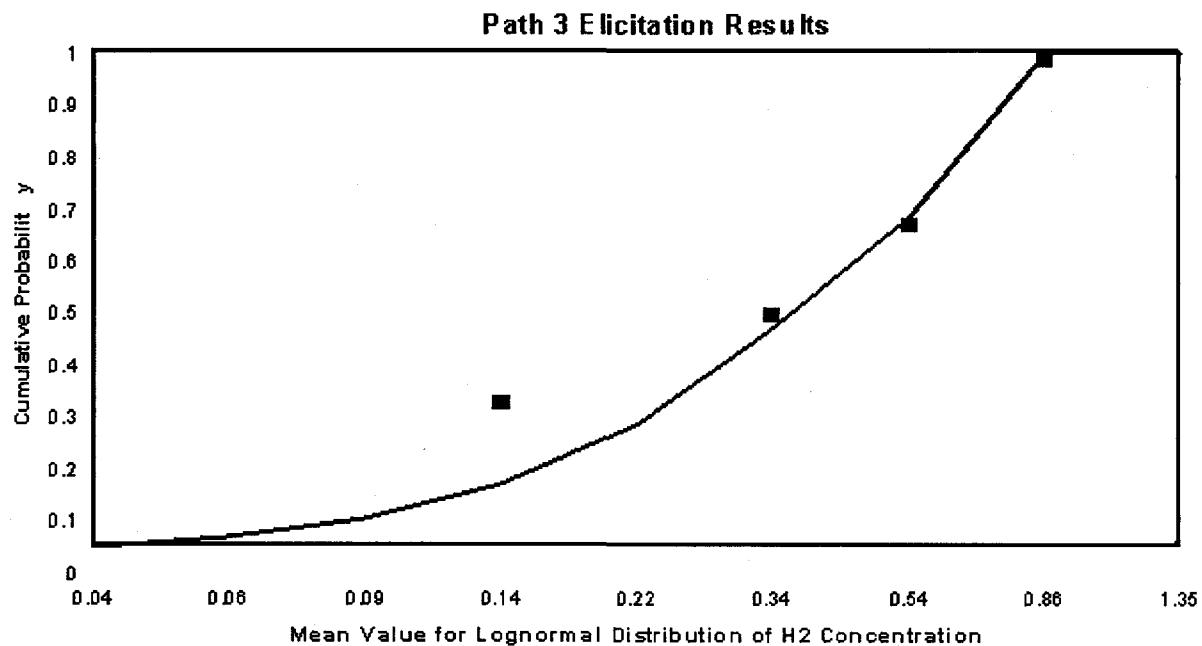


Figure D- 10. Distribution of Mean Values

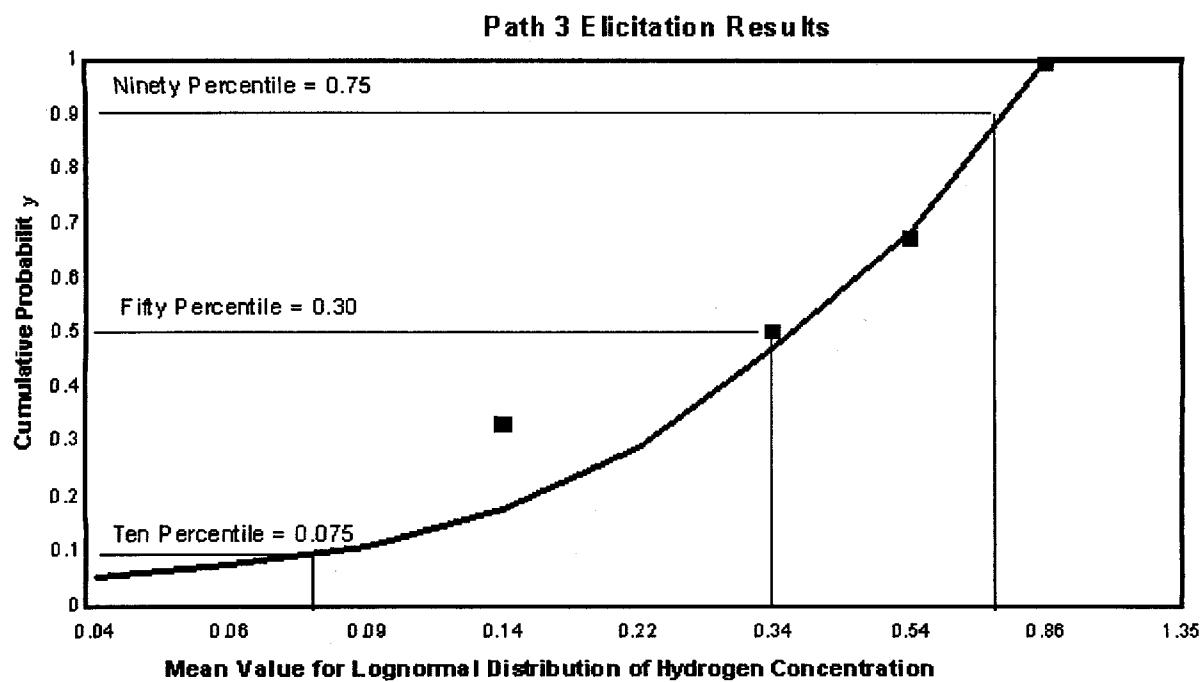


Figure D- 11. Representative Percentiles of Mean Values for the Decision Tree

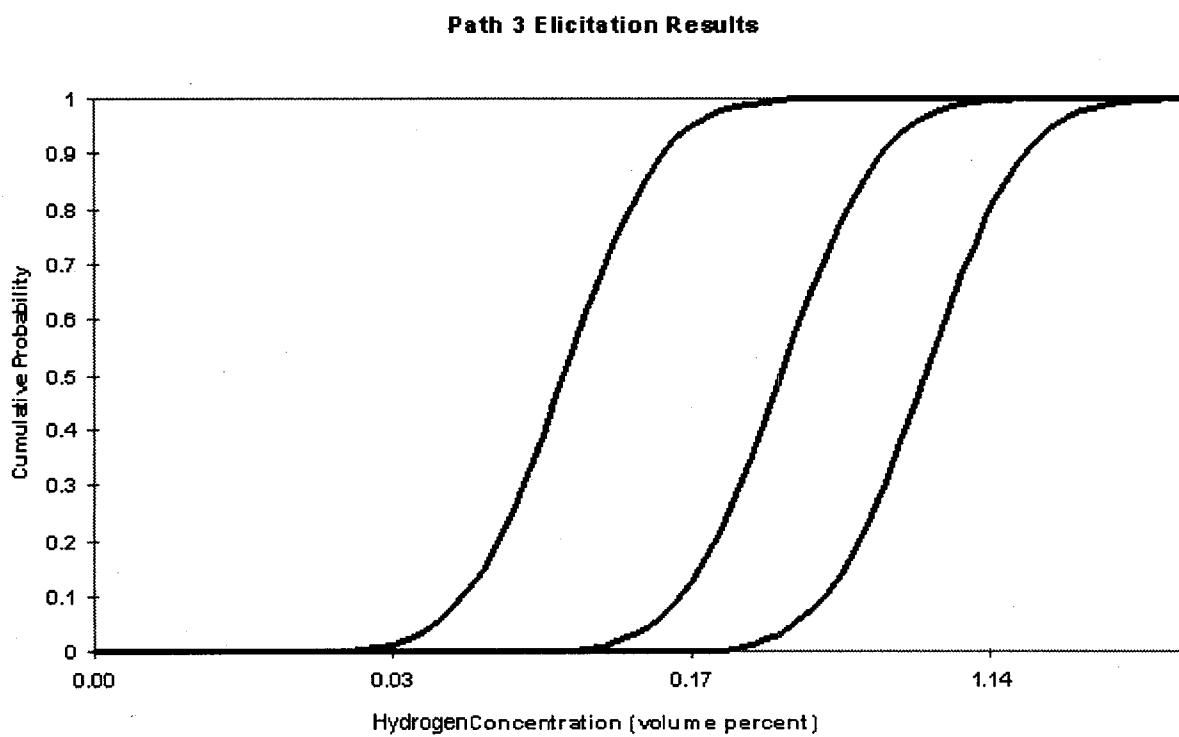


Figure D- 12. Representative Distributions for the Decision Tree

D-6. NRC Approval

The likelihood that the NRC would approve changes to the TRUPACT-II Certificate of Compliance based on the results of studies was the elicitation topic on Thursday, March 19 starting at 8 AM. The expert panel was made up of Murthy Devarakonda, Marrilyn Warrent, and Ruth Weiner. Dave Lechel began with a presentation of background information for the experts. The background material included a review of the decision analysis task, a discussion of the role of expert judgment, and a review of uncertainty, probability, and elicitation concepts.

The following issues were discussed in relation to the background information presented:

1. Marrilyn Warrent asked why the decision analysis did not include a path for testing of the hydrogen concentration while shipping or after shipping. Mike Brown noted that the inner layer of confinement is the issue (for hydrogen buildup) so drum behavior was looked at. Dave Lechel pointed out that very little of the Pu-238 TRU waste can be shipped under the current wattage limits. Therefore, testing of drums during or after transport may not yield much information. Mike Brown suggested that the Mixcat Program, under which drums from different shipping categories could be shipped together, may address some of these issues. He said that it may be worthwhile to consider adding the MixCat Program to the decision analysis. Murthy Devarakonda explained that Revision 17 of the TRUPACT-II Certificate of Compliance added a new waste type that was a combination of Types II and III for RFETS waste from incineration that had up to 5% organics. Dave Lechel said that possible changes to the decision analysis would be reviewed.
2. Murthy Devarakonda clarified the method used to classify waste into categories based on the layers of confinement. The number of layers of confinement is derived from knowledge of the packaging procedures. Classifications from larger facilities with more established packaging procedures will be more accurate. Some drums are opened and the layers are counted. Real-time radiography may also show a different number of layers. If real-time radiography shows a larger number of layers of confinement, the category is adjusted. If real-time radiography shows a lower number of layers, the category remains unchanged. The Environmental Protection Agency (EPA) has accepted an estimate of 93% accuracy in the sites' estimated number of layers of confinement.
3. Murthy Devarakonda also clarified the definition of recombiner versus getter. A recombiner acts as a catalyst for the reaction of hydrogen and oxygen to form water. Getters react with hydrogen to remove it from the atmosphere. Getters do not require oxygen. The addition of recombiners was not made a condition for shipping the test category waste because of concern that the DOE had not thoroughly investigated their use. The primary area of concern was that the recombiner would skew the measurement of the generation rate downward because hydrogen was being reacted. Once oxygen had been depleted in the drum, the amount of hydrogen would build up to exceed the 5% limit because of generation of hydrogen at the actual generation rate.
4. The addition of the requirement for a filter on the pipe overpack was discussed. The panel believed the NRC to be primarily concerned with criticality. In general, the NRC seems to be more concerned with criticality than with the potential for reaching explosive concentrations of hydrogen gas. For example, there is a 2-times error factor added for calculations of

criticality and only a 1-times error factor added for calculations involving the concentration of hydrogen (wattage limits).

5. Christi Leigh clarified the definitions of "highly effective," "moderately effective," and "minimally effective" on the decision tree. The terms refer to the amount of waste that might be shippable under the option. The terms are relative and may be very close together.
6. Christi Leigh clarified the distinction between the matrix depletion experiments path and the existing method for determining whether "Test Category" waste can be shipped. The matrix depletion experiments will result in a new set of G-values for categories of waste, whereas, the certification of Test Category waste involves testing of individual drums. Not all waste would be shippable with testing of every drum or new G-values. Christi Leigh also clarified the difference between the "Drum Testing" path on the decision tree and testing of the Test Category waste under the existing procedure. The existing procedure requires taking multiple samples over a 35-to-40-day period. The Drum Testing path requires only one sample. A well-established model relates the headspace gas concentration to the gas generation rate. The model was developed by Sinisia Djordevic (Benchmark Inc.) and has been used by Kevin Liekhus (INEEL) to model volatile organic compounds.
7. Ruth Weiner suggested that "NRC uncertainty" be changed to "NRC approves or does not approve test method" on the decision tree.

Murthy Devarakonda gave a presentation on "Revisions to the TRUPACT-II Safety Analysis Report and Certificate of Compliance." Christi Leigh facilitated a discussion of general issues that would affect NRC decisions. The following issues were identified:

1. How do you know that the scenario will work the way you say it will and that nothing will go wrong?
2. The NRC will look very closely at technical arguments.
3. The NRC is unfamiliar with "chemistry" as opposed to "mechanical" issues. However, they can be convinced by good experimental and technical arguments.
4. The NRC can understand statistical concepts/probability arguments.
5. The NRC is not comfortable with operator or administrative controls.
6. NRC decisions are very conservative; they are risk adverse.

Christi Leigh facilitated the discussion of the probability of NRC approval for the studies in each path. The following issues and assumptions were identified.

D-6.1 ASSUMPTIONS - All Paths

The probability of NRC approval will not depend on the technical success of the proposed change. However, the DOE will not propose changes unless experiments have shown that an improvement can be made in the amount of waste shippable.

D-6.2 ISSUES AND ASSUMPTIONS: Path 1

D-6.2.1 Issues

1. Hydrogen can escape from the drum even with getter (i.e., the hydrogen may bypass the getter).
2. How will the DOE ensure that the getter will still be effective when the drum is shipped?
3. There is a risk of high occupational dose required to repackaging with getters.

Discussion - The DOE has shown that repackaging can be done with little exposure. In addition, if this scenario were not implemented, the waste would have to be repackaged with a larger volume expansion factor. Reduction of the volume expansion factor should reduce exposure.

4. Poisons will be an issue.

Discussion - The NRC's confidence that the DOE has addressed this issue will be lower. The NRC will question the statement that "poisons will be neutralized."

5. The NRC will feel that the system is complicated and may not believe that laboratory experiments are representative of the "actual" system.

Discussion - Ruth Weiner said that she does not agree with this statement. She believes that the NRC will accept experimental data as long as the applicability of the experiments and quality of the data are high.

6. The expected volume expansion factors for various repackaging scenarios were discussed (see Table D-3).

Table D- 3. Expected Volume Expansion Factors for Various Repackaging Scenarios

Scenario	Volume Expansion Factor
repackage waste without filters	150
repackage waste with filters	15.6
repackage waste with filters and getters	1.56?

D-6.2.2 Assumptions

1. The system can be engineered so that the hydrogen must contact the getter material.
2. A management/administrative procedure could be implemented that would ensure that drums would be shipped immediately after getter was added.

D-6.3 ISSUES AND ASSUMPTIONS - Path 2

D-6.3.1 Issues

1. The DOE may not be able to show that matrix depletion occurs.

D-6.3.2 Assumptions

1. The DOE will only petition the NRC for changes in the Certificate of Compliance if it believes that the proposal is technically supportable.

D-6.4 ISSUES AND ASSUMPTIONS- Path 3

D-6.4.1 Issues

1. The NRC will require proof that the drums have reached steady state. Would taking the sample disturb the equilibrium of the drums?

Discussion - Taking the sample from the drum headspace would not disturb the equilibrium because the drums would be at steady state.

2. The NRC will require some validation of the model/data on actual waste.

Discussion - The model used to calculate the relationship between the headspace concentration and the inner bag concentration is the already-approved SARP model.

3. An upper bound is needed for the drum filters because higher diffusivity causes an underestimate of the concentration of hydrogen in the inner bags.

D-6.4.2 Assumptions

1. An upper bound will be developed for the diffusivity of the drum filter and gasket prior to the NRC application.

D-6.5 ISSUES AND ASSUMPTIONS - Path 4

D-6.5.1 Issues

1. The ICV is a large space; how will the DOE show that the hydrogen will reach the getter material?

Discussion - A cavity was designed into the ICV to hold recombiners. The hydrogen getter material would be placed in the same cavity. It has been shown that there will be no stratification of hydrogen within the ICV.

D-6.5.2 Assumptions

No specific assumptions were identified for this path.

D-6.6 ISSUES AND ASSUMPTIONS - Path 5

D-6.6.1 Issues

1. Darlene Steward clarified the definition of advanced filters. Advanced filters are filters that exist but have not been approved by the NRC. The filters may require further testing or development.

Discussion - Murthy Devarakonda pointed out that improved filters have been approved by the NRC in the past. Filters have been approved for non-sludge waste.

2. The NRC may review positive and negative aspects of repackaging.

Discussion - Repackaging is favorable because more will be learned about the waste. The downside of repackaging will be that the occupational exposure will be increased.

3. Will integrity of the package be compromised?

4. How will DOE ensure that the filters will always be used?
5. None of the probabilities will depend on the technical success.

D-6.6.2 Assumptions

No specific assumptions were identified for this path

D-6.7 QUALITATIVE ASSESSMENT - ALL PATHS

It was decided that the elicitation would be accomplished more effectively if the group discussed the probabilities rather than each person completing the evaluation individually. A matrix of the decisions (e.g., NRC approves the use of getters in drums) was developed (see Table D-4).

Table D- 4. Qualitative Ranking of Paths [The ranking is from 1 (best) to 5 (worst)]

PATH	1- Getters in Drums	2 - Hydrogen Generation	3 - Drum Testing	4 - Getters in the ICV	5 - Advanced Filters
Overall Assessment I					
MW	2	5	4	1	3
RW	1	5	2	3	4
MD	5	2	4	3	1
Overall Assessment II					
MW	5	4	3	2	1
RW	3	5	4	2	1
MD	5	3	4	2	1
Strength of Technical Argument					
MW	5	4	2	3	1
RW	2	5	4	3	1
MD	5 ^a	3	4	2	1
Implementation					
MW	4	2	5	3	1
RW	2	4	5	1	3
MD	4	3	5	1	2
Change in Conservatism					
MW	4	5	2	3	1
RW	3	5	4	2	1
MD	5	4	3	2	1
Vulnerability					
MW	5	4	3	2	1
RW	3 ^b	5	1	4	2
MD	5 ^c	4	3	2	1 ^d
Probability of Yes Answer					
MW	20%	30%	70%	75%	90%
RW ^{e,f}	50%	25%	60%	75%	80%
MD ^g	10%	60%	40%	70%	95%

Notes:

- a) This is the only thing that the NRC has rejected
- b) Getters have been used in other applications. Getters are a technically impressive concept, and performance is impressive.
- c) Vulnerable to poisons
- d) The NRC did not ask about implementation of filters, "what if" scenarios were not extensively questioned, but would tend to improve performance (e.g., tear in bag).
- e) Based on assumption that DOE will not go to the NRC with something that they do not believe will work
- f) Based on feeling that the NRC is not very consistent (MD - have gone repeatedly to the NRC with filters, got the same answer every time), both think that "its almost a sure thing"
- g) NRC rejected recombiners, but new filters were approved. Percentages are based on experience with the NRC.

Key:

Participants:

MW - Marilyn Warrent

RW - Ruth Weiner

MD - Murthy Devarakonda

Definitions:

Implementation - How will the DOE ensure that the change is implemented correctly in the field?

Weighing of benefit derived from repackaging will be assessed under Implementation rather than Technical Argument

Vulnerability - How do you know it will work the way you say it will, and nothing will go wrong (1 is least vulnerable).

Change in Conservatism - Each path requires NRC to relax its conservative stance. Which path represents the least change in the NCR's position?

D-7. REFERENCES

DOE (Department of Energy), 1997. *Safety Analysis Report for the TRUPACT-II Shipping Package*, Revision 17, March 1998, Carlsbad, NM.

D-8. ADDENDUM - Expert Panel Members

Douglas Berry

Affiliation:

Westinghouse Savannah River Company

Education:

B.S., Electrical Engineering, Michigan State University, 1990

Technical Experience:

Four years experience in TRU waste characterization

Four years experience in chemical processing of plutonium

Michael J. Connolly

Affiliation:

Lockheed Martin Idaho Technologies Company, Idaho National Engineering and Environmental Laboratory Idaho Falls, ID

Education:

BS Chemistry, Salem State College, May 1977

Ph.D. Analytical Chemistry, Montana State University, June 1985

Technical Experience:

Ten years in TRU waste management focusing on technology needs identification and associated solution development. Ten years in development and application of mass spectrometric techniques in support of organic compound identification and analysis. Techniques included atmospheric pressure ionization mass spectrometry (MS), liquid chromatography MS, MS-MS using triple quadrupole, high resolution gas chromatography (GC)-MS, fast atom bombardment MS, and static secondary ion MS. Five years experience in development and application of ultra-high vacuum based surface spectroscopy techniques to electronic materials. Techniques included Auger spectroscopy, X-ray photoelectron spectroscopy, ultraviolet photoelectron spectroscopy, high resolution electron energy loss spectroscopy, and secondary ion MS.

Michael J. Connolly (continued)

Pu-238 Decision Analysis Expertise:

Responsible for initiating and providing overall technical leadership for technology development projects addressing TRUPACT-II flammable gas (Hydrogen and volatile organic compounds [VOCs]). These projects included: using a combination of simulated waste, real waste studies and modeling to demonstrate that drum headspace VOC concentrations are representative of inner layers of confinement concentrations; using explicit flammability measurements coupled with modeling to demonstrate it is possible to predict the flammability limit of mixtures of VOCs; and using a combination of simulated and real waste studies and modeling to determine alpha radiolysis gas generation of potential of waste materials.

Murthy Devarakonda

Affiliation:

International Technology (IT) Corporation

Education:

Ph.D., Environmental Engineering (Department of Civil Engineering), University of Notre Dame, 1988
B. Tech, Chemical Engineering, Indian Institute of Technology, Madras, India, 1984

Technical Experience:

Ten years experience in radioactive waste management, transportation of TRU wastes, safety analysis in compliance with NRC regulations, TRU waste characterization and certification

Pu-238 Decision Analysis Area of Expertise:

Packaging Alternatives, TRUPACT-II, NRC Decisions.

Sinisia M. Djordjevic

Affiliation:

DJINDECO Consulting

Education:

M.ChE., Chemical Engineering, Illinois Institute of Technology 1986
B. S., Chemical Engineering, Northwestern University, 1984

Sinisia M. Djordjevic (continued)

Technical Experience:

Mr. Djordjevic is a chemical engineer with over 11 years of unparalleled environmental management experience that encompasses all aspects of DOE waste management from waste generation through characterization, treatment, certification, transportation, disposal, and remediation. He has analyzed conventional, innovative, and emerging waste treatment technologies with respect to performance, feasibility, mass and energy balances, risks, and lifecycle cost estimates. He has performed numerous risk and performance assessments within the DOE system. Mr. Djordjevic conceptualized and is currently participating in the implementation of several National Transuranic Program Office and Mixed Waste Focus Area transportation initiatives including the TRUPACT-II Matrix Depletion Program; the Flammability Assessment Methodology; an Alternative Method of Certifying TRU Waste Containers; Hydrogen Gas Getters; Mixing of TRUPACT-II Shipping Categories Program; RH TRU Waste Canister Sampling; and, Development of a Unified Flammable Gas Testing Procedure. He was a principal author of the TRUPACT-II and 72-B Cask Safety Analysis Reports for Packaging.

Pu-238 Decision Analysis Area of Expertise:

Matrix Depletion
Hydrogen Getters in Drums
Hydrogen Getters in the ICV

D. Bruce LeBrun

Affiliation:

DOE -Los Alamos Area Office

Education:

B.S. Computing Science, University of New Mexico, 1994

Technical Experience:

Twenty-five years of relevant experience in the management of nuclear/non-nuclear facilities and TRU waste. While at Los Alamos National Laboratory, served on the PU238 Waste Hydrogen Generation Study Team.

Pu238 Decision analysis area of expertise:

Waste packaging,
Waste forms,
Hydrogen generation.

Eugene Mroz

Affiliation:

Los Alamos National Laboratory

Education:

PhD., Chemistry, University of Maryland, 1976

B. S., Chemistry, Rockhurst College, Kansas City, MO, 1969

Technical Experience:

20 years: radiochemistry, gas chromatography, analytical chemistry .

3 years: radiolytic hydrogen generation from waste materials, hydrogen gettering.

Pu-238 Decision Analysis Area of Expertise:

Hydrogen generation

Matrix depletion

Hydrogen getters

Gerald A. O'Leary

Affiliation:

Rocky Mountain Remediation Service (RMRS)

Education:

M. S. Environmental Policy and Management, University of Denver, 1995

B. Geology, Slippery Rock University of Pennsylvania, 1978

Technical Experience:

Seventeen years of experience in the management of waste operations at nuclear facilities. Currently responsible for management, operations, characterization, certification and transportation of Transuranic and Transuranic-mixed waste at the Rocky Flats Environmental Technology Site.

John Schierloh

Affiliation:

Los Alamos Technical Assistance (LATA) - Rocky Flats Environmental Technology Site

Education:

B. S. Mech Eng, University of Michigan, 1983

Licensed Professional Engineer, State of Colorado, 1995

Technical Experience:

Four years as Technical Lead and Project Manager for Gas Generation Testing at RFETS

Pu238 Decision Analysis Area of Expertise:

Research Hydrogen generation in actual wastes.

Marilyn M. Warrant

Affiliation:

Sandia National Laboratories

Education:

M. S., Operations Research/Systems Analysis, 1977

Ph. D., Physics, University of Florida, 1971

B. S., Physics, University of Florida, 1966

Technical Experience:

8 years experience in transportation systems for defense transuranic waste, with emphasis on contents description and gas generation from radiolysis and thermal degradation.

Pu-238 Decision Analysis Area of Expertise:

Gas generation in TRU waste

Ruth F. Weiner

Affiliation:

Sandia National Laboratories

Education:

Ph. D. Physical Chemistry, The Johns Hopkins University, 1962

M. S., Physics, University of Illinois, 1957

B. S., Physics, University of Illinois, 1956

Technical Experience:

31 years experience as tenured Professor of Chemistry and Environmental Chemistry (Western Washington University, University of Washington, Florida International University, Colorado Women's College), Congressional Science Fellow (1984), 9 years experience analyzing risks of radioactive materials management and transportation (Brookhaven National Lab, Center for Nuclear Waste Regulatory Analyses,

Environmental Evaluation Group of N. M., Sandia National Laboratories), 95 technical publications, four environmental engineering textbooks.

Pu-238 Decision Analysis Area of Expertise:

Two years with NRC support contractor for HLW repository (Center for Nuclear Waste Regulatory Analyses), 9 years experience analyzing risks of TRU waste transportation (Brookhaven National Lab, Center for Nuclear Waste Regulatory Analyses, Environmental Evaluation Group of N. M., Sandia National Laboratories).

APPENDIX E

1998 ANNUAL REPORT

GAS GENERATION PROGRAM

**Prepared for the Department of Energy
Carlsbad Area Office by
Westinghouse Waste Isolation Division**

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ACRONYM LIST

CAO	Carlsbad Area Office
CH	Contact-handled
DOE	Department of Energy
eV	electron volt
GGTP	Gas Generation Test Program
G-value	hydrogen generation rate due to radiolysis, molecules/100 eV
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
NRC	Nuclear Regulatory Commission
Pu	plutonium
RFETS	Rocky Flats Environmental Technology Site
SARP	<i>Safety Analysis Report for the TRUPACT-II Shipping Package</i>
TRU	transuranic
TRUCON	TRUPACT-II Content Codes document
TRUPACT-II	Transuranic Package Transporter- II
WID	Waste Isolation Division
WIPP	Waste Isolation Pilot Plant

**TRUPACT-II GAS GENERATION TEST PROGRAM
FISCAL YEAR-1998 ANNUAL REPORT
October 1, 1998**

E-1. PURPOSE

The primary purpose of this report is to describe the major accomplishments and activities of the Transuranic Package Transporter-II (TRUPACT-II) Gas Generation Test Program (GGTP) during fiscal year 1998. The report also discusses GGTP plans for fiscal year-1999.

E-2. SCOPE

The scope of the GGTP includes those activities required to prepare and submit applications to the U.S. Nuclear Regulatory Commission (NRC) for increased TRUPACT-II wattage limits. The GGTP participants (see Attachment 1) also provide peer review for other initiatives to expand the envelope of authorized contents that may be shipped in the TRUPACT-II.

E-3. BACKGROUND

The GGTP was initiated by the U.S. Department of Energy (DOE)-Carlsbad Area Office (CAO) in 1992 for the following two reasons: 1. Address the need to qualify test category payload containers for shipment, and 2. Accumulate data that could be used to support applications for Safety Analysis Report for the TRUPACT-II Shipping Package (SARP) amendments with higher wattage limits (See Reference No. 1). The GGTP is coordinated by Westinghouse, Waste Isolation Division, and includes participants from the DOE-CAO, DOE transuranic (TRU) waste generator/storage sites, and support subcontractors. Since 1992, GGTP participants have met nine times. Annual reports of GGTP activities have been published since 1994 (See Reference Nos. 2-5).

Individual payload containers (e.g., 55-gallon drums and standard waste boxes) may be qualified for shipment in the TRUPACT-II provided it can be demonstrated by analysis or test that there will not be a flammable gas concentration inside a sealed TRUPACT-II during transport.¹ Payload containers that are below a calculated wattage limit belong to the "*analytic category*"; payload containers that exceed the wattage limit belong to the "*test category*".² It is estimated that up to one-third of the contact-handled (CH)-TRU waste at the DOE sites falls into the test category. As currently approved by the NRC, test category

¹ As described in the TRUPACT-II SARP, a nonflammable gas mixture is defined as less than 5% hydrogen in the innermost layer of confinement during a maximum transport period of 60 days.

² The individual payload container wattage limits in the TRUPACT-II SARP, based on hydrogen gas generation concerns, are imposed by the NRC irrespective of the packaging, and are not a function of the TRUPACT-II design.

waste may qualify for transport in the TRUPACT-II only if the actual rate of gas generation is determined by testing. The plan for gas generation testing is described in the TRUPACT-II SARP, Appendix 1.3.7, Attachment 2.

E-4. FISCAL YEAR 1998 ACTIVITIES / ACCOMPLISHMENTS

- The annual meeting of the GGTP was held in Albuquerque, New Mexico, on July 29 and 30, 1998. The emphasis of the meeting was on the gas generation testing at the sites, the initiatives in progress to facilitate the shipment of test category wastes, and the path forward to bring these initiatives to completion in the form of TRUPACT-II SARP amendments. The major topics discussed at the meeting are as follows:
 - Status of the TRUPACT-II SARP
 - Status of the 72-B Cask SARP and the HalfPACT Program
 - Update of gas generation test programs at the sites
 - Status of the Pu-238 Decision Model
 - Status of the Matrix Depletion Program
 - Status of the Hydrogen Gas Getters Program
 - Development of the Unified Flammable Gas Test Procedure³
 - Development of a standard filter testing procedure.

Detailed minutes of the meeting were provided to the attendees and GGTP participants under a separate transmittal.

- A Payload Expansion Initiatives meeting was held on November 12, 1997, between GGTP members. The purpose of the meeting was to discuss and develop a strategy for converting the initiatives into a payload expansion plan that would result in SARP amendments. Based on the results of the meeting, the Payload Expansion Plan was prepared (See Reference No. 6). The plan provides a systematic path forward for expanding the TRUPACT-II payload envelope. The plan, transmitted to the CAO on December 17, 1997, describes the following elements:
 - An analysis of the problems associated with shipping CH-TRU wastes to the Waste Isolation Pilot Plant (WIPP)
 - A listing of potential solutions to each of the problems and a review of the status of activities to increase the TRUPACT-II payload envelope
 - An integrated plan to ensure that all of the TRU waste inventory is shippable and the WIPP pipeline is filled.

³ The Unified Flammable Gas Test Procedure is a systematic process of demonstrating that an individual drum does not contain a flammable gas mixture – before, during, or after transport. The procedure begins with analysis, progresses through headspace gas sampling, and ends with full-scale drum testing. At any step of the procedure, if the drum passes the analysis/test, the procedure may be terminated and the drum qualified for shipment. The procedure will be submitted to the U.S. Nuclear Regulatory Commission for review as part of the application for Revision 19 of the TRUPACT-II Safety Analysis Report for Packaging

- The DOE-CAO approved the Payload Expansion Plan and funded Baseline Change Request, CAO # 076, to implement the Payload Expansion Plan's recommendations. TRUPACT-II SARP Revision 18, consisting solely of TRUPACT-II Content Code (TRUCON) changes, and Revision 19, consisting mainly of initiatives to increase TRUPACT-II wattage limits, are under development. The planning sequence to expand the TRUPACT-II payload envelope as presented in the Payload Expansion Plan is provided in Attachment 2.
- GGTP members supported and participated in development of the Pu-238 decision model developed by Sandia National Laboratories. Specifically, GGTP members participated in Expert Elicitation panel meetings during the week of March 16, 1998, regarding gas generation rates and mechanisms and the probability of success with the NRC for SARP amendments incorporating specific paths. The report is scheduled for release, October 1998
- Implementation of the GGTP continued at Idaho National Engineering and Environmental Laboratory (INEEL) and Rocky Flats Environmental Technology Site (RFETS) with a total of 114 drums tested at INEEL and 117 drums tested at RFETS. All of these tests indicate hydrogen gas generation rates well below the predicted rates from the bounding G values in the SARP. A potential artifact of the INEEL test setup was also identified that incorrectly implied the total gas generation rates were being exceeded. Most of this gas is simply air cycling from the tested drum, a situation not related to the sealed TRUPACT-II during transport. Los Alamos National Laboratory (LANL) initiated plans for gas generation testing during fiscal year 1998. Details of these site programs are provided in the minutes of the annual meeting.
- The new shipping category notation (proposed in Revision 17 of the TRUPACT-II SARP) was extensively used to analyze improvements in decay heat limits by studying different packaging configurations that more accurately reflect site practices, including the use of more efficient filters.
- Specific guidance was issued to RFETS, INEEL, and other sites regarding the quality assurance requirements applicable to the gas generation testing.
- GGTP members also provided input to DOE at TRU Waste Steering Committee meetings and DOE briefings regarding the issue of gas generation and TRU waste shippability.
- GGTP members provided technical input to the Matrix Depletion Program,⁴ including status meetings, review of the final report, and the development of a "watt-year" criterion for taking credit for matrix depletion based on the loading and age of the waste.

⁴ Matrix depletion is a concept that assumes the matrix of organic or hydrogenous material surrounding a radioactive particle is depleted as energy is absorbed. As matrix depletion occurs, less hydrogen gas is generated from radiolysis.

- On May 28, 1998, and July 29, 1998, GGTP members supported DOE in meetings of the National Academy of Sciences WIPP Panel and provided input regarding gas generation related limits and the basis for these limits.
- A series of meetings was held between January 1998 and June 1998 to discuss the development of the Unified Flammable Gas Test Procedure. This procedure will clarify and finalize the strategy for the shipment of test category wastes while incorporating recent gas generation initiatives (flammability assessment methodology, alternate method based on headspace sampling, etc.). These meetings were attended by personnel from DOE sites conducting gas generation testing at LANL, RFETS, INEEL, Westinghouse Waste Isolation Division (WID), and support contractors. Proposed gas generation test setups at these sites were also evaluated at the meetings.

E-5. PLANNED ACTIVITIES

- Following the NRC approval of Revision 17 of the TRUPACT-II SARP (currently under review by the NRC), implement new shipping category notation and G-values at sites.
- Following the NRC approval of Revision 17 of the TRUPACT-II SARP, meet with the NRC to discuss payload expansion initiatives and plans for applications for Revisions 18 and 19.
- Submit application for Revision 18 of the TRUPACT-II SARP to the NRC (revised TRUCON codes only).
- Submit application for Revision 19 of the TRUPACT-II SARP to the NRC (completed gas generation initiatives plus additional TRUCON codes).
- Finalize a draft Quality Assurance Program Plan for the GGTP and incorporate recent quality assurance guidance provided to sites.
- Provide peer review of site-specific gas generation related programs, including resolution of issues with existing programs and implementation of the Unified Flammable Gas Test Procedure concepts.

E-6. SUMMARY / CONCLUSION

The TRUPACT-II GGTP responded to the concerns of the program participants by preparing and submitting a report to the DOE-CAO titled, *TRUPACT-II Payload Expansion Plan*. The plan detailed steps to ensure that TRUPACT-II wattage limits will not restrict the complex's ability to ship CH-TRU waste to the WIPP. Based on the recommendations in the report, the DOE-CAO provided the required funding. The plan is on schedule to prepare and submit applications to the NRC for increased TRUPACT-II wattage limits.

The GGTP program participants have become a valuable resource as a "peer review" team to support activities to expand the TRUPACT-II payload envelope.

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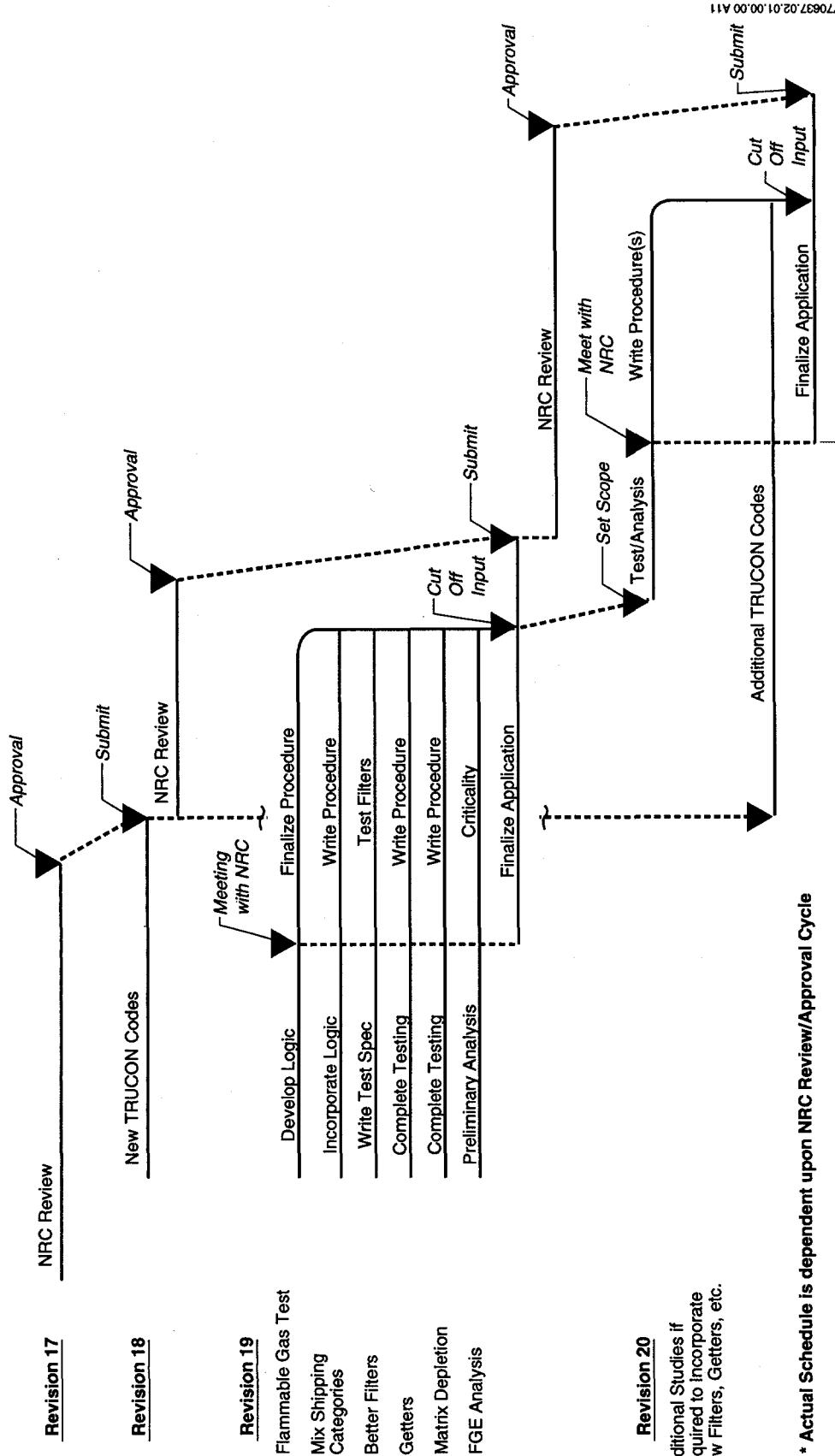
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ATTACHMENT 2
Planning Sequence to Expand TRUPACT-II Payload Envelope*



* Actual Schedule is dependent upon NRC Review/Approval Cycle

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