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Pacific Northwest National Laboratory

Operated by Battelle for the
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Prepared for the U.S. Department of Energy
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Overview

This report describes a disciplined, risk-based decision-making approach for determining characterization needs and resolving safety issues during the storage and remediation of radioactive waste stored in Hanford tanks. The strategy recommended uses interactive problem evaluation and decision analysis methods commonly used in industry to solve problems under conditions of uncertainty (i.e., lack of perfect knowledge). It acknowledges that problem resolution comes through both the application of high-quality science and human decisions based upon preferences and sometimes hard-to-compare choices. It recognizes that to firmly resolve a safety problem, the controlling waste characteristics and chemical phenomena must be measurable or estimated to an acceptable level of confidence tailored to the decision being made.

Critical interactive steps in the recommended strategy are to

- establish safety/risk resolution (and tank waste remediation) goals
- identify key waste characteristics, physical conditions, and chemical reactions that control problem(s) of interest
- assess problem using existing data and information
- evaluate uncertainty in data, model, and risk estimates
- compare cost/risk of alternative safety resolution, mitigation, or control options
- evaluate whether or not resolution goals are achieved
  - -- If goals are achieved, the problem is solved.
  - -- If goals are not achieved, perform new data collection or modeling to reduce uncertainty and/or implement new safety controls/mitigation measures.
- make decisions and take actions consistent with findings
- iterate process as needed.

Important attributes of the recommended strategy are that it

- keeps analyses and risk models as simple as the problem requires by matching problem solving methods (tools) and activities to problem resolution needs
- is risk based and recognizes uncertainty in knowledge of complex waste system characteristics and behavior
- uses only data/information of known quality to support decision making
- recognizes that understanding a problem and potential resolution actions is an evolving process
- uses expert knowledge and judgment independent of the U.S. Department of Energy for technical review.

In the recommended strategy, waste characterization is performed as an integrated activity inseparable from tank operation, safety resolution, or, waste remediation activities. In this setting, characterization actions can be justified as cost-saving measures to reduce or control risk.

This report is designed to develop an understanding of the recommended strategy and the role of specific methods (tools) by painting numerous pictures of the same landscape from different perspectives. Starting with the Overview and Executive Summary and continuing through the Introduction, the strategy and implementation tools are introduced and placed in context of the problems addressed. In Chapter 2.0, the strategy is presented as an iterative, step-by-step process to show how it can be implemented. Finally, Chapter 3.0 illustrates facets of the strategy by working out two examples of Hanford's tank safety problems: organics-oxidants and flammable gas. This intentionally repetitive approach was selected because of the necessity to address a broad range of readers who will each approach the document with different questions and perspectives. As a result, each chapter presents a nearly self-contained discussion or illustration of the recommended strategy—from different persepectives.

Executive Summary

The Hanford Tank Waste Characterization and Safety Issue Resolution Project has developed a technically based risk management strategy that addresses the role of and the need for characterization of wastes currently stored in the tanks at the U.S. Department of Energy's (DOE's) Hanford Site. To be technically justified, characterization must be an integral element of all tank waste management activities including interim storage, retrieval, treatment, disposal, and ultimately, final closure of the tanks. The technical justification for characterization is derived from a sound understanding of how new information will reduce the risks (i.e., health, technical, and program risks [including those associated with costs and schedule]) associated with waste storage and disposal. This report focuses mostly on safe interim storage of the waste, but the strategy is designed to be generally applicable to all waste disposal activities.

The safety issues explicitly considered in this report are

- criticality, the potential for a nuclear criticality leading to breach of the storage tank
- ferrocyanide, producing a potentially explosive fuel mixture
- organic liquids, a source of in-tank fires
- flammable gas, due to gases formed by thermal and radiolysis processes within the tanks
- organic-nitrate, due to organic materials commingled with nitrate and nitrite oxidizers in the tanks.

The distribution of these risks varies dramatically from tank to tank, depending upon what material was added over the lifetime of a particular tank and the operational history of that tank. For example, all tanks have the potential for organic-nitrate reactions, only 25 tanks are currently considered high flammable gas risks, 18 tanks are known to have received significant amounts of ferrocyanide (now, a non-safety issue), and the criticality risk is uniformly low.

The recommended strategy defines a disciplined, logical approach to solving Hanford waste safety and disposal issues. This strategy relies upon standard scientific methods by 1) assembling a team (called the Resolution Team) that is capable of solving the problem, 2) giving the team (or working with them to create) quantifiable measures of success (called desired outcomes) such as acceptable risk criteria, 3) using appropriate analysis capabilities (tools) to analyze the problem and develop defensible options for decisions, and 4) conducting independent (i.e., by an organization other than the DOE) technical reviews to assure the DOE and the public that an effective approach is being used to achieve real and pragmatic results. The importance of the problems associated with Hanford tank wastes demands the highest caliber effort in each of these steps.

The recommended strategy is designed to respond to this challenge by providing an approach based upon four principles: collecting only critical data, taking actions, learning while doing, and assuring technical competence and continuity in the work performed. The strategy also recognizes that problem resolution comes through the application of high-quality science and human decisions based upon preferences and sometimes hard-to-make choices.

Overall, the strategy's workflow includes the following four activities:

- The objective to be accomplished (i.e., resolve a safety issue) is identified, and the criteria for meeting the objective are defined.
- A Resolution Team conducts an initial analysis of the problem using existing information (i.e., the current understanding of the waste properties and the physics and chemistry that relate these properties to the problem at hand).
- If the initial analysis finds that the resolution criteria are met (globally for the issue at hand or on a tank-by-tank basis), the work is done.
- If the resolution criteria are not met, actions are taken in a series of iterative steps until problem analysis shows that the resolution criteria are met through achieving an improved understanding of the problem or by mitigation through changing tank waste conditions or adding operational controls.

The recommended strategy is characterized as being

- *outcome-focused.* It accelerates achievement of the waste storage and disposal outcomes by promoting actions on the waste and requiring characterization and other efforts to be justified by their quantitative effect on achieving specific waste remediation objectives (i.e., safe interim storage including waste stabilization actions, waste removal and processing, etc., leading to closure of each tank).
- *risk-based.* The success criteria are specified in terms of risk. This provides a risk basis for decisions about taking actions and the allocation of resources and requires acknowledgment of nonzero risk (i.e., accepting that there is always some risk) in making these decisions.
- *technically sound.* The implementation methods (problem analysis tools) provided are industry accepted and scientifically based. These tools are designed to be applied with a degree of rigor as required by the nature of the particular problem being addressed so as not to add undue complexity to a problem that might otherwise be solved simply.
- *economically justified.* Decisions about whether to undertake waste characterization efforts are based on the expected economic value of the new information in the context of risk reduction compared with the cost of acting in the absence of that information. When justified this way, characterization becomes a cost-saving investment. The strategy specifically evaluates the technical justification for characterization actions as well; i.e., whether they can successfully provide the information required.
- *fully integrated.* To evaluate the need for and value of individual characterization tasks requires understanding their effect on all related problems including each safety issue associated with safe interim storage and problems associated with waste disposal.

The complete understanding of complex chemical/physical waste systems is impossible and cannot be a prerequisite to taking actions. The knowledge base needed depends upon what problem is to be solved. What level of understanding is required for safe, effective actions? Answering this question requires predicting waste properties and waste/tank structural responses that have not been fully manifested; the major disruptive events of concern have not been observed. Thus, predictions of risk are based upon estimates of probabilities and consequences rather than extrapolations from experience. Tank waste is so compositionally varied and inhomogeneous that characterization with respect to each safety or remediation issue cannot be achieved by sampling and physical/chemical analysis alone. This situation calls for an iterative approach of modeling the controlling phenomena, acting to collect/generate critical information from a variety of sources as appropriate to obtain a better understanding of those phenomena, and then revising estimates of risk. A clear definition of problem closure for a particular action or issue (desired outcome) is required to avoid an endless model-characterize-model loop. The recommended strategy accomplishes this closure by using risk acceptance criteria to define "how safe is safe" and a technically defensible approach to determine when closure criteria are met. As this report shows, decisions about taking actions are strongly affected by the level of risk that is defined by decision makers as acceptable.

The strategy is to formulate a model(s) predicting the risk of a particular disruptive event, populate that model with current information, then evaluate the results to determine whether the results are sufficiently certain for taking actions (including not acting because an acceptable level of safety has been achieved) leading to resolution of the safety issue. To avoid making simple problems excessively complex, the process starts with simple models and existing information, becoming increasing detailed as the problem shows more complexity. The results at this preliminary stage in the analysis of the organic-nitrate safety issue in all 177 Hanford tanks are shown in Table S.1. These results are taken from Chapter 3.0. Each tank is classified as posing different levels of risk ranging from incredibly low (determined by the waste characteristics to meet any reasonable risk acceptance criteria) to high enough to require mitigative actions (e.g., waste mixing) on the waste contents. The question facing the Resolution Team is, what is the chance that a particular tank is incorrectly classified at this level of analysis? If the uncertainty is considered excessive, a characterization plan is devised to provide the information needed to reduce the level of uncertainty in this classification to acceptable levels. Then any required actions can be taken with confidence.

A full-scale test of this recommended strategy addressing the organic-nitrate safety issue in Hanford's 149 single-shell tanks was begun in December 1996 for completion and documentation in early 1997.

Table S.1. Results of First Iteration Calculation of Risk Classification For All Hanford Site Waste Tanks from an Organic-Nitrate Disruptive Event

Risk Classification	First Iteration Result	Recommended Options
Incredible (not possible)	57	Confirm, then no action
Risk acceptable (well resolved)	12	Confirm, then no action
Risk acceptable (close to requiring controls)	39	Confirm, then no action if risk is acceptable
Control initiators (well resolved)	62	Add controls <u>or</u> characterize
Control initiators (close to requiring mitigation)	4	Add controls <u>or</u> characterize
Mitigation required	3	Add moisture <u>or</u> characterize

The recommended strategy differs from existing practices at Hanford in several important ways. For example, the existing approach is more prescriptive (e.g., sample all tanks or collect some number of samples each year) than learning-based (e.g., make decisions about sampling based upon an evolving understanding of issues and phenomena). The existing strategy is not formally risk-based, uses problem analysis tools that are difficult to justify technically, provides no investment basis for determining when characterization work is complete for a specific need, and is not inherently and fully integrated. If the recommended strategy is adopted, the approach used will include the following:

- *Resolution Teams.* The teams responsible for developing a technical basis for problem resolution generally will be formed from permanent staff augmented by the best available experts in the nation. Furthermore, the teams will be managed to avoid any conflict of interest—currently, the operations contractor manages the justification *and* execution of the work. These teams will be supported by a Quality Review Committee and Review Panels.

- *Success criteria.* The recommended strategy proposes using risk and specific success criteria to guide decisions about work scope and priorities and to focus available resources on accomplishing specific waste storage and disposal outcomes. This approach is expected to provide more rapid progress in achieving waste storage and disposal objectives. Furthermore, in contrast to current practice, the recommended approach leads directly to the understanding of when characterization is complete and adequate to solve a particular problem. In addition, by specifying risk acceptance criteria, additional in-depth protection is afforded. For example, if the risk from small-scale unwanted events (e.g., an in-tank gas explosion that pops a high-efficiency particulate air [HEPA] filter without releasing waste) taking place has acceptably low probabilities and consequences, then larger-scale versions of the same event (e.g., collapse of tank dome from an in-tank gas explosion) are already covered in the simpler analysis.

- *Characterization plans.* The recommended strategy fully integrates justification of characterization work into the process of achieving specific outcomes. This can better ensure optimum use of limited characterization resources by making the end-use the driver for characterization work. Furthermore, the current Data Quality Objectives method for specifying waste characterization needs will be replaced with an industry-accepted method that is better suited for complex tank waste problems. The new method simultaneously provides the basis for computing risk and risk uncertainty, developing and evaluating alternative ways to solve a problem, screening and evaluating real/perceived problems, integrating across all drivers for characterization work, and justifying characterization work in terms of risk and cost reductions.

- *Understanding waste.* The requirement that characterization work be justified will replace the current approach that uses a prescribed waste sampling and analysis baseline. All sources of information (including existing information) will be considered in combination, lessening the demands for obtaining new data from sampling and analysis. Furthermore, characterization of waste while it is being acted upon (e.g., during waste removal or transfer actions) is recommended as an additional opportunity for obtaining new information.

- *Technical reviews.* Independent technical reviews will be used to assure the DOE and public of the technical soundness and viability of the work.

The statement of work for this project called for the development of a strategy with specific characteristics (shown below in bold italics and discussed in the following paragraphs).

The strategy will define the safety-related characterization requirements that can be met through the use of 1) models of targeted phenomena (i.e., disruptive events), 2) historical data on tank contents, 3) data acquired from tank waste sampling and analysis, 4) experimental studies using real waste and simulants, and 5) analysis of the impact of the proposed actions on reducing risks to the public and the Hanford workers.

The strategy will lead to the definition of the knowledge required to understand safety issues taking into account waste composition, configuration, and its controlling physical and chemical properties. The required knowledge will generally be derived from:

- ***historical and analytical data***
- ***predictive, mathematical models***
- ***experimental studies of targeted phenomena with real waste and simulants.***

The strategy will define a process that forms the basis for using risk assessment in making decisions concerning waste storage and processing. To the extent possible, risk assessment criteria will be developed for the existing waste tanks.

The prescribed models are contained in Structured Logic Diagrams that are discussed in general in the report and illustrated with simplified examples. Detailed descriptions are found in referenced documents. These diagrams create a basis for calculations of risks to the public and workers and what information is needed to establish the existence of those conditions. They guide the overall analysis and understanding of the problem. Preliminary Structured Logic Diagrams were developed for each of the previously identified Hanford tank safety issues and are contained in separate, referenced reports. This report also shows how Structured Logic Diagrams can be used to perform sensitivity, uncertainty, and value-of-information analyses to select the most appropriate source(s) of information or to choose actions to reduce risks. A separate report describes the factors leading to the establishment of risk assessment criteria.

The strategy will lead to the resolution of tank waste safety issues.

The recommended strategy, which is simplified and illustrated in Figure S.1, starts with the recognition that the criteria for defining safe storage or successfully achieving other outcomes must be established before any characterization program can be technically defined or defended. This leads naturally to an iterative series of modeling and characterization actions performed on a particular problem until that problem is well enough understood to know that the success criteria can be met. For safety issues, success criteria are generally met because 1) the nature of the waste meets the criteria (i.e., resolution through understanding), 2) the problems can be mitigated (i.e., change the nature of the waste), or 3) the systems and operational procedures needed to control the risks associated with the problem are known. For complex problems, the strategy develops Structured Logic Diagrams and decision analysis tools to support making risk-based and economically justified decisions based upon this understanding.

The strategy is fundamentally risk- and action-based when the resolution criteria are specified in terms of risk. The degree of complexity of the problem determines the depth and detail of analysis (i.e., the number of iterations and the extent to

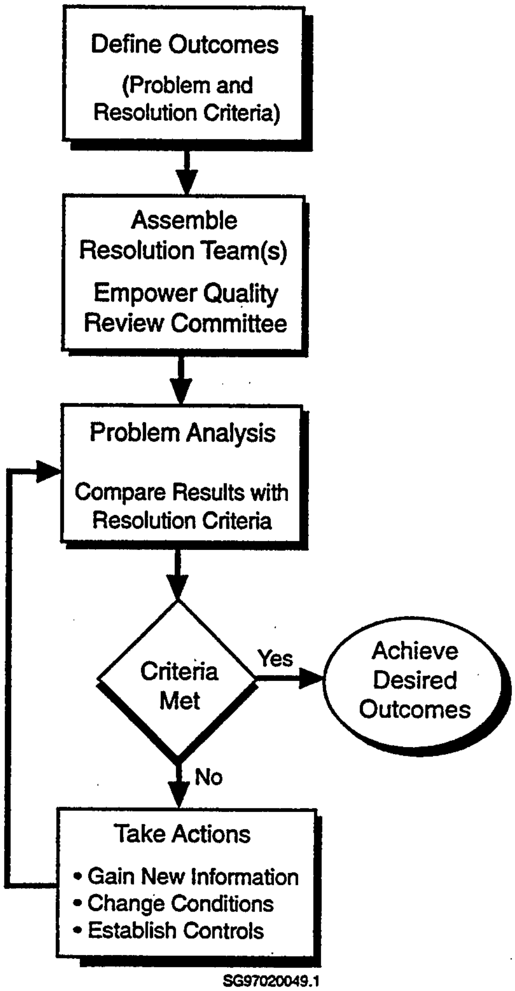

Figure S.1. Outline of the Recommended Strategy Showing Overall Features

which special tools are used in the problem analysis). Characterization work (i.e., gaining new information) becomes technically defensible by being intimately integrated into the process of problem resolution.

It is important, at the initial analysis stage, to identify features of the problem that will most sensitively affect the outcome. Predicting the probability and consequences of a disruptive event requires that a complex combination of numerous properties of the waste, of the tank itself, and of the pathways to exposure be determined. However, if particular waste properties can be identified that are controlling, there is potential for reducing risks to acceptable levels without completely knowing all related phenomena. For example, if the fuel driving an event of concern is found to be sufficiently low or diluted by unreactive material (e.g., water), the risk of that event can be determined to be acceptably low. Both the expected frequency and consequences become incredibly small. This creates an information hierarchy to guide characterization planning: information that can have the most profound effect upon decisions and actions is sought first. As the iterative analysis proceeds for persistent problems, the recommended strategy uses sensitivity analysis to identify the more important parameters. A formal value-of-information analysis is also used to determine whether obtaining particular information has sufficient value compared with the cost of obtaining that information or the costs of taking alternative routes to problem solution through mitigation or control steps. A safety issue is resolved (globally or for specific tanks) when it has been determined that the associated risk is sufficiently low, either because the existing tank contents are known to comply with this requirement or because mitigation or controlling actions have been taken to reduce the risk.

Table S.2 lists safety issues that were outstanding at the onset of this project, along with their controlling parameters (in italics).

Clearly, the understanding of each of these safety issues is at a different stage and will require different degrees of analyses to provide a defensible risk basis for their disposition.

The following three bold, italicized, statements were established at the beginning of this project in early 1996 as desired characteristics of the new strategy:

The strategy will not be an implementation plan detailing what samples are needed, how they are

Table S.2. Status of Outstanding Safety Issues Considered in This Report and Their Controlling Parameters

Safety Issue	Controlling Parameters and Conclusions
Criticality	*Amount of fissionable material, shape of the fissionable mass, and concentration of reaction moderators.* The conclusion in Appendix B that the risk of an in-tank criticality in Tank 102-SY is acceptably low was based primarily upon these considerations.
Ferrocyanide	Knowledge of the *amount, the rate, and mechanism for decomposition of such fuel* is leading those managing the waste at Hanford to the resolution of this potential concern. The DOE recently announced the closure of the ferrocyanide safety issue.
Organic liquids	*Amount and surface area of contiguous pools of flammable organic liquids, thermal reactive properties of the organic material, and oxygen available.* This remains an open issue.
Flammable gas	*Potential to store gas, potential to release significant bursts of gas, amount of stored gas, and the composition of stored gas.* For example, tanks with only solids or those with only liquids (no significant amounts of mixed phases) are expected to pass this test because they cannot store and release significant volumes of gas.
Organic-nitrate	*Amount of organic fuel, moisture content, rate and decomposition mechanism for degradation of organic constituents, spatial distribution of reactive material, and mechanism of reactions leading to rapid release of energy.* While many tanks show low risks in the preliminary analysis (described in Chapter 3.0), others are expected to require controls of reaction initiators and/or mitigation to increase moisture levels.

to be analyzed, etc. Rather, the strategy will identify requirements for additional knowledge and will lead to the definition of the requirements for additional data and the appropriate acquisition strategies or laboratory experiments (with real and/or simulated waste materials).

This requirement was met by execution of the step in the recommended strategy that requires information needs to be justified as to their need to support decisions about actions, their technical feasibility, their relative effect on risk reduction (revealed by sensitivity and uncertainty analyses), and their economical viability. Integration of the "needs justification step" across the range of storage and disposal needs adds further criteria for selection of characterization actions.

For example, when faced with the results in Table S.1, the Resolution Team will note that the uncertainty in the classification will be significantly reduced if it can be determined (by characterization actions) whether

- the organic materials in the waste have decayed to sufficiently low-energy species to no longer represent a source of significant energy
- the organic material is highly dispersed in the tank either by dissolution in the liquid phase or dispersion throughout the solids and sludges such that it cannot be ignited
- the energy and moisture content of the waste materials can be determined with sufficient

accuracy with respect to conservative threshold values that it's known that the organic material cannot be ignited.

The strategy will guide the analysis and interpretation of the data leading to actions required to mitigate safety concerns.

This work is performed by the Resolution Team during each iteration of the strategy until the problem at hand is resolved. Mitigation actions, if required, will be selected when they represent the least costly solution when compared with obtaining additional information or when the uncertainty in the understanding of the waste characteristics is known sufficiently well to determine that mitigation is the required action.

The strategy will be shown to evolve if necessary to meet the characterization needs of Operations, Waste Retrieval, Waste Pretreatment, Low Level Waste and High Level Waste.

The strategy is flexible to permit its use in solving a wide variety of tank problems. Examples of the application of the strategy to issues other than safe storage are provided in Appendix B of this report.

Acronyms

DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DOE-RL	U.S. Department of Energy-Richland Operations Office
DQO	Data Quality Objective
EDTA	ethylene diamine tetra-acetic acid
EPA	U.S. Environmental Protection Agency
GAO	Government Accounting Office
HEPA	high-efficiency particulate air (filter)
LANL	Los Alamos National Laboratory
NRC	Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
RSD	relative standard deviation
SLD	Structured Logic Diagram
STP	standard temperature and pressure
TOC	total organic carbon
WHC	Westinghouse Hanford Company

Contents

Figures

Tables

1.0 Introduction

This report presents a methodology for determining how much and what kind of characterization data are needed to resolve Hanford's tank safety problems. It describes attributes of a recommended strategy and gives examples of how the strategy can be used. It stresses the importance of articulating safety resolution goals, technically justifying data collection activities, and acknowledging uncertainties of knowledge and the methods/models used to support decision making. This report acknowledges that problem resolution comes through both the application of high-quality science and human decisions based upon preferences. It also recognizes that to resolve a safety problem, controlling waste characteristics, chemical phenomena, and risks must be measured or estimated to an acceptable level of confidence tailored to the decision being made.

The report is not an implementation plan. If the recommended strategy is adopted, additional effort will be required to develop and test such a plan. Neither, is this report a critique of the existing Hanford characterization or safety programs. Although the strategy was developed without constraints from past or present approaches, it took advantage of the best thinking that has taken place. Implementation would certainly build upon these advancements. Thus, those familiar with existing approaches will recognize some elements of the recommended strategy.

A test of this recommended strategy addressing the organic-nitrate safety issue in Hanford's 149 single-shell tanks was begun in December 1996 with completion and documentation planned for early 1997. The test uses existing data and models and will classify all single-shell tanks according to this element of their safety risk. It will also contain plans for characterization work needed to reduce uncertainties sufficiently to take corrective actions with confidence that they will be safe and cost-effective.

The report contains three chapters and five appendices. Additional details are found in references. This chapter sets the context. It provides introductory and background information, including why this study was undertaken, attributes of the recommended strategy, and the use of risk-assessment in decision-making. Finally, it defines frequently used terms. The recommended strategy is presented in Chapter 2.0. Two illustrations demonstrating the strategy are given in Chapter 3.0.

Appendix A is a copy of the U.S. Department of Energy (DOE)-Headquarters letter to the Pacific Northwest National Laboratory (PNNL) requesting development of an alternative characterization strategy to resolve Hanford's tank safety issues and to assist in the final disposition of those wastes. This report was developed in response to that request. Appendix B is a report from mostly outside (non-Hanford) experts called the *ab initio* team. They examined how to create a new scientifically based and practical approach to resolving tank waste characterization and safety issues "from the beginning" without considering whether it agreed with Hanford's present approach. Appendix C contains a summary of comments received about the recommended strategy from an international audience of researchers at a Gordon Research Conference on Nuclear Waste and Energy held in September 1996. Appendix D shows the location of all tanks and tank farms at the Hanford Site. Appendix E contains the resumes of this report's authors.

To accelerate the release, and therefore review, of this report, the *ab initio* team findings (see

Appendix B) and other referenced documents developed by this project have not undergone the same level of technical critique as the main report. (Although the referenced documents are available for review, some are identified as "unpublished." This means that they had not been completely edited at the time this report was published.)

Note: Text in ***bold italics*** within the report emphasizes key points.

1.1 Background

In December 1995, the DOE asked the PNNL to develop a technically sound and defensible approach (strategy) for waste characterization and resolution of safety issues associated with Hanford's underground tanks (see Appendix A). Specifically, the letter states that "DOE must develop a technically sound strategy that defines the actions leading to the transition of the Hanford Site tank wastes from the current state of significant uncertainty to a state of greatly reduced uncertainty. PNNL has been asked to create an alternative characterization component of that strategy. DOE expects to apply a modified characterization strategy to the resolution of the safety issues associated with the storage of the waste in tanks and to assist in the final disposition of the wastes." The request was driven by concerns raised in recent years within DOE and by non-Hanford organizations. For example:

> "DOE has not been able to develop a technically defensible strategy for efficiently characterizing the high-level waste tanks." (DNFSB 1995)

> "...to date no tank has yet been sufficiently characterized either to meet the Safety Board's [Defense Nuclear Facilities Safety Board] sampling requirements or to support any of the subsequent steps in the waste treatment process." (GAO 1996)

> "Information provided by the contractor through the Data Quality Objective (DQO) process has been insufficient to determine when a tank is fully characterized and the need for further sampling is no longer required. The root of this problem is a lack of adequate discipline in the definition of characterization needs and objectives, and the subsequent operations executed to accomplish those needs/objectives." (DOE-RL 1995)

Safe management and disposition of the 55 million gallons of radioactive waste stored in Hanford's 149 single-shell and 28 double-shell tanks (see Appendix D) is one of the greatest challenges facing the DOE. These wastes contain some 215 million curies of radioactivity and 240,000 tons of chemical residues created from three different chemical precipitation and solvent extraction processes used to separate plutonium from irradiated spent fuel from 1944 until the late 1980s (Gephart and Lundgren 1996). Before waste was pumped to underground carbon steel tanks, large volumes of sodium hydroxide were added to neutralize the acidic waste streams. This practice made the streams strongly alkaline and contributed to waste segregation (e.g., sludge formation and its separation from supernatant liquids). Subsequent operations used to 1) recover selected radioisotopes such as uranium, strontium, and cesium; 2) evaporate liquids; and 3) transfer wastes between tanks, as well as decades of radiolytic-induced decomposition and chemical reactions have added to the physical and chemical complexity of the waste mixtures now stored in many of the tanks. Some 67 single-shell tanks have also leaked 1 million gallons of waste into the underlying soil.

Chemical reactions and past waste management activities have created safety problems in Hanford's tanks. Most problems center on concerns about potential unwanted in-tank temperature or pressure rises that could result in the release of radionuclides. Key safety problems have included the presence of ferrocyanide, organic complexants (e.g., sodium acetate or ethylene diamine tetra-acetic acid (EDTA), organic solvents (e.g., methyl isobutyl ketone or tributyl phosphate), flammable gases (e.g., hydrogen, nitrous oxides, ammonia), high temperatures, and the potential for nuclear criticality. Public Law 101-510, Section 3137, commonly known as the Wyden Bill, requires DOE to identify and monitor Hanford tanks that require special safety precautions. **Hanford's tanks are slowly evolving chemical reactors rather than static waste storage vessels. Waste safety and characterization issues have changed and will continue to change over time** as the chemistry, chemical byproducts, and energetics of the waste evolve.

1.2 Overview of Recommended Strategy

The Hanford Tank Waste Characterization and Safety Issue Resolution Project was undertaken to address characterization and safety issues as DOE requested. This report describes an integrated set of processes that make up a recommended strategy for resolution of the tank waste characterization and safety issues. Resolution means that a problem is solved to an agreed-upon level of acceptance. **The recommended strategy is based on the use of an open, disciplined approach to problem-solving. It involves examining decision trade-offs that meet practical needs in the shortest possible time while factoring in institutional/ stakeholder values.**

The most pressing practical needs facing tank characterization and safety resolution that drive the recommended strategy are

- identifying the key waste characteristics, kinetics, and chemical phenomena controlling unwanted in-tank events (fires, explosions, etc.)
- assessing the probability and potential consequence(s) of such unwanted events taking place
- comparing the approaches and costs to resolve, mitigate, or control unacceptable or unknown risk.

In simple terms, the recommended strategy involves

- assembling expert teams without conflicts of interest to analyze an issue and solve the problem
- defining desired outcomes for resolving tank safety problems and providing this information to the team(s)
- outlining (diagraming) the problems and potential approaches for solving the problems
- analyzing and comparing the cost and risk of different approaches for problem solving
- collecting data, performing analyses, and conducting experiments to gain additional data if existing data are insufficient to solve the problem
- conducting periodic technical reviews of the work performed
- solving the safety issue.

In more detail, the recommended strategy, which is described in Chapter 2.0 and illustrated using examples in Chapter 3.0, is based on the recognition that **a set of desired outcomes must be established before safety issues can be fully closed (i.e., resolved).** Such outcomes define future end-states; that is, the point at which most everyone agrees that work has been satisfactorily completed. In our everyday lives, such end-states are achieved when we are "comfortable" with the outcome of an activity, whether it's making a purchase or building a house. From a sense of benefit gained from experience, we know when a task is done and it has been or will be worth the cost and effort spent.

For solving tank safety problems, scientifically based "comfort" levels must be achieved. For example, within the environmental cleanup industry, a one-in-a-million chance that an unwanted event will take place is commonly considered an acceptable risk (risk equals probability multiplied by consequence). Other risk levels could also be used if agreed upon by the parties affected. At other times, based upon the chemistry or physics controlling reactions one might calculate that it is impossible for some unwanted event to take place. Regardless of the approach taken, the technical, social, and regulatory resolution of complex problems such as Hanford waste storage tanks is seldom self-evident. Rather, resolution is achieved through an interactive process of data examination, data collection, analysis, and tradeoffs.

Resolution of Hanford's tank safety issues will involve actions that

- *resolve the problem*; for example, determining that the chemistry and physics of the waste precludes a certain undesirable event from taking place.

- *mitigate the problem*; for example, installing a mixer pump that allows flammable gases to be released continuously rather than episodically. Mitigation involves changing waste conditions to reduce the chance that an undesirable event will take place.

- *control the problem*; for example, installing forced ventilation on a tank or imposing strict operational controls for instrumentation inserted in the tank to reduce the risk that an undesirable event (such as an in-tank electrical spark occurring during release of a large volume of hydrogen) will take place.

The recommended strategy employs various methods (called tools) that are common to industry but have not been used at Hanford in the manner proposed. These methods are described in Chapter 2.0. They include: 1) structured logic techniques (i.e., diagraming and outlining) to assist in understanding the problem and visualizing solutions, and 2) decision analysis methods (e.g., risk assessment, uncertainty evaluation, sensitivity studies) for assessing the cost and risk of following one solution path versus another and the value of obtaining one type of characterization data over another. Characterization data have both scientific and economic value. Scientific value derives from our ability to use the data to solve critical unknowns such as the chemical energetics of a tank's waste. Economic value is gained from estimating the most cost-effective approach to resolving, mitigating, or controlling unwanted risks taking place within a tank.

Decision makers use this comparative information to make choices about which safety resolution approach is most acceptable. The logic process and methods used are dictated by the complexity of the problem. Some problems may be solved by examining existing data and applying scientific principles. Others may require more complex approaches.

If only a single approach (no options) existed for resolving tank waste issues, then decision making would be simplified. Only one path would lie between what exists today and what we seek for tomorrow. However, multiple approaches having unique costs, risks, and likely stakeholder preferences exist for achieving desired outcomes. This report proposes a process for identifying, comparing, and unifying (when justified) the merits of various solutions so that more informed and sound choices can be made. **The defensibility of this process or any other process followed depends on the technical expertise of the staff who perform it. Its effectiveness depends upon the commitment of decision makers to take actions, follow through on sustained commitments, and accept risk resulting from actions.**

Creating an approach to decision making that is too complex for the problem being addressed or that relies upon quantifying the unquantifiable must be avoided. It is possible, for example, for radiochemists to resolve concerns about a potential nuclear criticality event or ferrocyanide explosion taking place in a tank by using historical data from reprocessing plant operations, existing analytical data, and simple calculations. However, the organic complexant safety concern regarding the potential of a spontaneous or propagating chemical reaction is an example of a more complex technical issue that may require several cost and risk comparisons and tradeoffs before decision makers are comfortable with recommending one solution over another. Thus, decision makers must have the right methods (tools) to provide information tailored to the problem addressed.

Similarly, by specifying risk acceptance criteria, decision makers are given additional protection in depth. For example, if the risk from small-scale unwanted events (e.g., an in-tank gas explosion that pops a high-efficiency particulate air [HEPA] filter without releasing waste) taking place have acceptably low probabilities, then larger-scale versions of the same event (e.g., collapse of tank dome from an in-tank gas explosion) are even less probable. This approach can greatly simplify the use of risks in decision making by tailoring risk models to the degree of simplicity or complexity required.

The application of quantitative techniques for assessing and managing risk is common to our everyday lives and has benefited society for years. For example, the laws of probability underlie our confidence in the structural integrity of bridges/buildings, the health protection offered by vaccinations, and the advantage of having life insurance to protect one's family (Bernstein 1996a). Wise risk takers who make progress for themselves and others are those who weigh the potential benefit and liability of actions and then take action. The same is true for solving Hanford tank waste safety and disposal issues.

The potential adverse effects of carrying out a technically flawed strategy are significant. Under-estimated risks can lead to actions or waste release events that unnecessarily expose workers, the environment, or the public to radionuclides and hazardous materials. Over-estimated or ill-defined risks can unnecessarily constrain decision-making processes by avoiding actions that could lower risk or gain waste characterization data critical to understanding waste behavior under static (i.e., left undisturbed) or perturbed (e.g., pumped) conditions. Delays and increased costs resulting from improperly structured or poorly considered efforts can also erode public confidence and support. **"Informed risk taking" is the basis for achieving safe and cost-effective resolution of Hanford's tank waste characterization and interim storage problems.**

1.3 Conflict of Interest

The recommended strategy emphasizes the involvement of multidisciplinary, qualified scientific and technical issue Resolution Teams with expertise that spans chemistry, physics, and the technology embodied in problem solving (see Chapter 2.0)

Many talented experts already serve in various technical review capacities at Hanford. Some of these experts also serve on panels convened to conduct reviews similar to that proposed for the Resolution Team(s). However, these personnel are typically managed by and make recommendations to the same organizations responsible for conducting the work. **Thus, the same organization requesting reviews also accepts or rejects the very recommendations that could affect their business. This is a clear conflict of interest, making it difficult to implement changes, especially fundamental changes, in how an organization conducts its business.** This practice must change for DOE to receive the technical and programmatic quality needed to accomplish its waste management and cleanup mission successfully and for critical reviews to be effective.

1.4 What is New and Different? Outcome-Focused Versus Program-Based

The recommended outcome-focused strategy differs from a more traditional program-based approach in several ways. The most fundamental distinction centers on end objectives. For example, achieving final closure of a safety issue is a specified up-front objective of an outcome-focused strategy. Determining how to achieve such objectives is part of the work scope of those implementing an outcome-focused strategy. To achieve this goal, a total strategy (beginning to end) is built *before* waste characterization and other activities are undertaken. This strategy is a learning-based, iterative process where characterization approaches evolve to achieve specified end objectives. The program-based strategy presumes that the program managers can, at the onset, select a work scope that will ultimately achieve the desired waste safety outcome though that outcome is not quantified. Program-based strategies often result in undertaking activities without a clear definition of how those activities are integrated to achieve issue closure.

At Hanford, the planning, implementation, and oversight of the waste characterization and tank safety programs are carried out under multiple contractors making it even more difficult to define meaningful, integrated characterization and safety resolution program goals.

For resolving Hanford tank issues, using the existing program-based strategy is like building a house using only owner-drawn sketches that illustrate the general layout of portions of the house. Even if the sketch is prepared in consultation with the builder, the primary responsibility for success is placed on the owner, who created the plan. This limits the owner's ability to require the builder to deliver a quality product. In contrast, an outcome-focused approach recognizes that creating and keeping the blueprints updated for a complicated structure is a major, ongoing activity. The homeowner's role is to specify the desired outcomes, select a team that can act with confidence, and monitor progress. The design and construction activity requires an expert team of architects, engineers, builders, and inspectors working together in a disciplined, integrated process. This team remains engaged throughout the project to address and resolve unanticipated issues and problems that inevitably arise. Blueprints are essential for ordering the right construction materials, measuring progress, assembling the

parts in a logical sequence, and for knowing when the house is finished. The results must then be compared with the blueprints to gain final approval by the homeowner and acceptance by building inspectors. Based upon the complexity of the safety or waste remediation issue being addressed, nothing less should be expected of any approach to solve Hanford's tank problems.

Using existing information, as illustrated in Figure 1.1, the recommended outcome-focused strategy begins with an initial assessment based upon an objective defined by the desired level of risk not exceeding a specified or threshold value of risk.

Program-based strategies delineate activities to expand information (e.g., estimate the tank contents using studies of existing information, collect a certain number of samples per tank, or analyze for a specified set of chemical constituents) without gauging how that information affects achieving final risk reduction levels.

After objectives are defined in the outcome-focused strategy, a technical analysis is performed to

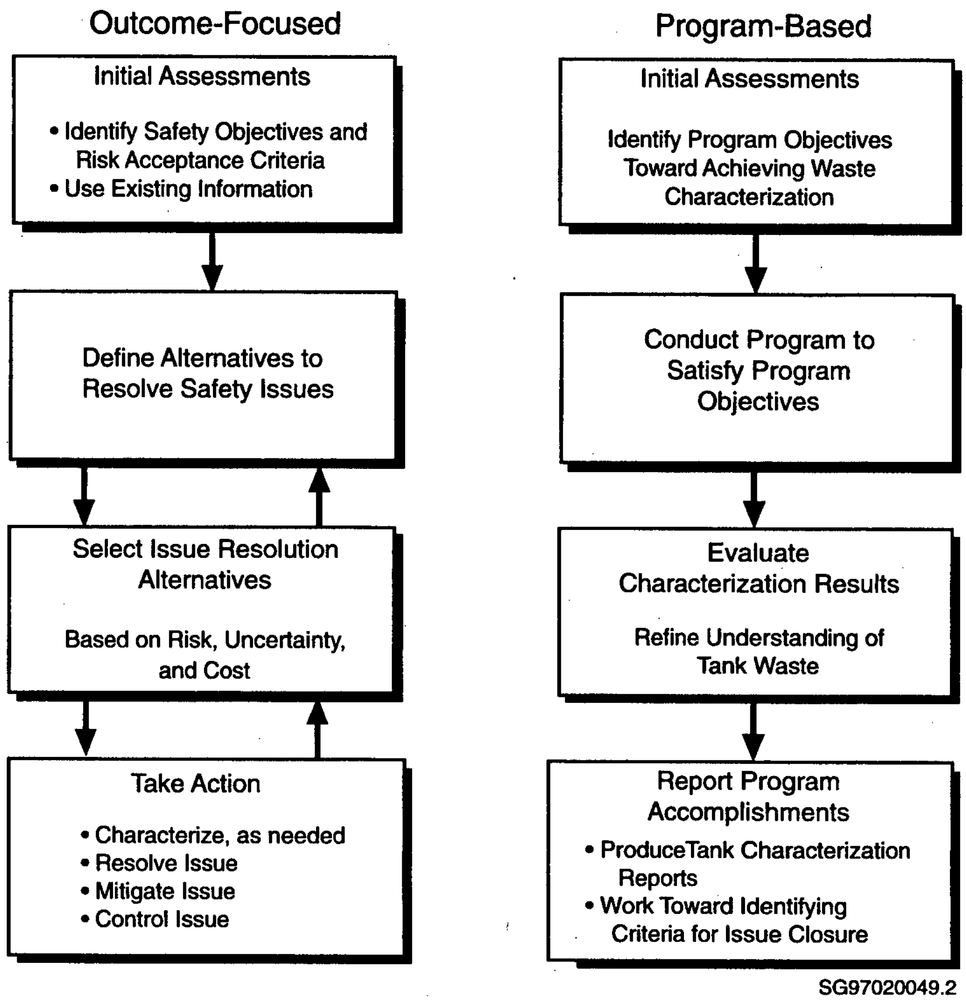

Figure 1.1. Outcome-Focused Strategy Versus Program-Based Strategy

provide alternative paths for achieving the objective and identifying information needs associated with each alternative. The risk uncertainty and cost in relationship to potential decisions are evaluated; then actions are taken to 1) obtain the data/ information known to reduce uncertainty, risk, and costs or 2) accomplish the stated objective (i.e., to resolve, mitigate, or control as appropriate for safety issues).

Program-based objectives are often based upon sampling and analysis. Typically, samples are collected and analyzed, reports are prepared, and the characterization program documents its success (x number of samples collected and analyzed over some time period). Such a program-based approach is demonstrated in the report *Flammable Gas Tank Safety Program: Data Requirements for Core Sample Analysis Developed Through the Data Quality Objectives Process* (Benar 1995):

> "This DQO document does not in itself provide for closure [of the flammable gas safety issue]... The product of this core sampling DQO is a list of data requirements. As an understanding is developed, it may be possible to specify decisions that can be made on the basis of core sampling results. Once this is done, this DQO document will be revised to incorporate the requisite decisions."

In many cases, program objectives are defined in terms of how much sampling must be performed to meet the real or perceived needs of the Tri-Party Agreement (Ecology, EPA, and DOE 1996), recommendations made by oversight committees, or organizational performance goals. **The activities undertaken to satisfy these multiple objectives are rarely integrated. Tying program-based objectives to end-disposal or safety objectives is sometimes implied but not always accomplished.**

The outcome-focused strategy develops a technical basis for using existing knowledge *first* and *then* decides whether or not specific additional information is required to reduce uncertainty in support of safety or disposal decisions. In addition, the recommended strategy does not assume a separate baseline program for waste sampling and analysis. **All sampling and analyses are performed within the context of knowing why specific characterization activities, integrated across multiple safety needs, are being undertaken.**

Finally, the product of the recommended outcome-focused approach is action on wastes based on existing or new justifiably obtained information. The final products of the program-based characterization strategy are commonly characterization data provided in reports and databases.

The program-based results may be matched to issues (questions asked in the case of DQOs), decisions, and actions but not within the framework of uncertainty reduction for the purpose of decision making for final issue resolution. The program-based strategy relies on the objectives definition being tied to safety issues and therefore for products (e.g., characterization reports) to be tied *in advance* to safety issues. Thus, the program-based approach relies heavily on the ability of the client and contractor program managers to determine characterization objectives that are technically sound and, if possible, how they are relevant to waste management objectives. The outcome-focused strategy places this responsibility on a Resolution Team whose success is measured by its ability to achieve specific waste management objectives. This approach leads to a strategy in which the characterization work is iterative and opportunistic and is justified by a detailed technical analysis of the problem to be solved. **Program-based schedules easily become organizationally**

driven schedules. Concerns about such organizational drivers were addressed by the National Research Council (1996.)

1.5 Attributes of a Successful Strategy

Whatever approach is used for resolving either near-term tank safety or longer-term waste remediation issues requires a clear understanding and acceptance of what resolution means. That understanding should then be incorporated into DOE's Authorization Basis for the management of tank farm operations. Frequently, achieving this understanding involves comparing risks, costs, and technologies. When safety resolution is not achieved through knowledge (understanding) of waste properties and conditions, then new mitigation or control technologies must be used.

For any strategy to work and be accepted, it must have the following attributes and benefits:

- **Its outcomes (objectives) and acceptance criteria must be clearly specified.**

  Without clearly defined objectives and acceptance criteria driving the resolution of safety issues, there is no basis for change from the status quo and little awareness of when problem resolution is achieved. As shown in Chapter 3.0, it is possible to perform decision analyses with respect to a set of risk acceptance criteria, allowing decision makers to understand the costs and technical challenges associated with achieving a given level of risk. In this way, the system can work toward the safest, affordable waste state.

- **It must be integrated.**

  The resolution of a single safety issue may not justify a given waste characterization activity. But when the advantages of that characterization step also address other safety issues (as well as other waste management needs), then the combination may be sufficient to justify collecting new data. Likewise, the efficient use of characterization actions (e.g., waste sampling) requires that as much information as possible be obtained from each such action. Thus, characterization needs and strategies must be integrated across all functions requiring information about the waste and its properties.

- **It must be technically driven and scientifically sound.**

  The technical basis for achieving desired outcomes must be documented with systematic analysis and justification supporting key conclusions. Analyses must describe how data were collected, information was processed/modeled, uncertainties were addressed, and conclusions were reached. Limitations should be documented and understood. The technical basis must be periodically reviewed by the technical community, especially those without vested interest, and adjusted, if justified, as data and information change. The frequency and extent of these reviews must be balanced against the opposing needs to ensure competence and to avoid undue interference with conducting work.

- **It must be action-oriented and practical.**

  The strategy must be capable of implementation within the constraints of the operational and regulatory environment governing tank farm activities. Similarly, the strategy must support the collection of critical information required for decision making and corrective actions. The goal is to take actions toward desired outcomes, not just study or monitor the waste.

- **It must be understandable.**

  Strategies developed with input from diverse stakeholder interests are an important element of the consensus-building process. A key aspect is to communicate information in a defensible, clear, and comprehensive manner to a wide range of audiences. However, there is no proven approach to creating this understanding and incorporating stakeholder concerns except in the most general manner.

- **It must be disciplined, flexible, and iterative.**

  The strategy must be rigorous, yet flexible enough to achieve the desired outcome with the least effort and use of resources. It must accommodate problems ranging from simple to complex. Because decision making is an ever-changing process, the strategy must be iterative and self-correcting. Such a strategy provides the information needed for decision analysis methods including calculation of the "value of information" to optimize resource allocations.

  An industry-proven and flexible strategy can be adapted or adopted as is and used by whichever private company or government contractor is responsible for managing tank farm operations and waste remediation. **Problem resolution is not well-served by using strategies or methods that are contractor-dependent. Problem resolution is possible when strategies are well defined, scientifically based, and built upon industrial practices.**

- **It must provide alternative solution paths to achieve outcome(s).**

  Single solutions rarely exist. Multiple paths have overlapping and yet sometimes unique risk, cost, and technology considerations. An effective strategy must permit decision makers to compare the potential outcomes of options and select preferred actions.

- **It must be economically justifiable.**

  The decisions made and actions undertaken must be economically justifiable for the information gained, risks taken, and problems solved.

- **When appropriate, it must be risk-based.**

  When the solution is not easily calculated or self-evident, a risk-based strategy is an effective component of decision making. The complexity of issue resolution must not preclude its solution. It is this complexity that requires a technical basis for achieving a desired outcome. Performance of activities and achievement of a desired outcome within a framework of risk management are standard industry practices (AICHE 1995). DOE has adopted a risk-based, decision-making process (Alm 1996), as recommended by the National Research Council (1994). The specific methods (i.e., tools) used must be well known and tested.

- **It must manage data and information uncertainties.**

It is important to understand the uncertainty of data and information inputs to estimates of risk and to identify those data whose reduced uncertainty will significantly contribute to revealing and managing the overall uncertainty in decision making.

1.6 Framework for Waste Characterization

The key principles underlying the development and implementation of the recommended strategy are noted above. However, there are additional principles underlying the framework of the recommended strategy's approach to waste characterization:

- **Waste characterization is an integral component of the approach to achieving waste safety and disposal goals, not a stand-alone prerequisite to actions.**
- **Characterization is an iterative process that is complete when the data collected and information analyzed are sufficient to take actions and achieve desired outcomes.**
- **Data must be of known quality to be used reliably to support decision making.**

Traditionally, characterization has been viewed by some as part of a linear process: first the waste was sampled and analyzed, then it was acted upon. For example:

> "It is unclear whether the current characterization effort will produce enough information to support moving to the next steps of the cleanup effort." (GAO 1996)

The recommended strategy is based on the assertion that characterization is an integral part of an ongoing, iterative process of managing and treating the waste now contained in Hanford's tanks. The role of characterization is to reduce risk to predefined, acceptable levels known as desired outcomes. When the goal is safe interim storage, the risk of interest is to workers, the public, and the environment. When the goal is successful waste treatment and disposal, this expands to include the technical risks to the treatment processes used.

Characterization of the waste stored in Hanford's tanks is difficult for several reasons: the waste is radioactive and chemically hazardous; it is physically and chemically heterogeneous; and currently available waste sampling and analyses methods have limitations. The risk and cost involved, even in basic characterization steps such as core sampling, are significant. The best technical approach to tank characterization has been the center of a national debate for years.

The recommended strategy states that **characterization, to be technically and economically justified, must measurably decrease the risk of Hanford's stored waste through issue resolution or mitigation and control actions or contribute to the safety and efficiency of later waste treatment actions.** In this sense, characterization is a means for obtaining physical/chemical data about the waste and for understanding radiolytic and chemical phenomena. This justification will enable technically sound decisions to be made and desired outcomes to be accomplished in a cost-effective manner (collect only the data needed). **If a characterization action is not technically justified, it should not be undertaken.**

"Complete" characterization of waste in any tank is not technically possible or even desirable. Tank waste contents have changed and will continue to undergo chemical and physical changes before waste treatment is undertaken. Waste sampled today contains the byproducts of nearly 50 years of chemical and radiological reactions and is not what was originally placed in the tanks. Furthermore, waste stabilization and processing actions will significantly change the contents of any given tank. **Thus, waste characteristics change with time, and complete waste characterization is neither an achievable nor a desirable goal. Rather, characterization actions must be targeted at achieving desired problem resolution outcomes. Otherwise, as noted in Section 1.4, one is building a house and purchasing materials without an agreed upon plan.**

1.7 Defensibility of Waste Characterization Knowledge and Decisions

The defensibility of safety decisions depends upon the scientific soundness (quality) of the data, information, and assumptions used. **Uncertainties inherent in these inputs must be recognized and factored into the decision-making process. This is as true for simple analysis methods (e.g., "back of the envelope" calculations based upon best available data or professional judgment) as for more complex analyses involving quantitative evaluations of event probabilities and consequences.**

As noted previously, much of Hanford's tank waste radiochemistry and phenomena may never be known and this knowledge is not needed to safely store and process the waste (see Appendix B, Section 2.3). This is because only those radiochemical characteristics, kinetics, phenomena, and waste physical conditions that directly control unwanted in-tank events (fires, explosions, etc.) need to be understood. This understanding comes from several sources such as waste sampling, experiments, and modeling. Models can be simple calculations or complex computer simulations. Where knowledge is incomplete, scientifically based assumptions are made and then tested. The closer these models approach reality, the more valid is our understanding of the system and our ability to predict waste behavior. These models are refined and assumptions are tested in an iterative process as data are collected and information is generated. This is the basis of the scientific process that eliminates poor ideas while validating good ones. This iterative process continues until the waste system is sufficiently understood to support decision making.

Data are acquired by equipment measuring parameters of interest. The accuracy of these measurements and their representation of the larger waste system not sampled, measured, or tested imposes limitations on what we know and how well we know it. Data are considered accurate when they measure the parameter of interest to a specified level of confidence. Data are of high value when they are both accurate and pertinent to resolving a key question. **To collect data or generate information of high value, a clear understanding of safety resolution goals and waste characterization needs must exist.**

Difficult choices about data use will center around the validation of historical tank contents data and the related model-generated information. For critical decisions, it is not known how much reliance can be placed upon some historical data sources of questionable quality. This is a critical issue because inaccurate data can lead to inaccurate estimations of risk and poor decisions. Furthermore, at this time there is much unintegrated data available on Hanford's tank waste. **Therefore, the first major step recommended for developing an integrated waste characterization program is to establish a technically defensible "best available database" on a tank-by-tank basis for all data users. Presently, Hanford does not have a single, validated source of reliable tank waste data and information.**

1.8 Use of Risk Assessment

The use of comparative risk analyses to support DOE decision making is growing in importance as more risk reduction and environmental protection benefits are required of the available resources. This section highlights one general and one Hanford-specific risk study commissioned by the DOE. The philosophy, approach, and issues encountered in these studies, to the extent that they affect the implementation of risk-based decision making, are also pertinent to the recommended strategy.

In 1993, a committee working for the National Research Council was formed to address a problem raised by Thomas P. Grumbly (then DOE's Assistant Secretary for Environmental Restoration and Waste Management). Mr. Grumbly requested a fundamental re-evaluation of DOE's environmental program with an emphasis on "whether a risk-based approach to evaluating the consequences of alternative [cleanup] actions is feasible and desirable" (National Research Council 1994). The committee concluded that a credible, scientifically based risk assessment program is feasible, desirable, and essential for dealing effectively with DOE's environmental cleanup problems. Working in concert with stakeholder groups, "risk assessment can become an important element of consensus-building for key decisions" (National Research Council 1994).

In general terms, many of the key elements of the recommended strategy are embedded in the National Research Council report *Building Consensus Through Risk Assessment and Management of the Department of Energy's Environmental Remediation Program* (National Research Council 1994):

- Risk assessment is a highly desirable component of the remediation decision-making process. It is especially useful in providing input for managing and reducing risk encountered by workers and the local population.

- When properly used, risk assessment is a manifestation of the scientific method in that it specifies how information is gathered, uncertainty is determined, potential future outcomes are explored in an objective and reproducible manner, and how the likelihood of these outcomes is displayed clearly and comprehensively.

- Risk assessment is iterative and supports a continuous (evolving) decision-making process. Useful risk assessments are feasible even in situations where current information is limited, as long as its purposes and limitations are defined.

- Risk assessment can be effective in comparing different potential outcomes of possible future actions and their cost-effectiveness.

- Risk assessment must involve issues that concern the public.

- While risk assessment can be conducted in many organizational settings, ways should be sought to combine the advantage of using accessible information (via DOE and its site and prime contractors) and the credibility of outside groups.

- Risk assessment has limitations that should be clearly understood. Similarly, risk assessment is one of a number of elements in the decision-making process and should not be treated as the only one. These elements include political, social, financial, and technological factors.

In 1995, the Hanford Site contractors developed a conceptual set of risk-based cleanup strategies for

Hanford (Hesser et al. 1995). Hesser et al. used risk-based decision making and comparative cost, risk, and schedule tradeoffs between alternative cleanup strategies. Use of tradeoffs is a common theme in this report.

The Hesser study was also done at Mr. Grumbly's request. It was issued to illustrate how a sitewide integrated, risk-based cleanup strategy could provide policy-making insights in approaching Hanford cleanup.

All cleanup strategies proposed by Hesser et al. (1995) were required to 1) protect people and the environment, 2) be executable technically, and 3) fit within anticipated funding levels. The methodology used followed a systematic approach to problem evaluation in which

- existing data, information, and program objectives were evaluated
- performance objectives (goals) were established
- a general set of cleanup strategies and decision rules were defined to achieve risk reduction, land-use, and mortgage reduction objectives
- potential risks, costs, and schedule impacts of alternative strategies were analyzed and compared with existing cleanup objectives
- sensitivity analyses were conducted
- recommendations were made for implementing the risk-based approach including stakeholder and regulatory participation.

Hesser et al. (1995) also identified some fundamental challenges and actions necessary to implement risk-based decision making at Hanford. For example:

> "Current Hanford Site cleanup plans are not consistent in addressing environmental, worker safety, or public health risk. There is not a national or Site policy for risk reduction, and plans for cleanup activities in the same area do not lead to a consistent end state. Cleanup plans are not generally based on risk or risk-reducing goals and there is not general agreement on quantifiable standards for cleanup."

> "The DOE and stakeholder participation in the development and approval of a risk-based strategy is needed. The first decision of whether to develop and implement a risk-based strategy is the responsibility of the Assistant Secretary of Environmental Management. Given the Assistant Secretary of Environmental Management supports the development of a risk-based strategy, DOE and stakeholders will develop a follow-on process. The process will most likely require additional analyses of alternatives, risk, cost, schedule, technology, regulations, and land availability. The DOE and stakeholders will develop recommendations on objectives, decision rules, end states, interim states, and actions. Several key decisions are needed to define end states, the interim state, and the actions to support those states."

Similar issues face the use and implementation of this recommended strategy for tank waste safety and characterization.

1.9 Limitations of Any Planning and Decision-Support Process

"The essence of risk management lies in maximizing the areas where we have some control over the outcomes while minimizing the areas where we have absolutely no control over the outcome and linkage between effect and cause is hidden from us" (Bernstein 1996b).

As noted earlier, the National Research Council recognized that risk assessments have limitations. In fact, any planning and decision-support process has limitations (just as data have limitations), whether based upon risk approaches, group consensus, or an individual's intuition. What is most important is that the decision-support processes used are appropriate to the problem being addressed and the limitations (uncertainties) of the data and decision process are accounted for and identified.

One must not have a blind reliance on decision support tools (e.g., value-of-information decision analysis, Structured Logic Diagrams, risk analyses) or any such decision-support method. The human element and the lack of "complete" knowledge about complex chemical or engineered systems naturally introduce unquantified uncertainty. Thus, the potential for error exists, especially when trying to predict reliably events that have never occurred before and for which reliable data are lacking. Infrequently, decisions result in an undesirable event in spite of rigorous planning and option tradeoffs.

This underscores the importance of the role of the Resolution Team in interpreting the information provided by the decision analysis tools.

Operations as complex as tank waste cleanup will not be free of risk regardless of the methods used to make decisions or manage risk. **At the same time, if risks are not managed, an illusion of control can emerge wherein there is an even greater likelihood that costly, undesirable events will take place. If some risk is not taken, progress will not be made on resolving tank safety and cleanup issues.** Therefore, it is critical to ensure that the process used for supporting decision making is carried out in an open, disciplined, and scientifically defensible manner. This practice will minimize the chance of some critical factor being missed in the logic used and the analyses performed. **Because there is no such thing as a zero-risk action or non-action, there will always be some risk associated with what is done to Hanford's tank waste. The recommended strategy is designed to identify and manage that risk *throughout* the issue resolution process so that it becomes a matter of choice rather than of chance.**

It is recognized that mistakes resulting from action tend to be viewed as more "painful" by decision makers than ones resulting from inaction. Nevertheless, in spite of limitations inherent in decision support processes, the risk, cost, and control of complex systems such as Hanford tanks are best managed by well-informed, proactively driven decision making.

It is in the above context that the recommended strategy is offered as a means for decision makers to evaluate wisely and compare safety resolution and characterization options. The recommended strategy does not make decisions; people do. The methods employed in the recommended approach have been used by industry for years to successfully analyze and solve complex scientific and engineering problems.

1.10 Definitions

Several key words or phrases that are used in this report are defined here:

Characterization: Characterization means obtaining sufficient information (data and understanding of chemical and physical properties) to describe chemical processes/phenomena taking place in the waste to the level of certainty needed to take a specific action within an acceptable level of risk. This information may be obtained by review of historical information, waste sampling and analysis, tank monitoring, laboratory research, computer modeling, and other activities.

Desired Outcomes: These are understandable, logical statements identifying what final issue resolution means. For example, what it means to achieve safe interim waste storage or acceptable waste disposal. For safety issues, desired outcomes are expressed in terms of meeting acceptable criteria (e.g., predicting an event's frequency to be less than one in a million years with 95% confidence) by which issues are resolved, mitigated, or controlled. Disposal issues are defined in terms of waste-form performance criteria and acceptable risk criteria for a waste disposal site.

Resolution: Resolution means that an issue of concern is solved to a specified, defined level of acceptance. Resolutions may range from installing equipment in a tank to prevent a condition (e.g., flammable gas buildup) to a technical assessment that a given waste reaction could not occur because of the fundamental chemistry and physics of the waste.

Risk: Risk is the product of probability of occurrence per unit of time and expected harm (consequence) associated with the occurrence of a disruptive event. The risk may be a technical or program failure or an event that might affect public health, worker health and safety, or environmental quality. It is expressed as a probability function taking uncertainty into account. Risk may be a single or cumulative property associated with one or more disruptive events.

Safety: Safety expresses an adequate degree of confidence that there will not be a disruptive event leading to the unwanted release of the contents of a tank(s) or processing systems with direct exposure to workers or the public.

2.0 The Recommended Strategy

The details of the recommended strategy are described in this chapter, which focuses on the Hanford waste tank problem analysis process. Descriptions of each process step are prefaced by sections that discuss the strategy's underlying concept of risk, the use of risk analysis, and need for risk-based management; the risk-based and outcome-focused nature of the strategy; and the waste characterization efforts that include taking advantage of routine, waste operations and processing activities to derive characterization information.

Figure 2.1 shows a generalized outline of the recommended strategy, in which the work flow is as follows:

- The objective to be accomplished (i.e., resolve a safety problem) is identified, the desired outcome is specified, and resolution criteria for meeting the objective are defined.

- A Resolution Team is assembled and conducts an initial analysis of the problem using existing information (i.e., the current understanding of the waste properties and the physics and chemistry controlling the resolution of the problem of interest). A quality review ensures that data quality represents the needs of the Resolution Team.

- If the initial analysis finds that the resolution criteria are met (globally for the issue at hand or on a tank-by-tank basis), the desired outcome has been achieved.

- If the initial analysis finds that the resolution criteria are *not* met, actions are taken in a series of iterative steps until problem analysis shows that the resolution criteria *are* met through an improved understanding of the wastes' chemistry or physical condition or by mitigation through changing the waste properties or adding operational controls.

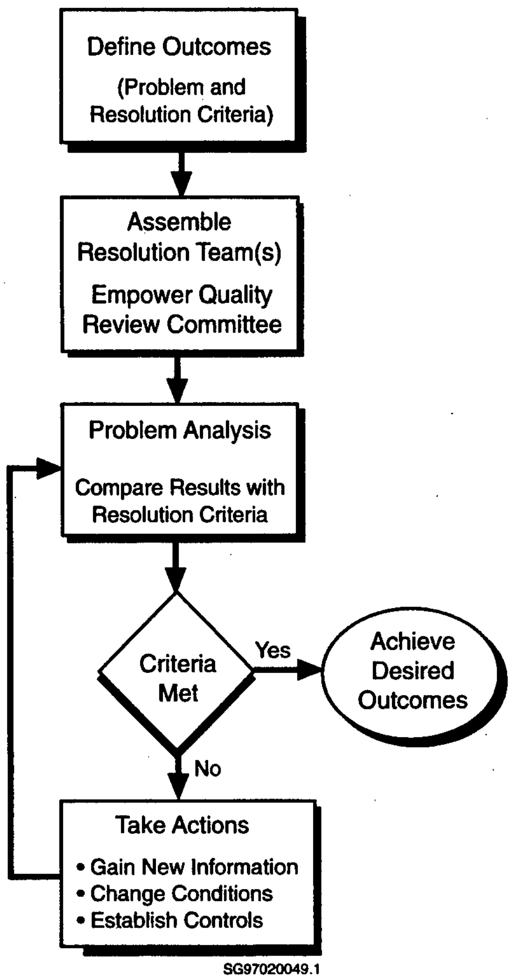

Figure 2.1. Outline of the Recommended Strategy

The success of this characterization strategy depends heavily on the decisions of the Resolution Team. The Resolution Team is key in managing the application of the recommended strategy. This team must be certain that the strategy is applied with the appropriate level of rigor to lead to timely and cost-effective actions. The team must eventually recommend to decision makers the actions that will lead to the accomplishment of the defined objectives. Success of the Resolution Team requires mechanisms for

- ensuring that all relevant information is addressed by the team
- managing the influence of business, programmatic, and other nontechnical considerations on decisions. (Appointing team members who do not have a vested interest in the outcome of the decision analysis might be difficult if the team members are to be engineers and scientists with sufficient understanding of the problems).

An approach used in other venues can successfully respond to these needs and concerns by providing appropriate checks and balances. The key features of this approach are as follows:

- The team is composed of technical staff who have the appropriate expertise to address the issue under consideration. These staff can be from DOE contractors, universities, national laboratories, and industry.
- The leadership and many team members may come from one contractor, but to avoid conflict of interest, that contractor should not be responsible for most of the implementation work.
- The team members are drawn from the broad scientific and technical community, as needed.
- A review process is implemented to ensure that the team's decisions are technically sound, respond to the need for implementable, timely solutions, and do not involve any conflict of interest.

The Resolution Team is expected to work full-time if necessary until it has established a sound technical basis for resolution of the issue.

Establishment of a standing Quality Review Committee composed of highly qualified personnel from the national laboratories, industry, and academia is proposed as part of the recommended strategy. This committee would ensure that a data quality assurance program is in place and that it provides a scientifically justified and rigorous technical assessment of all data requests and results. The fundamental criterion for judging data quality is that the data reliably respond to the data needs specified by the Resolution Team.

The proposed basis for organizing the Quality Review Committee would include the following components:

- Membership is by appointment and based on technical qualifications and freedom from conflict of interest.
- Representative(s) of any party fiscally involved in an action are disqualified from making decisions benefiting their institution.
- Expert subcommittees may exist for select topics.
- The Quality Review Committee acts promptly if an urgent and unexpected technical issue arises in between regular reviews.

The Hanford Tank Waste Advisory Panel is an example of an existing review panel that could be changed to provide the Quality Review Committee function.

In summary, the recommended strategy calls for the establishment of three types of teams/committees/ panels to accomplish the work:

- **Resolution Teams**. These are contractor staff, augmented by others, who are responsible for identifying the details of the strategy(ies) and data needs required to resolve Hanford's tank characterization and interim-stage safety problems. The contractor primarily responsible for this part of the work may be the operations contractor, some other contractor, or a national laboratory. The key points are that the teams must work without conflict of interest and that the team members must have appropriate qualifications for the work. Some problems will require the contractor to build upon its core staff with subcontractors from universities, industry, the national laboratories, etc.

- **Quality Review Committee**. This committee is to ensure that the data obtained through sampling and analysis of wastes will respond reliably to the data needs specified by the Resolution Teams. For example, it is expected that this committee would have identified an alternative to the measurement of total organic carbon (TOC), which is only a weak indicator of the contribution of organic materials to the energy content of the waste.

- **Review Panels**. These can be standing or ad hoc panels that are to review the quality of the work, the capabilities/appropriateness of the key staff, and the work environment (e.g., evaluating whether Resolution Teams have sufficient authority and stability to be successful). This is not a technical advisory function. If those responsible for the work are in need of significant technical advice, then the Resolution Teams should be strengthened such that the DOE and the public can be assured of the technical competence of the work.

This approach represents a clarification and simplification of current practices. Resolution Teams already exist by definition—they are the individuals working to address particular issues or concerns. However, they may not meet the criteria described previously. The Quality Review Committee and Peer Review Panels would replace existing advisory panels, separating their roles of helping to solve technical problems and reviewing progress such that one body is not reviewing actions that they themselves have directly or indirectly encouraged or planned.

2.1 Use of Risk Analysis

Before the strategy is described, it is important to discuss how the concept of risk is used in two different ways in this strategy. **First, risk is used to define the acceptance criteria for the various elements (i.e., safe interim storage, etc.) of the waste storage and disposal mission (Harper et al. 1996).** Risk includes both the probability and consequences of an unwanted event taking place. For this application, the criteria used need to respond to health and environmental protection needs as well as to programmatic concerns about the effect of an incident on the waste disposal mission. Limits of time and resources prevent the acceptable risk criteria from being set at arbitrary low levels. In working with regulators and stakeholders to set these criteria, the DOE is bound by the constraints of physical and fiscal reality. Establishing these bounds defines an important role for characterization work.

Risk is also used to guide decisions about taking the actions needed to achieve the waste storage and disposal mission. Not only must the results of selected actions (i.e., waste retrieval, transport, blending, processing, etc.) aid in achieving the criteria for success of the mission, but the actions themselves involve risk. Quantification of the risk associated with taking a particular action on the waste requires knowledge of the waste contents and properties as provided by waste characterization work. Using risk to select actions is discussed in Appendix B, Section 2.4, where it is noted that, while it is important to stay below acceptable risk limits, just taking the actions of lowest risk may not be the best decision. Some riskier actions might be justified if the data/information gained are expected to have sufficiently large beneficial effects.

The successful implementation of the recommended strategy requires that safety and waste disposal activities also be managed in a risk-based framework. The first and most basic requirement for management systems is that risk-management principles be used consistently across all related programs. This requirement means that **the management of safety and waste disposal functions acknowledges that achieving zero risk is not possible. In tank safety management, we cannot maintain that "there are no significant risks but we just cannot quite prove it yet." Risk must be acknowledged to gauge the incentive(s) to conduct appropriate characterization activities. The level of acceptable risk can be made as small as is affordable, but a position that "any risk is too much" cannot be realistically maintained.**

In the realm of waste retrieval and processing, risk-based management allows for some tolerable degree of uncertainty in process development and application. A workable reprocessing technology at Hanford would never have been developed if a requirement had been imposed that the first process successfully used (bismuth phosphate) be perfectly efficient. The degree of uncertainty permitted need not be large or reflect a permanent end-state, but it should allow for enough flexibility to actually do some waste processing and to learn while doing so. The best technical solution will emerge from experience. **Learning takes practice, and practice requires that decisions be made and actions be undertaken. There is no substitute for the experience that comes from actually dealing with the tank waste within constraints that limit risks to acceptable levels.** (Managing tradeoffs between risk and information gained related to possible actions is discussed in Appendix B.)

2.2 Outcome-Focused Approach

The characterization effort must be intimately tied and integrated into the work required to achieve specific waste management objectives. It focuses on achieving the specific set of outcomes that rely upon understanding the waste and related systems. Characterization work seeks to answer questions like, do the properties of the waste represent a potential energy release hazard and how much risk is associated with that energy release? Characterization, safety/risk analysis, decision making, and large-scale remedial actions applicable to tanks are all part of the same interrelated and interactive system (Figure 2.2) in which justification for new data, characterization actions, validation/refinement of the model(s), and risk and decision analyses takes place. This is in contrast to the current situation where the characterization and safety programs are managed by multiple Hanford contractors, making coordination and integration difficult.

In some instances, all steps shown in Figure 2.2 (from defining desired outcomes to taking actions) are exercised as the recommended process is worked. For other iterations, only select steps are used based on specific data/information needs of analyses or option comparisons required by decision makers. In this fashion, flexibility is built into the recommended strategy as it is tailored to address the problem(s) at hand. This approach forms the basis for an integrated and effective characterization strategy. Ongoing characterization work cannot be considered "complete" until the final acceptable end-state of any given tank has been achieved. At each iteration, the need for additional characterization work must be justified. The recommended strategy uses risk analysis as a basis for justifying

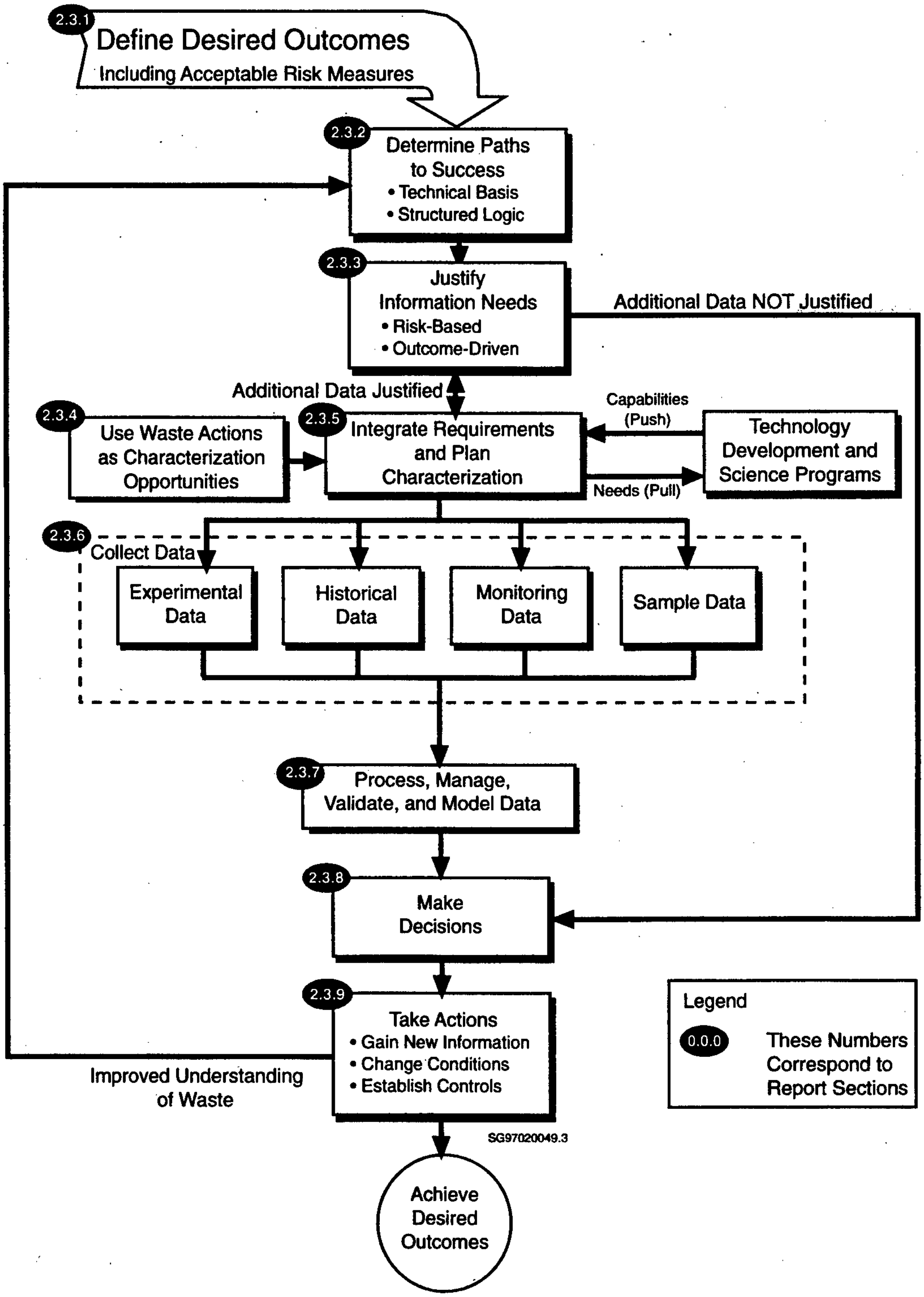

Figure 2.2. Problem Analysis Process

data needs. In fact, one of the key strengths of a risk-based strategy is that the criteria provide a quantitative basis to break the collect-data/model/collect-data cycle that is otherwise difficult to complete. When is the amount of information sufficient? It is sufficient when the cost of obtaining additional information exceeds the cost of remediation or control actions needed to reduce risks to sufficiently low levels.

Waste characterization, defined as obtaining the physical and/or chemical intelligence that provides sufficient information to allow actions to be taken to achieve a specified level of risk, will enable the quickest and most cost-effective, task-by-task (or tank-by-tank) closure of characterization work.

2.3 The Problem Analysis Process

The problem analysis process is shown in Figure 2.2 and described in Sections 2.3.1 through 2.3.9. The strategy uses Structured Logic Diagrams to provide a graphic representation of the model(s) used to describe the phenomena associated with the disruptive event that is the basis of the safety issue. **Structured logic tools guide development of an understanding of the problem. Decision analysis tools are then used to make risk-based decisions based upon this understanding.** These problem-solving tools are developed and used to the degree of complexity to match the complexity of the problem at hand.

Using the tools does not guarantee success, but when used by a team who understands the limitations of the available information and analysis methods the likelihood of success is increased.

2.3.1 Define Desired Outcomes

Defining the desired outcomes (i.e., selecting a level of risk that is acceptable and that is believed to be physically and financially attainable) is the role of decision makers. Presently, discussions are ongoing about what constitutes resolution of a safety issue. For example, concerns about minimizing risks can lead to the desire for no unexpected event to occur within a tank, even an event that would be too small to cause worker or public harm. Obviously, costs and other factors will be strongly affected by the level of risk that is deemed acceptable. Definition of these desired outcomes, including acceptable risk and risk uncertainty, is based on current understanding of the technical requirements underlying resolution of the safety issue, augmented by input about preferences and values of stakeholders (oversight panels, Native American Tribes, the public), regulators (federal and state), and national policies. The definition process is illustrated in Figure 2.3.

As shown in Figure 2.3, decisions about the 177 waste storage tanks at Hanford are a subset of the full range of DOE decision making, ranging from concerns about safety issues to other issues requiring resolution during the restoration of the Hanford Site. The needs and requirements of all sources are assimilated into desired outcomes. Either formally or informally, desired outcomes are defined for all waste management issues, including safe interim storage and waste disposal. In some cases, a general consensus has been forged (i.e., the disposition of the Hanford tanks as described in the Tri-Party Agreement [Ecology, EPA, and DOE 1996] between the DOE, U.S. Environmental Protection Agency [EPA] and the State of Washington)

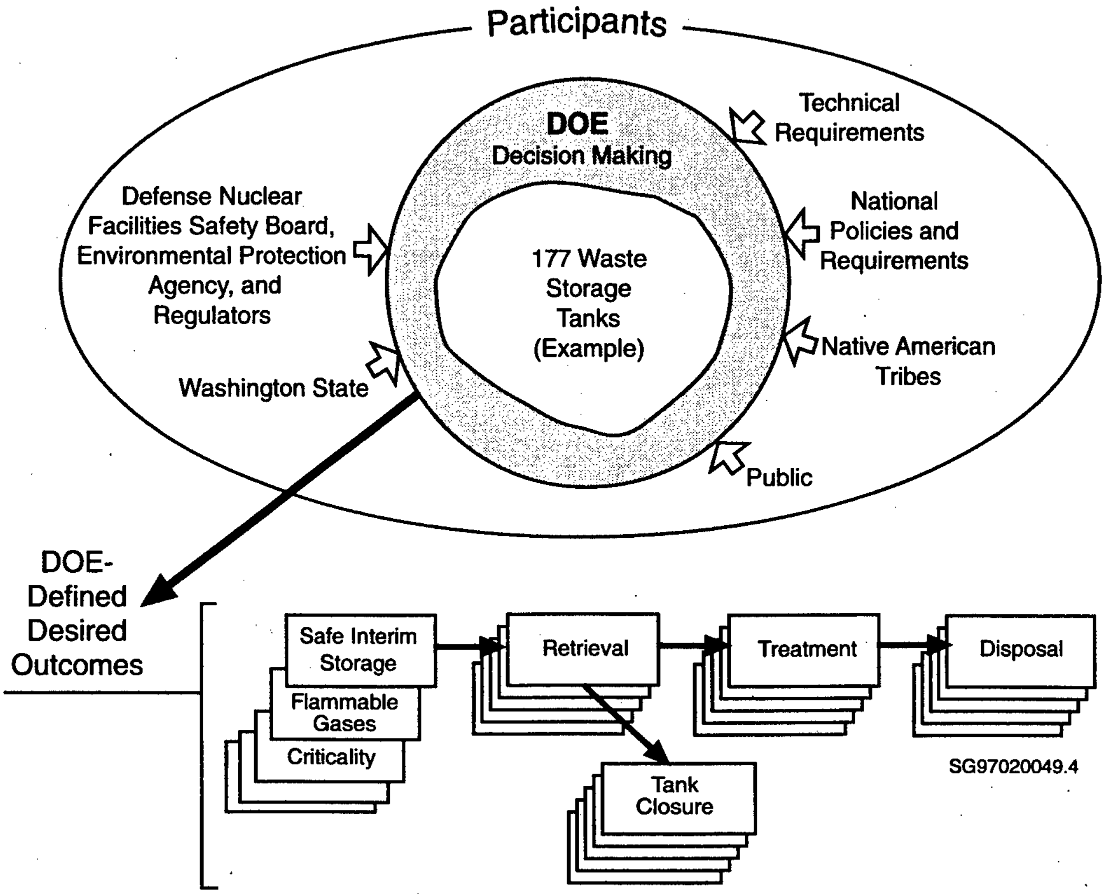

Figure 2.3. Participants in a Process for Defining Desired Outcomes

and in others, such as land end-states for the Hanford Site, the development of consensus is ongoing. A recommended, integral part of this process is early and open sharing of information and ideas among the project teams, DOE, regulators, stakeholders, tribes, and the public. This is often an iterative process as information about risks and the costs of managing risks is refined. Application of the recommended strategy will play an important role in this process by providing decision makers with the required technical information such as the current level of risk associated with each tank and the costs and tradeoffs associated with reducing that risk and its uncertainty.

Not all tanks pose the same level of risk from a particular phenomenon, for example, an organic complexant fire is incredibly unlikely in a tank that is mostly water. Nor are the risks from particular hazards separable. A flammable gas fire might ignite dry flammable solids. The strategy calls for the management of all tanks to a level of acceptable risk when integrated over all credible hazards. Some tanks may pass this test with ease, while others may require considerable study and modification of the tank contents or installation of operational controls to meet the acceptance criteria.

Acceptable risk and risk uncertainty must be developed into a measurable and appropriate set of risk attributes. These attributes will contain technical and programmatic risks. Risk constraints and the methodologies to develop meaningful risk constraint levels are further detailed by Harper et al.

(1996). As the understanding of the safety problem evolves and the level of available funding is specified, planning will account for what can realistically be accomplished. **The technical feasibility and clarity of the desired outcomes and acceptance criteria will have a major effect on *any* strategy designed for managing tank safety risks.**

2.3.2 Determine Paths to Success

To achieve specific tank safety and remediation objectives (desired outcomes), the recommended strategy calls for the Resolution Team to manage the development of models that show

- alternative and technically sound solutions (paths to success) leading to each objective
- physical and chemical conditions that must exist to achieve those solutions
- information needed to assess the probability that each of these required conditions can be met.

A technical analysis approach called structured logic is a well-established tool for documenting the options for resolution of a problem and its associated information needs. Structured logic was found to be wellsuited to analysis of the tank waste safety issues. The results of this approach are contained in a Structured Logic Diagram. The basic factors considered in preparing the structured Logic Diagram are illustrated in Figure 2.4. Such analysis of a problem generally leads to a variety of technically feasible options for achieving the desired outcomes. At the very least, the options include resolution through understanding, mitigation, and/or addition of controls. There may be several options within each of these categories. **Structured logic provides a formal and detailed approach to guide the development of the technical basis for achieving specific desired outcomes.** Structured Logic Diagrams provide concise documentation of the desired outcome, definition of alternative success paths, definition of data needs, and modeling requirements or data processing requirements.

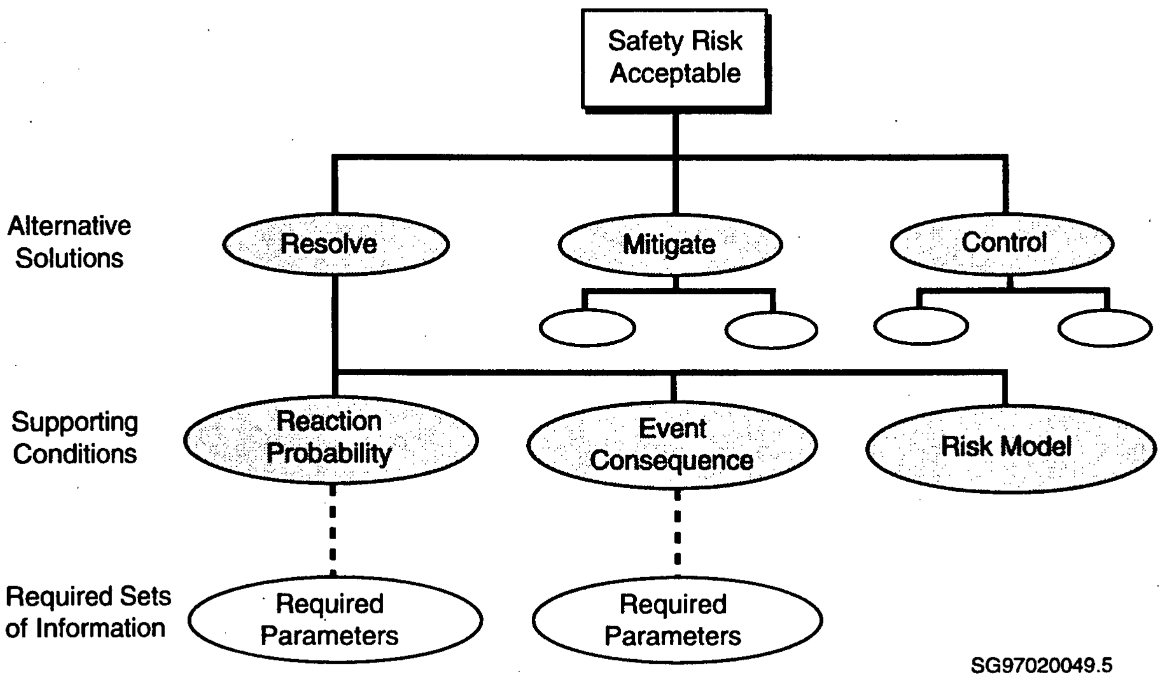

Figure 2.4. Underlying Thought Process for Preparing and Organizing Structured Logic Diagrams

Creation of the Structured Logic Diagrams requires qualified, multidisciplined scientific and technical teams, termed Resolution Teams, whose capability base spans the chemistry, physics, and technology that the problem embodies. For the most challenging and enduring problems (e.g., safety problems caused by production of flammable gases by reactions within the tank waste), these teams become standing scientific panels that create and manage the development of the Structured Logic Diagrams and overall implementation of the recommended strategy until the related objective has been accomplished. The technical capabilities of Resolution Teams and any associated consultants and staff are key to ensuring the successful implementation of the strategy.

As shown in Figure 2.4, the Structured Logic Diagrams for safety issues are organized to consider the three primary options for issue closure: 1) **resolve** through knowledge that existing risks are acceptable, 2) **mitigate** to change the waste conditions sufficiently to make the risks acceptable, and 3) **control** to properly manage any tanks for which risks are known to be unacceptable. This approach is a disciplined means of developing an understanding of the physics and chemistry of the waste, its associated phenomenology, and how this phenomenology relates to risk. Furthermore, when the Structured Logic Diagram is organized as in Figure 2.4, one works down the left-hand column and then to the right, recognizing that the normally preferred solutions are found in that order. For example, determination that the waste properties are such that the probability of a proposed event is incredibly small is the most desired solution. It provides the highest assurance that acceptable risk can be achieved without additional mitigation or control actions. Generally, mitigation is better than procedural or instrumental controls because it relies more upon adjusting the waste's chemical or physical conditions to avoid an unwanted event than upon workers adhering to work procedures. Likewise, mitigation is preferable to exercising controls. An exception would be the addition of water to a leaky tank. Obviously, in that circumstance, it would be better to implement a control to keep the risk acceptable. Using the approach described, the Structured Logic Diagrams will be developed only to the extent that they are sufficient to make defensible decisions.

This leads to a hierarchy when considering alternative solutions. For example, the resolution option can be achieved if the chemical reaction of concern is not credible, the frequency of the event is extremely low, or the resulting event is inconsequential. While in principle each has equal weight in the overall health or environmental risk calculation, a contained fire inside a tank, for example, could still have significant programmatic consequences. Thus, waste conditions in which reaction probabilities are very low would be the preferred outcome. A Structured Logic Diagram developed along these lines would naturally reflect the degree of rigor needed to obtain the most valuable solutions. Although it would not reveal all possible solutions, the top-down, left-to-right development approach is designed to discover the most desired solutions first. Simple issues with relatively uncomplicated phenomenology will entail straightforward Structured Logic Diagrams that can be quickly developed. For more complex, less straightforward issues requiring a rigorous technical analysis, the Structured Logic Diagram will offer multiple paths to success and will provide guidance for evaluating how individual parameters are related to the overall risk. This leads naturally to the use of risk in decision making. Whereas the Structured Logic Diagram is expected to be broadly applicable to tank waste remediation and disposal, the underlying logic diagrams for activities beyond safe interim storage are not identified or addressed in this document.

In every case, the top event chosen for each Structured Logic Diagram is the establishment of an acceptable level of risk for a specific safety issue. All basic components of a potential unwanted event (initiating factors, conditioning event scenarios, primary event scenarios, secondary event scenarios, release scenarios, possible source-term configurations and amounts, pathway scenarios, and waste uptake and consequence scenarios) are included in the Structured Logic Diagram. The Structured Logic Diagram shows the technical basis for four fundamental models listed here; each is an essential component of the tank safety analysis resolution strategy:

- A model of the phenomenology itself. A fully developed Structured Logic Diagram includes the physical and chemical conditions related to a proposed action or decision, the frequency of potential reaction initiators, physical and engineering factors such as weaknesses or strengths of the containment vessel or its components, and the consequences of possible disruptive events related to the waste, including transport and fate models and long-term and secondary consequence possibilities.

- A model for uncertainty analysis that reflects the flow of information and propagation of uncertainty from tank conditions to the uncertainty in the estimate of risk.

- A model for evaluating the logical completeness of the tank safety analysis, including the systematic inclusion and analysis of new safety concerns.

- A model for systematic resolution of the large-scale composite tank safety problem that focuses on key data and information needs. By treating the Structured Logic Diagram as a large-scale, decomposable problem, it is possible to eliminate, simplify, or combine subproblems for faster, easier, and more economical solutions.

Structured logic is a tool for visually presenting and analyzing the underlying, causative phenomenology for each safety issue that allows for systematic application of logic for problem resolution.

The following sections discuss structured logic as a tool; how the Structured Logic Diagram is used; how uncertainty analysis is applied to tank safety issues; how the Structured Logic Diagram is used as a computational model for uncertainty analysis; and how safety issues raised by new hypotheses are identified and resolved.

Structured Logic as a Tool

A major issue in ensuring tank waste storage reliability is establishing standard methods to ensure a review of the technical basis that provides a systematic examination of all conceivable pathways by which a disruptive event can contribute to risk. Herein lies a potential pitfall: "conceivable" means the ability of a human to conceive an idea, and this is a highly unpredictable variable. Structured logic is a standard tool in the chemical and nuclear industries where it serves to optimize yields of highly characterized processes and reduce the risk of failures. Detailed descriptions of structured logic for each safety issue developed using this strategy, and its depiction in the Structured Logic Diagram, are given in separate, yet unpublished, reports (Doherty et al. 1996; Goheen et al. 1996; Liebetrau et al. 1996; Pulsipher et al. 1996; Stewart, Brewster, and Roberts 1996).

Structured Logic Diagrams illustrate how failure can be eliminated, and allow for a systematic examination of all identified ways that failure

can be eliminated. By so doing, the most desirable approach(es) to eliminating failure can be identified from among all options.

There is danger in "blind" reliance on structured logic or any other decision support tool (see Section 1.9). The human element and lack of complete knowledge about the systems (e.g., tank waste) being evaluated naturally introduce unquantified uncertainty and the potential for errors of judgment. Many human-caused disasters have taken place in spite of very rigorous planning. Operations as complex as tank waste cleanup will not be at zero-risk, even if structured logic and other quantitative risk assessment methods predict an acceptable risk margin for a given action. Because of their quantitative flavor, such methods may nurture a false security. Therefore, it is critical to ensure that the structured logic process is carried out in an open, disciplined, and scientifically defensible manner to lessen the chance for occurrence of a major unwanted event.

Using the Structured Logic Diagram

Addressing any one of the tank waste safety issues can require solving a few or many (more than 100 in some cases) smaller component problems of varying degrees of difficulty. These subproblems can range from data sampling problems to developing and applying models of the events that represent safety issues to be resolved, mitigated, or controlled. The speculative nature of much of the waste, the deteriorating condition of the tanks, and the difficulty of taking and analyzing samples of radioactive material make uncertainty a significant factor in the evaluation of tank safety issues. The uncertainty component of risk can be quantified in the structured logic approach and documented for each key parameter on the Structured Logic Diagram. **The uncertainty about noncritical parameters, properties, or chemical reactions, those with little effect upon risk, can be ignored.** Acceptance of nonzero risk decisions requires that areas of uncertainty be acknowledged and understood and that their effect on potential actions be assessed.

Many of the identified component problems may be eliminated by identifying controlling relationships among them. These relationships will be identified in the Structured Logic Diagram. For example, information about the nature and amount of fuel (e.g., organic waste) can dominate information about possible reaction initiators (e.g., spark or high heat source). If there is no fuel, reaction initiators are not a concern and the problem is resolved without a formal risk calculation. This leads naturally to a hierarchy of importance in knowing particular factors that contribute to risk. If the potential for an event occurring is sufficiently low, there is no need to know the amount of energy released, the effect of that energy on the tank, the amount and means of release of tank contents, how the contents are dispersed to the workers and the public, and the health consequences of the resultant exposure, if any. On the contrary, if the potential event is likely, then each of these additional data needs becomes important in a progressive manner depending upon the projected severity of the purported event. Hence, the strategy calls for the iterative development and application of the structured logic analysis of the problem. The selection of acceptable risk criteria also plays an important role in constraining the complexity of the problem analysis. The expectations of the public are that the frequency of events of the *type* that might represent a public risk (i.e., a small in-tank fire) must be maintained sufficiently low that the potential of a larger event with significant health and environmental risks becomes incredibly low. Managing to this more conservative measure of risk greatly simplifies the range of phenomena that must be contained in the problem analysis. The discussion in Chapter 3.0 illustrates the importance of establishing risk criteria that are technically achievable and affordable.

Uncertainty and Sensitivity Analysis Applied to Tank Safety Issues

The logic and phenomenology captured in the Structured Logic Diagram for each tank safety issue can be evaluated to estimate the expected value of risk for comparison with acceptability criteria, especially applicable regulatory or tank operation safety limits. However, for the comparison to be meaningful, the risk estimate must be accompanied by a reliable estimate of its uncertainty. At a minimum, the uncertainty should capture variability in model parameters, especially in the input data and any lack of knowledge about the phenomenological processes involved.

Quantitative risk uncertainty analysis is required for any process undertaken to provide a technically defensible estimate of risk. The analysis is incomplete, and in the worst case can be misleading, until such an estimate is determined. This is true whether or not the analyses rely upon back-of-the-envelope calculations or complex numerical models.

The Structured Logic Diagrams greatly facilitate the analysis of risk uncertainty by exposing the sources of uncertainty associated with each phenomenology and by helping to focus on the controlling drivers (parameters and reactions) in the analysis. The uncertainty model involves obtaining the known (or an estimate of) uncertainty for each data need and then, at each junction in the Structured Logic Diagram, showing how variability in the inputs is propagated to the output(s).

Distributions that describe uncertainty in data needs or models can be propagated through a computational structure based on the Structured Logic Diagram. Thus, the Structured Logic Diagram also serves as a convenient calculational template for uncertainty analysis. Uncertainty distributions may be obtained empirically through actual knowledge about error in the data collection processes or they may be obtained theoretically through numerical methods. Propagation of uncertainty through each of the alternative paths through the structured logic allows the nature and amount of uncertainty to be realized for each option under consideration in the decision and subsequent action recommendations. Demonstration of uncertainty propagation through a Structured Logic Diagram is shown by Liebetrau et al. (1996).

Uncertainty issues are at the core of each safety issue, and developing the uncertainty estimation strategy is crucial to the satisfactory resolution of every tank safety issue. **Using structured logic, the decision maker is fully aware of the risk uncertainty in each potential decision.**

Using the Structured Logic Diagram also assists in the sensitivity analysis of the data. **Sensitivity analysis estimates the effect on a calculated output (i.e., level of risk) due to variation in one or more input parameters.** A sensitivity analysis is undertaken for two reasons. First, to achieve a minimal representation of the model (in this case, the Structured Logic Diagram and its key component models) by identifying noninfluential variables and components that can be ignored in subsequent uncertainty analysis. Thus, sensitivity analysis is a quantitative tool used to pare down the Structured Logic Diagram to a minimal set of pathways essential to solve the safety problem. Because the analytical steps involved in sensitivity analysis are closely related to those for uncertainty analysis, the second reason to do a sensitivity analysis is to provide the basic information required for uncertainty analysis.

Uncertainty in risk estimates can arise from a variety of sources. One of the most familiar is measurement variability mainly due to sampling errors and, to a lesser extent, due to instrument errors. Uncertainty can also arise for other reasons such as a lack of information. The concentration estimates from the Historical Tank Contents Estimation model (Brevick, Gaddis, and Johnson 1995; Brevick, Gaddis, and Pickett 1995a, b, and c; Agnew et al. 1996), for example, are uncertain because (among other reasons) the records used to derive them are incomplete. Uncertainty also appears in the form of incomplete or inadequate phenomenological models; that is, models that do not adequately predict the phenomenon they are designed to model. The Structured Logic Diagram helps deal with the inescapable sources of uncertainty and variability in characterization by displaying how that uncertainty will affect or influence answers and where significant sources of variability lie.

Just how uncertainty is represented is important in any structure with the logical rigor of the Structured Logic Diagram. There are many ways to represent uncertainty. These include the variance; the range, determined by the highest and lowest possible values; tolerance intervals, etc. The usefulness of these measures differs depending on how they are derived and what form they take. The variance, for example, is not appropriate for characterizing the variability of a parameter that has a highly skewed or bimodal distribution. The one representation that always contains all the relevant uncertainty information for a given quantity is its distribution function. In fact, all other representations of uncertainty can be derived from the distribution function. Empirical distribution functions derived from observational or experimental data measure analysis variability. A distribution function may also be selected for theoretical reasons. In all cases, the distribution functions are formally treated alike in the subsequent uncertainty analysis. The importance of uncertainty analysis in safety issue resolution is further discussed by Liebetrau et al. (1996).

Identification and Resolution of Safety Issues Raised by New Hypotheses

Confidence in the structured logic is based on an accurate data and problem description plus rigorous expert analysis. Such an approach can give the false impression that complex, dynamic systems can be definitively understood. Therefore, a process for accounting for the discovery of new sources of risk is described further in this section and in Appendix B.

By their nature and history, Hanford tank wastes preclude the *a priori* definition of all possible safety concerns. In some cases, it is uncertain what material and material quantities have been placed in the tanks. Furthermore, the wastes are chemical reaction systems that continually produce new substances as the organic complexants and solvents undergo radiolysis and chemical conversion. Hence, while it is important to encourage the ongoing generation of new hypotheses about and analysis of potential safety issues, it is also important that the new hypotheses pass a credibility test before they are allowed to affect tank waste characterization and management decisions. A formal and open process will assure all concerned parties that the identification and analysis of potential safety concerns is being given appropriate attention. The recommended strategy provides a logical approach for resolving questions raised by a safety-related hypotheses. *It is important to note that since 1990, only six major safety issues related to the tank waste itself have been identified and several have been or are approaching resolution* (see Section 1.1).

An example of the strategic handling of questions raised by new hypotheses has been developed in Appendix B, Section 3.5, and illustrates the

- dynamic and sometimes unknown chemical nature of the waste

- potential consequences of prolonged storage of the waste
- importance of validated chemical models in studying the waste and asking speculative "what-if" questions
- ability of the recommended strategy to address new issues.

New safety concerns may arise as additional information becomes available about the waste and/or as its properties are modified through waste retrieval and management. The first response is to develop a technical analysis of the potential existence of a problem (i.e., are the proposed circumstances credible and, if so, do they represent a significant risk?). Using information in the scientific literature about the proposed phenomena and using existing data about the tank contents, a model is created to test the safety risk hypothesis. The validity and quality of the these data are considered. New issues can bring new data quality and completeness requirements. For example, a more complete analysis of existing mass spectrum or optical spectral data may be required to look for species previously not thought to be important. Evaluating many of the suggested concerns will be accelerated because they naturally fit within the structure of existing Structured Logic Diagrams, appearing as new energetic species or reaction initiators. For concerns that pass the initial credibility test, the strategy is then fully exercised as information needs are justified and met, and the findings are used to decide on appropriate actions. This type of problem emphasizes the value of an iterative strategy where screening information (e.g., looking for species that are indicators of the existence or absence of the proposed safety conditions) is obtained before a more costly sampling and analysis campaign is undertaken to prove or refute the validity of the proposed safety concern.

2.3.3 Justify Information Needs

Sampling and analysis are costly, time consuming, and involve risky actions. Therefore, the recommended strategy does not assume a waste sampling and analysis baseline for obtaining required information. **Only information that reduces waste storage and disposal risks to acceptable levels is pursued.**

To provide a technically defensible and economically justified basis for waste characterization, the recommended strategy employs an approach that explicitly links sampling, waste analysis, physical-chemical modeling, and other learning activities to risk reduction and decision making. After the technical basis for decisions has been developed and reviewed, the knowledge that is genuinely needed to make better decisions must be determined. Justification for additional information requires specific demonstration that it can reduce uncertainty in health and environmental risks, or potentially change a decision about the system. **If new data or information derived from those data cannot reduce uncertainty, it is not justified and should not be collected. If new data will not change a decision based on current information, they are not justified and should not be collected.** If new data are not justified, the next appropriate steps are immediate decision making for this issue. In Figure 2.2, this is shown by the direct line from Section 2.3.3 to Section 2.3.8 (from Justify Information Needs to Make Decisions).

A tool that may be used to analyze risk-based requirements in complex problems is value-of-information decision analysis (Raiffa 1968; Keeney and Raiffa 1976; von Winterfeldt and Edwards 1986; Clemen 1991). Simply stated, the output of this analysis indicates that if the cost of acquiring additional information is greater than the expected costs of a wrong decision made without the information, then the information is not worth obtaining. The result is a clear measure of completion. **Characterization for a given action or decision is complete when the costs of additional characterization activities exceed the calculated value of the information for decision making or risk reduction.** Conversely, additional waste characterization is justified when the calculated value of new information exceeds the cost of obtaining it. This decision analysis approach is to be applied with a degree of rigor that is tailored to the level of difficulty and complexity of the issue being addressed. While not burdening straightforward problem analysis, it enables effective decision analysis of complex problems.

In addition to guiding characterization decisions, knowing the value of obtaining specific information will provide an explicit basis for investments in research and/or technology development to reduce health risks, costs, and technical uncertainty.

The technical analysis of each desired outcome (see Section 2.3.2) results in a set of alternatives ("paths to success") and associated information needs. The challenge is to select an acceptable alternative that achieves the desired level of risk at the lowest cost.

The attributes of the selected alternative then provide the fiscal and technical justification for needed information.

Risk and Fiscal Justification of Characterization Work

A preliminary risk evaluation is conducted using the best available information, including its uncertainty, as described in Section 2.3.2. This evaluation serves two purposes. First, it provides an initial look at where an issue or decision lies with regard to a desired risk value. To illustrate, Figure 2.5 shows four hypothetical risk evaluations for four tanks, with associated risk uncertainties given in the vertical lines. For example, the uncertainty associated with the risk estimated for Tank 3 is much greater than for Tank 2. The acceptable risk criterion is given as the horizontal line. For many industrial practices, this criterion represents a one-in-a-million chance that an unacceptable event will take place. If the predicted risk, including its uncertainty, is significantly below or above the acceptable risk threshold (as in Tank 1 and Tank 2), the issue will be summarily resolved (Tank 2) or will require mitigative action (Tank 1). **There is no role for additional characterization in either case if, in fact, the problem has been properly described and analyzed.** Because the uncertainty in the risk of Tank 3 crosses into the acceptable risk criterion value, additional characterization may be beneficial to determine if the safety issue in this tank must be mitigated or controlled. Decision makers must make that judgment. On the other hand, the risk of Tank 4 is mostly in the acceptable range; however, there is enough uncertainty in the risk estimate that the chance of an unacceptable risk existing merits more assurance that its risk is indeed acceptable. Thus, there is a strong basis for collecting additional characterization data. Sensitivity analysis (see Section 2.3.2) can then be used to identify the solution paths that have the highest likelihood for success and identify which data needs have the greatest effect on the overall risk calculation. As a result, further analysis of the value of information is less complex and focuses on the highest payback items. The inherent structure of the decision model allows for quantitative probabilistic estimates of the risk associated with the decision alternatives to be generated. Once this is done, comparison with established risk acceptance levels and evaluation of cost/risk-reduction tradeoffs become possible.

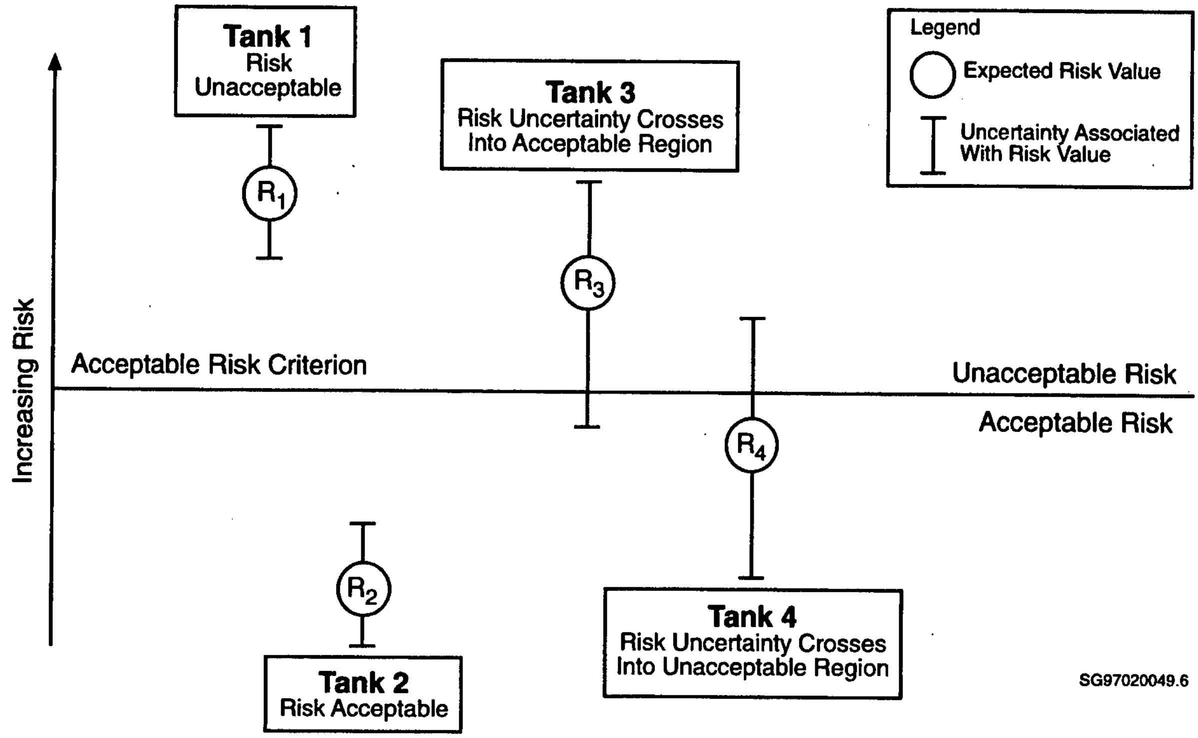

Figure 2.5. Example of Preliminary Risk Evaluation

The biggest challenge in using this approach is in obtaining a high degree of confidence in the estimate of uncertainty in the calculated risk. **Hence, when making decisions with significant consequences, it is important to evaluate carefully the validity/uncertainty of data that has the largest effect on risk uncertainty. Value of information is defined as the difference in the expected value of making the decision based on existing knowledge and making the decision with better information.** Existing information consists of prior sampling and analysis data, results of tank content models (e.g., Agnew et al. 1996; Brevick, Gaddis, and Johnson 1995; Brevick, Gaddis, and Pickett 1995a, b, c), and/or expert opinion. Value-of-information decision analysis places a distinct burden-of-proof on those who want better information to show how it will benefit decision making. A decision to undertake additional characterization work must compete for resources with decisions to undertake other activities such as mitigative or treatment actions or to accept the risk of not taking any action.

The technique initially calculates the value of perfect information (i.e., information that would allow a decision to be made with no uncertainty about the input data). Because all real data collection activities will entail some uncertainty, the value of perfect information represents the upper bound of how much it is worth to know a specific piece of information, i.e., a limit to the resources that should be allocated to obtain that information. Many potential characterization options can be ruled out because the characterization cost is greater than the value of perfect information.

The value of information decreases as the quality of the information decreases. An example for the organic-nitrate safety issue is shown in Figure 2.6 and is documented by Fassbender et al. (1996). For this example, information about tank contents

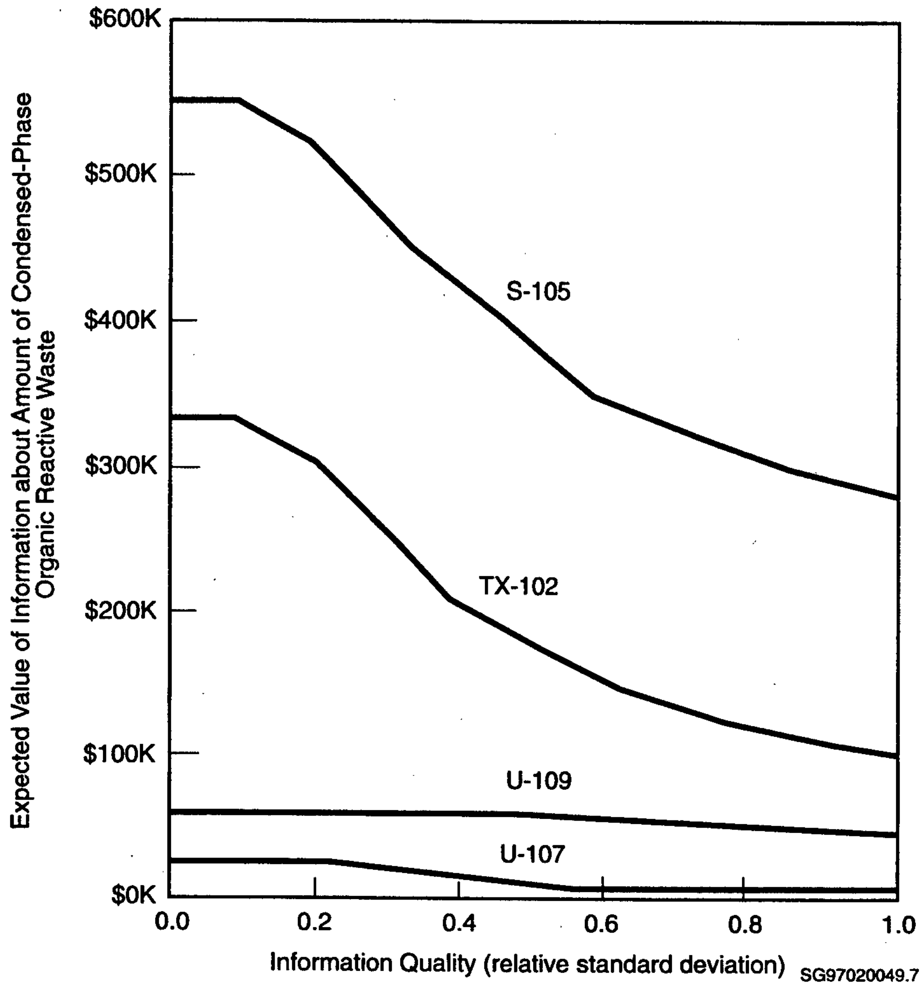

Figure 2.6. Example of Value of Information as a Function of Uncertainty

is described by the amount (volume) of reactive waste within increasingly larger increments of tank waste. Reactive waste is measured by the combined fuel and moisture content that can cause a condensed-phase organic-nitrate reaction. This figure presents the expected value of information as a function of information quality for four actual Hanford tanks: S-105, TX-102, U-109, and U-107 (see Appendix D for locations of tanks in Hanford's 18 tanks farms). One measure of quality is the relative standard deviation (RSD), which is the standard deviation divided by the mean. Perfect information has a RSD of zero. The quality of information decreases as the RSD increases. The y-axis in Figure 2.6 presents the expected value of information (for knowing the amount of reactive organic waste) in thousands of dollars, and the x-axis shows the information quality. Although a general trend of decreasing value as a function of decreasing quality can be observed, the slope and shape of the loss curve are very much tank-dependent. For example, these curves are affected by the availability and quality of prior information, the proximity of the prior estimate to the decision threshold, and the cost effectiveness of potential mitigative actions.

Additional data from Tanks U-109 and U-107 generally have a low value of information. Controlling ignition sources is an effective and inexpensive alternative to reducing the risk from these wastes.

The availability of an effective, low-cost option limits the value of collecting additional information. These two tanks are also relatively insensitive to information quality because the information has very little effect on the decision under consideration. If no changes in decisions are affected by changes in information quality, then the value of information will remain relatively flat such as for Tanks U-109 and U-107.

Tanks S-105 and TX-102 show a different scenario. The prior information cannot establish whether the waste is sufficiently damp to be unreactive. The recommended action (do nothing or conduct mitigative actions) is highly dependent on whether the waste is reactive or damp. Information on these parameters can greatly affect the decision and, therefore, establish a value for that information. For these tanks, the recommended action changes as the quality of information changes. Therefore, there is a relatively sharp decrease in the value of information as a function of decreasing quality.

The conclusions that can be drawn from the curves in Figure 2.6 are as follows: If resolving the organic-nitrate safety issue was the only concern associated with those tanks, further characterization of Tanks U-109 and U-107 would not be justified. However, gathering information from Tanks S-105 and TX-102 may be justified if it can be collected at a given level of quality for less cost than the value of information at the same level of accuracy. For example, if this information could be obtained at a quality level of 0.6 RSD for a cost of $300K, then further characterization would be justified for Tank S-105 but not for Tank TX-102. These curves provide a finite "completion" criteria.

The implementation of this value of information requires integration across all needs for information (see Section 2.3.5).

Technical Justification of Characterization Work

Technical justification of characterization work relates to the need for new information for decision making and to the feasibility of acquiring information. The justification must be rigorously and consistently applied in a scientifically defensible manner. It must be determined whether it is technically feasible for the planned approach to provide information of sufficient quality to effect decisions. Otherwise, costly and time-consuming waste characterization campaigns have no technical merit. **Technical justification is a critical factor in gaining cost control and defensibility for waste characterization activities.**

Once the required data quality is obtained, sampling ceases. For some issues, resolution may not require information about the average tank content, thus greatly reducing waste sampling constraints. For example, resolution of the ferrocyanide safety issue required only the knowledge of a ratio of constituents (nickel and cyanide) to be determined in tanks that had received ferrocyanide- and nickel sulfate-bearing wastes.

2.3.4 Use Waste Actions as Characterization Opportunities

The principal technical difficulty in the successful characterization of waste and the resolution of safety issues originates in the chemical diversity of the waste types and their physical, chemical, and radiological heterogeneity. Attempts to "completely characterize" sludges, slurries, saltcakes, crusts, and other forms of solid-laden materials are so severely restricted by the requirement for many randomly selected samples that the approach is impractical. The recommended strategy circumvents this problem by developing and taking advantage of a wide range of waste actions as opportunities for waste characterization. **For example, obtaining data during waste actions**

reduces the risk and uncertainty of future decisions because it provides understanding of the behavior of tank waste during relatively large-scale perturbations.

Actions on waste (waste operations and processing functions) are seen as key opportunities to obtain characterization information. Complex, inhomogeneous systems such as the Hanford tank wastes are extremely difficult to "characterize" using a waste sampling approach in their current stored state. However, when the waste is disturbed, measuring the response of the waste system is a standard approach to characterization that is often used in industry. Examples of such characterization opportunities may include obtaining grab samples or on-line measurements in waste transfer lines and conducting vapor, liquid, and solid sampling during and after actions to retrieve waste. At these times, better characterization information can be obtained using fewer operational and financial resources than required to obtain representative sampling and analysis results from a chemically and physically complex waste system. For example, salt well pumping has been shown to release gases that were trapped within the waste (WHC 1996). Simultaneous sampling and analysis of these gases will provide information on 1) their amount and flammability for understanding the flammable gas safety problem, 2) the existence of any new safety concerns (see the discussion on safety issues raised by new hypotheses in Section 2.3.2 and Appendix B, Section 3.5), and 3) decomposition products from organic precursors that are important elements in organic waste aging models (Webb et al. 1995).

Applying the concept of the transfer function (the ratio of the system input to the system output, where the system input is perturbed and the response is measured), the response of the tank waste system is predicted and then measured. The response of any measured parameter compared with its predicted value can validate the model or identify where improvements are required. For example, resolution of the flammable gas safety issue requires a model of the amount and composition of stored gas in each tank or group of tanks. Actions that remove liquids from a tank predictably reduce the gas storage capacity of the remaining waste. Monitoring changes in the type and concentration of head space gases will test the gas retention model for that tank. **Major actions such as salt-well pumping, tank-to-tank waste transfer, etc., are justified opportunities to obtain valuable characterization information.**

Acquiring waste data when the waste is being disturbed will add costs and complexity to waste management and processing work and therefore also must be justified by analyzing the value of information expected and comparing it with the additional costs. **The proper application of such an "opportunistic approach" significantly increases the effectiveness of waste characterization work by using waste operations and processing functions (including work by privatization contractors) as a cost-effective method to collect additional information from large waste volumes.** The approach requires modification of operational practices to allow for the addition of characterization instruments and work. These opportunities must be carefully designed to provide the highest return on investment in waste characterization. The recommended strategy also acknowledges that characterization is not a one-time event. As wastes proceed through the interim storage/treatment/disposal life cycle, their composition and characteristics will be altered either naturally or through operations actions.

The contractual framework in which privatization vendors and support waste management functions do their work needs to support characterization as a risk management tool. For example, the preparation of waste feeds for use by vendors should support characterization needs

broader than just performing vitrification demonstrations on that feed. It is also recommended that the privatization contracts require the contractor(s) to disclose extensive data about the waste composition, properties, and behavior while being treated—data that they might otherwise consider proprietary. Especially during the early years, these data will provide valuable information about the waste that remains in the tanks from which the waste was retrieved for delivery to the privatization contractor and about waste in similar tanks.

2.3.5 Integrate Requirements and Plan Characterization

The output from the risk-based and value-of-information requirements analysis process provides an explicit and potentially quantitative basis for integrating characterization needs from each issue and each tank to form a complete, comprehensive, and defensible characterization plan. This integration leads to the appropriate selection of sampling and analysis, monitoring, special studies, and laboratory experiments to form an implementation plan for a defensible and cost-effective characterization supporting the waste disposal program. This approach will also provide a defensible basis for budgeting and scheduling decisions by justifying and prioritizing characterization work for funding. Characterization work conducted in this context will become a cost-saving investment because it selects only those characterization actions that are less costly (more valued) than taking alternative actions to achieve waste safety or disposal goals without the additional information that additional characterization work would provide.

Characterization decisions will not be based solely on individual issues. The risk-based requirements analysis process estimates the value of information about a specific issue in a given tank. However, characterization decisions will be based on the combined need for information in a given tank or for the combined value of knowledge gained from quantifying a particular parameter or chemical process across multiple tanks versus the cost of obtaining it. Techniques for combining value of information across issues and tanks are addressed by Fassbender et al. (1996).

Decisions regarding further justified characterization and the relative tank priorities discussed above provide a defensible basis for preparing short- and long-term characterization plans and optimizing characterization schedules. Individual tank characterization plans will be developed for each tank, group of tanks, or waste actions based on the combined value of performing characterization activities in that tank. These plans document the rationale for collecting or not collecting further data.

2.3.6 Collect Data

Data collection activities will be conducted based on the tank waste and waste actions characterization plans. These activities can include historical records retrieval, laboratory experiments (e.g., aging of organic wastes), on-line monitoring of tank conditions (e.g., hydrogen monitoring sampling and analyses, results from modeling [e.g., tank layering model]), or review of work in the scientific literature.

Raw data are collected in any of the methods listed above, then processed and validated to become useable information for the Resolution Team. It is critical that these data accurately represent the parameters the Resolution Team requires for making technical decisions.

Historical and Expert Judgment Data

One source of information is historical data available on a tank. If the source is sufficiently reliable, then the information would be provided and the request satisfied (see Appendix B, Section 2.3.1).

An example of a historical data source is the Historical Tank Contents Estimation model (Brevick, Gaddis, and Johnson 1995; Brevick, Gaddis, and Pickett 1995a, b, c; Agnew et al. 1996). This information is based on the use of historical processing and waste transfer/storage records to infer current tank contents. The most reliable historical data sources will have been validated and peer-reviewed to ensure the required data quality. The above noted data sources have not been validated by external experts. Much of the historical raw data must be combined with numerical modeling (e.g., radiological aging of components and physical layering) to produce valuable information.

Another method for developing estimates of parameters is to elicit the values based on expert judgment. This method is an adaptation of the Nuclear Regulatory Commission (NRC) methodology documented in the NUREG-1150 risk analyses of several nuclear power plants (NRC 1989; Keeney and von Winterfeldt 1991). The NUREG-1150 methodology involves a formal elicitation of probabilities using expert judgment combined with extensive existing data and model calculations. Some of the important features of the methodology are

- clear definitions of the parameters and variables to reduce ambiguities about what is to be elicited
- careful selection of experts to preserve a broad range of approaches and diversity of opinions about the variables
- training of the experts in expressing their judgments as probabilities and probability distributions
- aggregation of the expert judgments to preserve the range of opinions and approaches
- documentation of the results in a form that allows reviewers to scrutinize the reasoning of each individual expert.

Recent studies of flammable gas safety have relied on this method for estimation of some parameters and are summarized in Chapter 3.0. Elicitation of values from experts should only be used when sufficiently reliable data are not otherwise available. Details on the elicitation process are provided by Fassbender et al. (1996).

Experimental and Modeling Data

Experimental data are another source of information. Laboratory experiments are performed on actual (or simulated) waste to provide information about phenomena and to estimate key parameters.

For example, important information has been provided in this manner about the mechanisms of the formation of flammable gases, the decay of energetic compounds, and the distribution of chemical species among different phases within the waste materials.

Modeling data result from mathematical representations of physical and chemical phenomena. Modeling results are used when a first estimate of a parameter is required, or when it is difficult to measure an actual value because of time, costs, or operational constraints. Existing tank layering models, organic aging models, and tank waste grouping models are examples of numerical representations of actual phenomena. Models also help to interrelate divergent data sources. For example, it may be possible for modeling (e.g., a chemical reaction model) to relate information about the liquid and vapor phases (information retrieved via sampling or monitoring) to the contents of the solids in the same tank.

Monitoring, Sampling, and Analysis Data

Tank monitoring data are parameters such as in situ temperature, liquid level, and vapor space measurements. Acquisition of these data has some of the same vulnerabilities as retrieved samples (e.g., grab, auger, or core samples) in terms of how well the data represent actual tank conditions.

One of the most vulnerable points in any characterization strategy is the acquisition of samples. This applies both to physically removing the waste for subsequent ex situ analysis or to placing an in situ measuring instrument in the waste. Sampling of the nearly homogeneous liquid and vapor phases in the tanks avoids the major concerns about sample representativeness that strongly affect the value of sampling thick slurries, sludges, and saltcakes (see Appendix B, Section 2.3.1). The solid phases of the wastes are typically heterogeneous and not necessarily in equilibrium with each other or with the liquid and vapor phases. A defensible strategy for justification of solids sampling requires consideration of the number of samples, their location(s), the waste handling and processing requirements for analysis, etc. Any sampling plan will be constrained by the locations of access. Existing access ports into the tanks 1) limit the use of random or fixed grid sampling schemes, and 2) may be over waste that is not representative of waste in the entire tank. A potential resolution of this problem is to use the technology needed to sample the tanks at any location (e.g., flexible robotics) or to characterize the wastes after they have been removed from the tanks. Another method is to use waste perturbations as characterization opportunities by predicting and measuring the system response to change (see Section 2.3.4 and Appendix B, Section 2.3).

Statistical modeling approaches (e.g., models of lateral heterogeneity, grouping tanks by waste types [Hill, Anderson, and Simpson 1995], etc.) may prove useful in specifying the number of samples required. Once the required data quality is obtained, sampling ceases. For some issues, resolution may not require information about the average tank content, thus greatly reducing waste sampling constraints. For example, resolution of the ferrocyanide safety problem required only the knowledge of a ratio of constituents (nickel and cyanide) to be determined in tanks that received ferrocyanide-bearing waste.

2.3.7 Process, Manage, Validate, and Model Data

A strong data management system is vital to the success of the recommended strategy. Data collected will be systematically captured and preserved by a reliable data management system. The data management system will provide the data and data quality information to the Resolution Team and all interested technical experts, decision makers, and stakeholders. Openness is key to maintaining the involvement of the broad scientific community in assuring the quality of the approach and the results. Electronic access to characterization information is also a requirement of the Tri-Party Agreement (Ecology, EPA, and DOE 1996). The information structure provided by the Structured Logic Diagrams will provide an important guide to organization of the information in the database.

Commonly, data by themselves do not constitute information. Information is derived from the data through chemical, physical, and/or mathematical models that relate the data to the phenomena of interest. Data that have been obtained for a particular purpose may or may not prove to be useful in responding to other information needs. If data do not meet the quality standards for the intended purpose other means must be derived to obtain the required information. If the results fundamentally change the understanding of the problem, the characterization strategy will iterate back to the technical basis development/refinement step to benefit from this new understanding.

It is also important to evaluate objectively the quality of information relied upon for decision making because technically and economically important decisions depend upon using information of known quality. The defensibility of subsequent action depends upon the technical and scientific soundness of the inputs and the decision process followed. For example, in determining the moisture content in solids, precision is only important near a threshold value. The waste type varies sufficiently from sample to sample to affect how each measurement should be performed. Thus, "data quality" may be damaged rather than enhanced by using a nationally certified and traceable method for generic solids. Data quality must also be evaluated by independent (free from conflict of interest) and technically qualified personnel.

2.3.8 Make Decisions

If the execution of the recommended strategy is sound, results will promote making well-documented, defensible decisions that lead to actions with acceptable risk. The objective of the entire strategy is to guide the application of characterization resources so that their use is technically defensible, economically justified in the context of acceptable risk, and advances the safe storage and successful disposal of Hanford tank wastes.

The inputs to safety issue resolution decisions are the appropriate risk constraint measures, understanding of the parameters driving risk, and the risk-based decision model(s) for the issue. If the current state of knowledge satisfies all of the appropriate risk constraint measures, then the safety issue is resolved and the desired outcome is achieved. Thus, a perceived problem will have been resolved through understanding that the properties of the waste pose no unacceptable risk due to the related safety concern, and no mitigation or control actions are required as long as the controlling properties of the waste remain within acceptable limits. **If the issue cannot be resolved through understanding gained from existing information, then risk reduction tradeoffs will be evaluated. These include taking mitigative action, establishing operational controls, or performing a more thorough evaluation of risk and cost consequences.** Mitigative actions can either permanently mitigate the hazard or conditionally mitigate the hazard so that continued intervention becomes necessary. Installation of the mixer pump in Tank SY-101 is an example of conditional mitigation. Operational controls do not remove the hazard, but attempt to reduce, for example, the occurrence of initiators that might trigger a disruptive event such as a flammable gas explosion.

Disposal decisions also begin with the same set of inputs. The appropriate set of risk measures will be more far-reaching than for safety issue resolution decisions and will encompass issues such as long-term environmental risk, sociocultural risk, and programmatic risk in addition to the human health risks that dominate decisions related to safety issue resolution. These risk constraints and the methodologies to develop meaningful risk constraint levels are detailed by Harper et al. (1996).

If a prospective decision alternative meets all established decision criteria (risk constraint measures), then action can be taken directly to achieve the desired outcome. However, if some criteria are not satisfied by the best alternative, then further interaction with regulators and other representatives who work with the DOE to establish the decision criteria may result in a renegotiated basis for action to achieve the desired outcome. If neither of these paths are attainable, further evaluation of the problem will be required. A successful implementation of the risk management strategy requires that the parties involved in the decision-making process plus technical staff have a mutual understanding of the quantitative aspects of risk and cost-benefit calculations (Section 2.3.3).

2.3.9 Take Actions

The goal of the outcome-focused strategy is to take actions towards achieving the desired waste safety and disposal outcomes under the conditions of well-managed risk.

The types of actions being considered are 1) those designed specifically for obtaining waste characterization data, 2) mitigative actions such as salt-well pumping or adding mixers to tanks, 3) addition of monitors and/or controls leading to improved operational safety, and 4) actions on the waste in direct support of waste disposal (i.e., preparation and delivery of waste for processing). When fully developed, the recommended strategy will provide the basis for justifying such actions. It will provide decision makers with the projected risk reduction benefits and with information about the risks and inherent uncertainties involved in taking specific actions.

When sufficient knowledge has been accumulated, a decision will be made by the DOE or its contractor personnel from prospective alternatives. Generally, the most effective alternative in terms of risk reduction, cost-effectiveness, and public acceptance will be selected. **If a solution is found in which the risk, cost, and schedule are all acceptable, then the proposed action will be taken.** If no such solution is available, the process iterates back to evaluation of the technical basis to develop new alternatives or solutions. Key criteria in the justification of characterization actions are that their cost should not exceed the value of the information gained for guiding decisions about other actions.

If a prospective decision alternative meets all established decision criteria, then action can be taken directly to achieve the desired outcome. Note that 1) the choice of an action is made by individuals and will not be without risk even when based upon rigorous logic and quantitative risk analysis, and 2) the decision to not take any action also carries a certain amount of risk and must be technically defensible.

The recommended strategy also incorporates characterization actions into other actions that significantly perturb the waste. Properly designed characterization work conducted while taking actions will provide further knowledge that will refine the technical understanding for resolution of other issues and future decisions. Such events represent unique opportunities to gain further knowledge about the wastes.

Any action affecting large volumes of the waste can be seen as a deliberate perturbation of the model for that tank or group of tanks and should be used to refine the model. An example of applied characterization accompanying an action is evaluating the temporal fluctuations of the hydrogen concentration in the dome of Tank SY-101 following pump installation. To take advantage of these opportunities, the planning and approval of characterization actions must be rapid and flexible. **This, in turn, will require reassessment of the current operational constraints on obtaining access into and on conducting studies inside the tanks to take better advantage of these characterization opportunities.**

3.0 Application of the Strategy: Two Illustrations

The objective of this chapter is to show how the tools of the recommended strategy work when applied to an actual safety problem. These tools include: logic-based problem analysis, iterative development of understanding, justification of characterization actions including the use of sensitivity and uncertainty analysis, and risk-based decision making. Creation of an integrated characterization plan using value of information and consideration of other factors, such as operational capabilities, would be included in an implementation plan if the recommended strategy is adopted. The two safety issues used in this chapter do not represent full integration of the characterization needs of the six safety issues facing Hanford tank farm operations; all issues should be addressed in an integrated program to guide and justify characterization work. Full application of the strategy would include integration across information needs for safety issue resolution and other waste management and disposal needs. These illustrations demonstrate how the strategy is used to determine if a potential safety problem exists for each particular tank, and if it does, how to identify the information needed to resolve, mitigate, or control the issue (see Section 2.3.2).

This chapter illustrates the application of the recommended strategy for the organics-oxidants safety issue (see Section 3.2) and the flammable gas safety issue (see Section 3.3); both safety issues potentially exist in many of the waste tanks at the Hanford Site. Application of the strategy is illustrated by working through the steps of the recommended strategy (described in Chapter 2.0). The same process is found in Appendix B, Section 3.2, where the strategy is applied specifically to the flammable gas safety issue in greater detail than is discussed here. **Successful accomplishment of any of the options to resolve, mitigate, or control the safety issue requires that acceptable risk criteria for the specific safety issue be defined and used as the basis for determining when further investigation/study is no longer needed.** The flammable gas safety issue discussed here specifically illustrates the effect that various risk acceptance criteria can have on decisions and recommended actions. The results for both examples should be viewed as illustrative of those that will be obtained using the recommended strategy.

As noted in Section 1.0, a test of the recommended strategy addressing the organic-nitrate safety issue in Hanford's 149 single-shell tanks was begun in December 1996 with completion and documentation scheduled for early 1997. This test uses existing data and models and will classify all tanks according to this element of their safety risk. It will also contain plans for characterization work needed to reduce uncertainties sufficiently to take corrective actions, if necessary, with confidence that those actions will be safe and cost-effective.

3.1 Classification of Hanford Tanks Using the Recommended Strategy

The result of applying the recommended strategy to any given safety issue is the classification of the current status of each tank with respect to the risk acceptance criteria. This classification can, and should, result in the grouping of tanks as those for which 1) sufficient information exists to make the decision that the risk of a disruptive event is extremely low (i.e., the disruptive event is not credible), 2) the calculated risk is found to be acceptable, 3) mitigation is required to achieve acceptable risk, or 4) controls are required to achieve acceptable risk. The objective of determining that any

given tank is "safe" will have been met if the risk is shown to be acceptable, or mitigation and/or controls are implemented that achieve acceptable risk. Although unlikely, it is possible that the safety issue cannot be resolved using existing or obtainable information, and that neither mitigation nor controls are sufficient to achieve the desired risk acceptance criteria. If this case occurs, alternatives may be limited to either accepting a greater than desired level of risk or implementing extreme measures such as emptying the tank of all waste.
In addition, the risk classification may change as a function of time as a result of changes in tank contents due to chemical reactions, loss/removal of moisture from the waste, or other operations on the tank and its contents. A clearly identified and documented description of the chemical and physical characteristics and phenomena contributing to the risk of a disruptive event permits the risk to be analyzed as a function of the changes in tank contents with time. The recommended strategy accomplishes this by use of a Structured Logic Diagram (see Section 2.3.2). The Structured Logic Diagram can also be used to predict the consequences of a disruptive event change as natural or planned events alter the amount and composition of the tank waste.

A definitive and documented method to determine when enough information has been obtained to make a defensible decision is essential. The recommended strategy accomplishes this by using risk acceptance criteria to define what is "safe" and a technically defensible and documented approach to determine if these criteria have been met. The determination of what is safe is usually expressed as the risk meets or is less than an acceptable criterion (e.g., less than 10^{-6} events per year having a particular consequence) with an acceptable level of confidence (e.g., 95% confidence). Meeting these conditions establishes the basis for solving the issue. As shown in this section, decisions about actions, information needs, and acceptable uncertainty in the information are strongly affected by the level of risk defined as acceptable. This level of risk is based upon the preferences and values expressed by decision makers.

Organic solvents and complexants present in tank wastes, and their potential rapid reaction with oxidants, constitute two of the five safety issues addressed in this report. The organics and their degradation products are present in the tanks in varying quantities, as are the oxidants such as nitrates and nitrites. Flammable gases, principally hydrogen, originate in the tank wastes as a product of radiolytic and chemical reactions.

Consideration of the underlying phenomena led to the identification (or acknowledgment) of the following controlling parameters (in italics) and associated conclusions for the organics-oxidants safety issue and the flammable gas safety issue:

- Organics-oxidants. *Amount of organic fuel; moisture content; rate, and decomposition mechanism for degradation of organic constituents; energy content, and spatial distribution of reactive material; and mechanism of reactions leading to rapid release of energy.* Numerous waste tanks (see Section 3.2.3) at the Hanford Site show low risks in preliminary analyses. Others do not yet have enough information or data to determine their risk without a large uncertainty, and some show a greater than acceptable risk. Control of reaction initiators and/or mitigation to increase moisture levels are options for the tanks that have a greater than desired risk. As additional information and data are obtained, the risk for a given tank will be reassessed.

- Flammable Gas. *Potential to store gas; amount of stored gas; composition of stored gas; and the potential to release significant quantities of stored gas in a brief time period.*

All waste tanks will generate some quantity of flammable gas; only those tanks that have the potential for a flammable quantity of gas to exist and react are of concern.

Numerical values of acceptable risk do not need to be determined before the potential occurrence of a disruptive event is addressed through developing the chemical and physical models of such an event and assembling existing information relevant to the phenomena these models represent. However, numerical values of risk, or some other clearly defined risk acceptance criteria, are required for defensible classification of the tanks on the basis of the risk of a disruptive event and for making informed decisions regarding operations and actions on the waste.

All parties want risk to be as low as possible within limits of cost, programmatic schedules, and other constraints that may be imposed. Calculation of the risk of a disruptive event, the uncertainty associated with that risk, and identification of the information having the greatest influence on the risk provide the decision maker with the data needed to weigh the merits and potential liability of further actions. These are illustrated in subsequent sections.

3.2 Organics-Oxidants Illustration

3.2.1 Determine Paths to Success

An annotated version of Figure 2.2 is shown in Figure 3.1 for the organics-oxidants safety issue. The risk acceptance criteria chosen for this illustration are that the expected radiation dose to workers or the public will be within acceptable limits. There are several ways that this risk can be specified. For this illustration, we will use those methods described in WHC-CM-4-46, Rev. 0 (WHC 1989), which requires less risk for events expected to be more likely to take place. A structured logic analysis of the organics-oxidants safety issue has been performed (Goheen et al. 1996). This analysis documents the disruptive event model in terms of the chemical and physical information needed to determine the risk of the disruptive event. A simplified version of the resulting Structured Logic Diagram is shown in Figure 3.2. The disruptive event model is used to predict both the probability and consequence of an event that, in combination, determine the risk. The event model is itself composed of submodels of the reaction of organics and oxidants, the response of the tank to the energy released by such reactions, and the release and dispersal of radioactive and hazardous material from the tank due to the disruptive event. These submodels are often coupled, as shown by the dotted lines in Figure 3.2, indicating that the waste release properties and the energy released are directly related to the energy content in the waste.

The structured logic approach illustrated in Figure 3.2 and shown in greater detail in the full Structured Logic Diagram (Goheen et al. 1996) provides numerous ways to show that a given waste tank is within the acceptable safety criteria, or can most likely be made to be within such criteria by mitigation or application of controls. Any given set of information that permits the risk of a disruptive event to be determined and compared with the risk criteria identifies a potential "path to success" (a method to assess the safety of the tank contents with respect to the risk of a disruptive event).

For example, a tank may contain very hazardous and reactive waste but the amount of reactive waste may be small enough to pose no risk of damage to the containment structure even if a disruptive event occurs as a result of that reactive waste. In fact, there may be key parameters or parameter sets that, if known with sufficient accuracy, can be used to

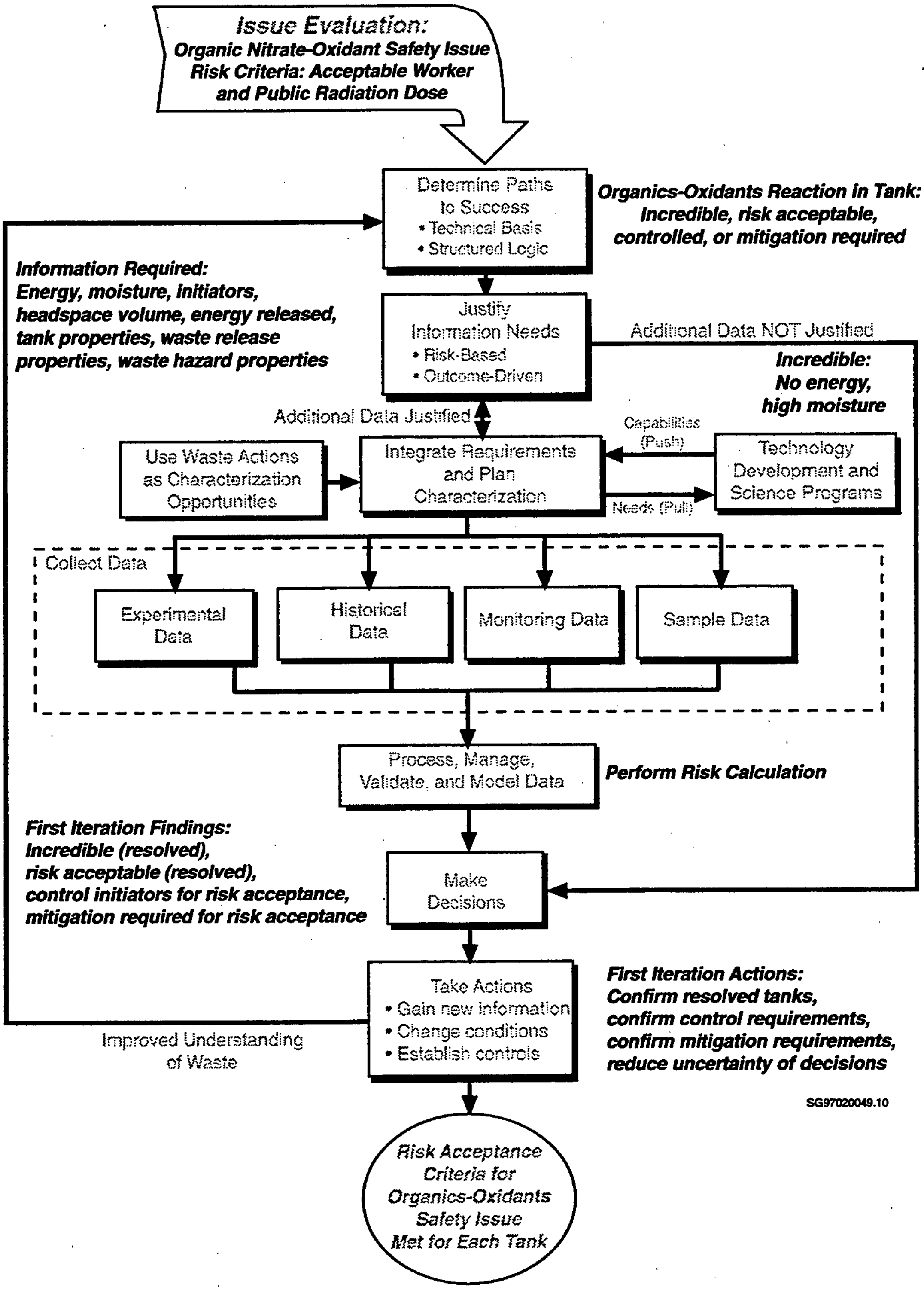

Figure 3.1. Annotated Problem Analysis Process for the Organics-Oxidants Safety Issue Using the Recommended Strategy

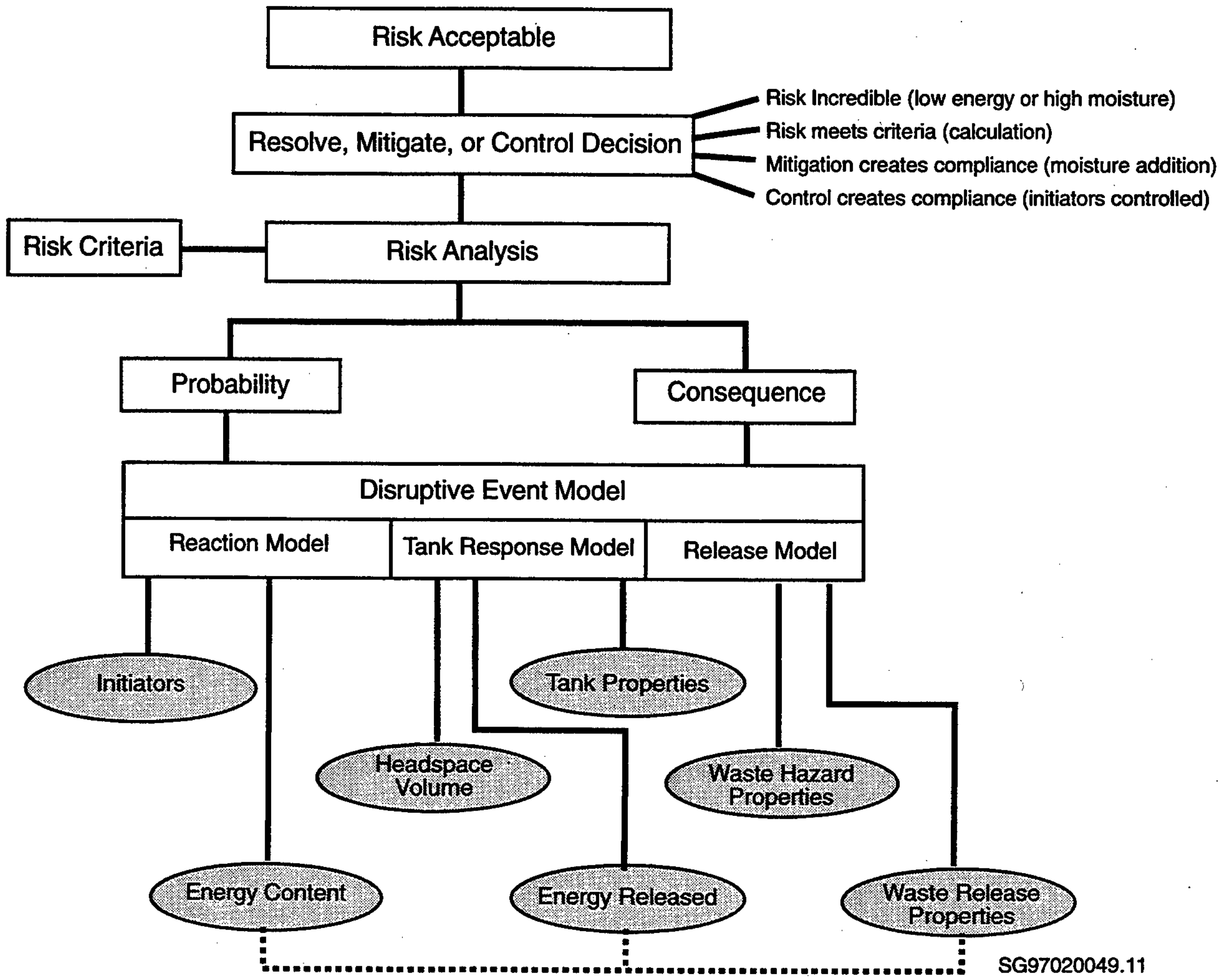

Figure 3.2. Simplified Structured Logic Diagram Used to Illustrate the Organics-Oxidants Safety Issue

demonstrate that the risk of a disruptive event for a tank or a group of tanks is incredibly small (vide infra).

3.2.2 Justify Information Needs

In the first iteration of the analysis of risk through the strategy (Figure 3.1), all available information needed to assess the risk is considered "justified." Thus, the first iteration uses existing information, including its uncertainty, to determine if the risk acceptance criteria can be met by at least one pathway—if the criteria are met, no further information is needed (i.e., additional characterization is not justified). However, as illustrated in Appendix B, Chapter 3.0, several iterations of the strategy may be needed to develop a reasonable model of the event for conditions applicable to Hanford's waste tanks. That description is not repeated here.

In our illustration, information exists for estimates of the waste content (Cowley 1996; Van Keuren 1996; Agnew 1996; Agnew 1997), the reactivity of various organics-oxidants mixtures (Scheele et al. 1995; Camaioni et al. 1994; Burger 1993; Barney 1994), and estimates of the amount of reactive waste in many tanks from waste sampling and analysis data (FAI 1996; Plys, Malinovic, and Lee

1996). Source-term information used to describe and calculate the dose consequences resulting from an unwanted organic-nitrate reaction in a tank was based on Agnew et al. (1966). This existing information will be used to illustrate implementation of the strategy.

3.2.3 Calculate Risk

The Structured Logic Diagram can be used as the basis for calculating risk once the input parameters are known or estimated. If the parameters have little uncertainty, calculation of the risk is a straightforward process. **However, accounting for uncertainty in the parameters in a way that facilitates meaningful decision making is an essential component of any risk-based strategy.** For the upcoming illustration, risk acceptance is to be determined as a function of both the frequency and consequences of the descriptive event—as noted, the risk criteria used (WHC 1989) require events with expected greater frequency of occurrence to have lower consequences.

The uncertainty in the risk calculation, and therefore confidence in making a decision about whether the risk is acceptable, depends on both the frequency and consequences of the disruptive event. This requires the frequency and consequences to be calculated simultaneously, using the parameters and their ranges of uncertainty that apply to each. The numerical values of the parameters and their range of uncertainty are determined through characterization activities. A formal or informal sensitivity analysis can be used to limit at least the initial set of viable parameters so that the number of such calculations is manageable and meaningful. The parameter variations are performed in a statistically sound manner (using Monte Carlo methods) to avoid biasing the results. The results of each calculation are then plotted and compared with the acceptance criteria as illustrated in the hypothetical example shown in Figure 3.3.

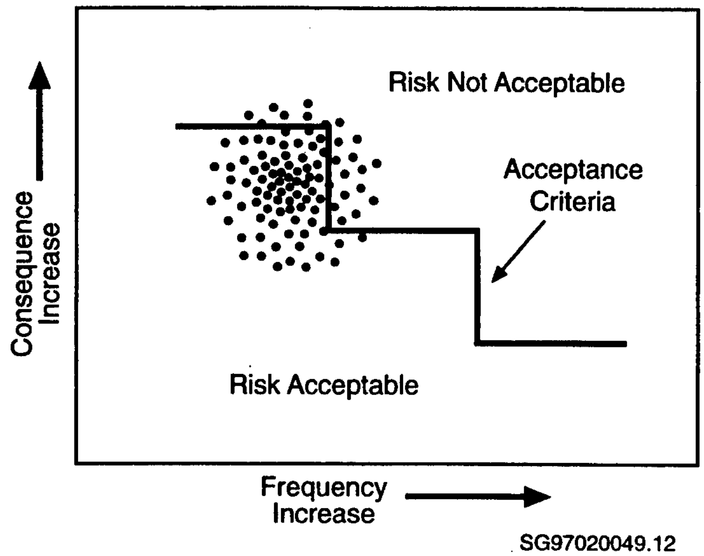

Figure 3.3. Risk Calculation Results Incorporating Parameter Uncertainties for a Hypothetical Example

The expected value of the risk is then obtained by averaging all of the calculations. The degree of confidence that this value represents acceptable risk to the decision maker is determined by the fraction of the calculations that fall within the acceptable range of values. For example, if 95% of all calculations predict acceptable risks to the decision maker, then the system is deemed safe with 95% confidence. Other confidence levels can be used if acceptable to decision makers.

Some risk-based decisions are primarily a function of event frequency without explicit consideration of consequences. The programmatic effect (e.g., due to work stoppage, situation analysis, investigations, and imposition of work-limiting controls) of a disruptive event in one of the Hanford tanks can be very large. Thus, a more constraining criterion that would supersede the health and safety risk criteria would be to require the potential risk of a disruptive event such as a contained, in-tank fire, to have a frequency of occurrence of less than one in a million years even if the disruptive event had no direct health risk consequences. For this type of risk assessment, it is better to compute the cumulative probability of a disruptive event occurring as a function of frequency, as shown in Figure 3.4. The cumulative probability of an event occurring at or at less than a given frequency is the fraction of all calculations that predict that given frequency or lower frequencies. When displayed as in Figure 3.4, the degree of confidence in the prediction of the frequency can be read directly and compared with the risk criteria. Uncertainty in the calculated risk (due to inaccurate data or models) is reflected in the shape of the cumulative probability curve illustrated in Figure 3.4. A sharper (near step function) curve reflects little uncertainty. A gradual

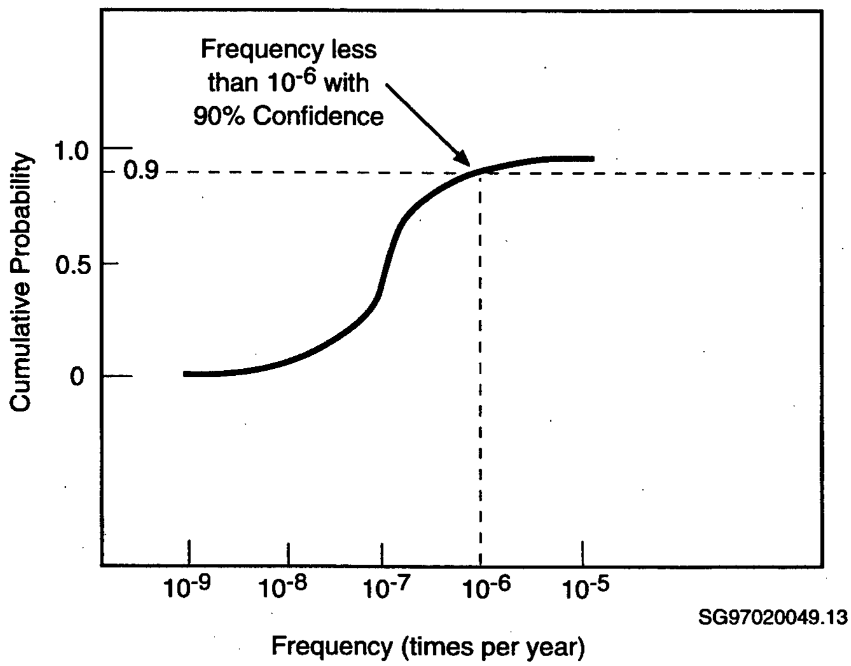

Figure 3.4. Use of Cumulative Probability to Establish Acceptance Criteria Based on Frequency of Occurrence

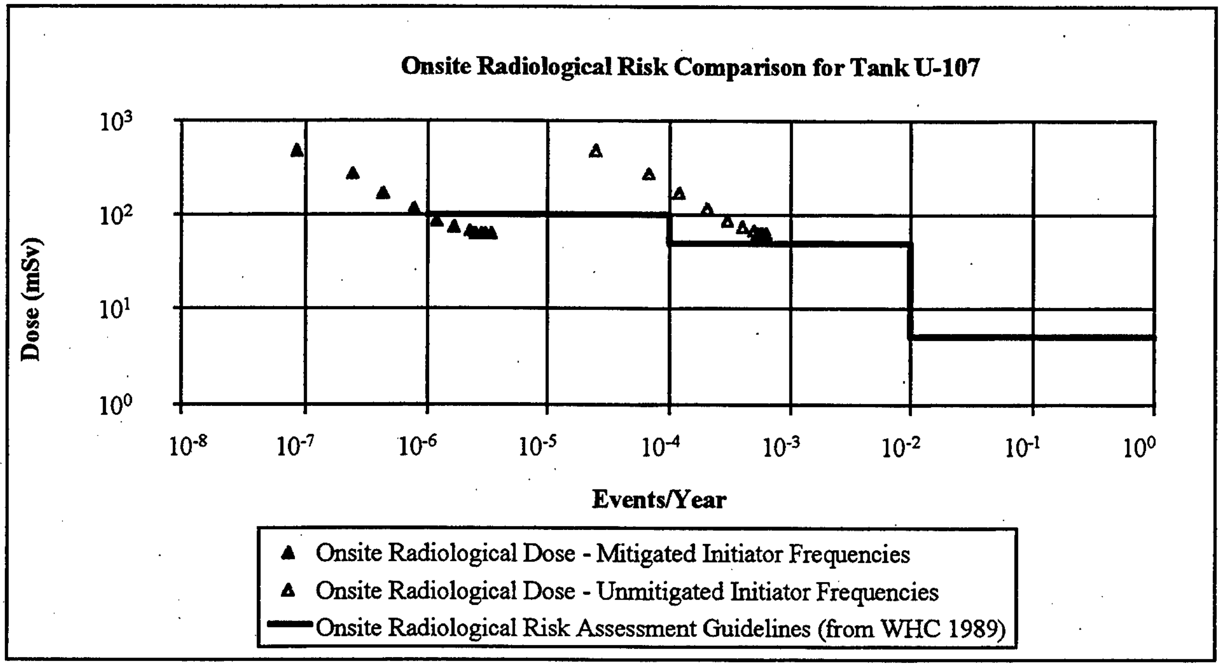

Figure 3.5. Calculated Radiological Risk to Workers from an Organics-Oxidants Disruptive Event, Waste Tank U-107

steepening of the cumulative probability curve denotes a higher degree of uncertainty.

For the first-pass analysis of the organics-oxidants risk, calculations were performed in which two parameters were varied. The amount of reactive waste was varied over the full range of its known uncertainty and the frequency of reaction initiators was given two values, the currently expected value and the value expected if controls were put in place. The calculated radiological risk to onsite workers resulting from an organics-oxidants disruptive event in Tank U-107 is shown in Figure 3.5 (tank locations are shown in Appendix D). For the organics-oxidants safety issue, there is a correlation between event consequences and frequencies. As the amount of reactive waste increases, the event consequence increases, as does the likelihood that the waste will be ignited. Most initiators are point sources such as an overheated waste sampler or a spark. Thus, as the amount and hence the cross-section of the reactive waste volume increases, the expected frequency for an event increases as does the event consequence. This is illustrated in Figure 3.5 by plotting the expected frequency of an event as a function of the predicted event consequence (dose to onsite workers) for the waste in Tank U-107. This figure shows that this tank does not meet acceptance criteria (the radiological risk assessment guidelines shown in Figure 3.5) unless controls on possible reaction initiators are implemented, and it may just meet acceptance criteria even with controls on possible reaction initiators.

For this illustration, the decision maker must determine whether obtaining additional and/or more accurate information on the amount of reactive waste is cost-effective relative to accepting the calculated risk, whether mitigation by adding moisture to the reactive waste will result in acceptable risk, or whether better models of the phenomena, including waste release and dispersal models, are needed. The recommended strategy facilitates the decision-making process by framing the issues to be addressed in a technically defensible and documented manner using the Structured Logic Diagram to describe the important phenomena, and by conducting sensitivity analyses to determine which data have the biggest effect on risk and risk uncertainty and hence on the decisions. Then, value-of-information techniques can be applied to determine whether it is more cost-effective to 1) obtain additional information, 2) act directly to mitigate the issue, or 3) accept the current level of risk for some period of time until such actions are taken to process or stabilize the waste in a given tank.

The calculation described above was performed for each waste tank at the Hanford Site by a team of PNNL and other Hanford Site scientists. Only a brief general outline of the work is described here. The distribution of reactive waste was estimated in a conservative manner. The amount of reactive waste and its energy content were determined using total organic carbon (TOC) measurements of the waste, or estimates of TOC, which is the method currently being used at Hanford. This illustration does not presuppose that TOC is either the correct or even an adequate measure of the quantity of reactive waste and its energy content. The recommended strategy would require that this question be addressed by the Resolution Team. The results of these calculations were a set of graphs like Figure 3.5, one for each tank. The conclusions drawn from the analysis of these graphs are shown in Table 3.1. The comparison of these results and the current Watch List of 54 waste tanks (Hanlon 1996a) for this safety issue is shown in Table 3.2

Based upon available data and information, the differences are significant because the results of applying the recommended strategy show that at least four tanks on the Watch List have an acceptable risk. **Such results imply that the basis of selecting/identifying the Watch List tanks for this safety issue is not complete.** See Appendix D for tank locations in Hanford's 200-East and 200-West Areas.

3.2.4 Make Decisions

Initial analysis of existing information and its use in calculating the risk of a disruptive event provides the first iteration in determining whether the risk is acceptable. The results of this first iteration may be sufficient to determine that the risk of a given disruptive event is acceptable for a number of waste tanks, i.e., those shown to have risks whose magnitude is very small compared with the value of acceptable risk (Table 3.1). However, this preliminary analysis did not vary all possible key sensitive parameters. In addition to considering the amount of reactive waste, the uncertainty in the rate and decomposition mechanism for degradation of organic constituents, the spatial distribution of reactive material, and the mechanism of reactions leading to rapid release of energy must also be considered. Furthermore, the uncertainty in obtaining the amount of reactive fuel from measurements of moisture levels and of TOC must be carefully evaluated. Also, waste characteristics were derived from a tank grouping model for tanks for which no sampling and analysis data existed during the time period the calculations were performed. Uncertainty about the validity of waste characteristics obtained by sampling also

Table 3.1. Results of First Iteration Calculation of Risk Classification for All Hanford Site Waste Tanks from an Organics-Oxidants Disruptive Event

Risk Classification	First Iteration Result	Recommended Actions
Incredible (not possible)	57	Confirm, then no action
Risk acceptable (well resolved)	12	Confirm, then no action
Risk acceptable (close to requiring controls)	39	Confirm, then no action if risk is acceptable
Control initiators (well resolved)	62	Add controls or characterize
Control initiators (close to requiring mitigation)	4	Add controls or characterize
Mitigation required	3	Add moisture or characterize

Table 3.2. Comparison of Organics-Oxidants Watch List Tanks with Risk Assessment Criteria Using the Recommended Strategy

Tanks on May 1996 Organics Watch List (Hanlon 1996a)	Risk Assessment of Tank Using Recommended Strategy
B-103, T-111, TY-104, U-204	Resolved (incredible—not possible)
none	Risk acceptable (well resolved)
C-102, C-103, U-203	Risk acceptable (close to requiring controls)
A-101, S-102, SX-103, SX-106, TX-105, TX-118, U-106, U-107, U-111	Control initiators (well resolved)
S-111	Control initiators (close to requiring mitigation)
AX-102, U-103, U-105	Mitigation required

exists. The Resolution Team would consider all such contributions to the uncertainty in knowing the risk before recommending specific decisions to either obtain more information (recycle to Justify Information step in Figure 3.1) or take specific actions as described in Section 3.2.6.

The organics-oxidants results shown in Table 3.1 illustrate that not all waste tanks require the same level of detail of information to permit defensible safety resolution decisions. Using the Structured Logic Diagram and determining the information that has the greatest effect on the total risk of a disruptive event permits making defensible decisions based on available information. If needed, value-of-information techniques are used. Risk is calculated during each iteration through the recommended strategy (Figure 3.1) until a defensible recommendation is obtained.

This illustration has been treated as an "independent" disruptive event with the risk acceptance criteria limited to radiological risk to the public and workers. The strategy indicates the need to integrate the various disruptive events and their information needs; furthermore, the strategy provides the tools to conduct this integration.

3.2.5 Justify Data for Next Iteration of Analysis

If additional and/or more accurate information is needed to show that the risk of the disruptive event is within acceptable criteria, then the optimum information to obtain must be determined. As noted in Section 2.3.2, this can be done by using the Structured Logic Diagram to identify what information will result in the understanding required to assess the risk. The optimum information is then identified by determining 1) that if certain critical parameters were known to a sufficient level of accuracy, direct resolution of the safety issue would be achieved; 2) whether new information would result in changes of decisions regarding actions; 3) whether obtaining the information is feasible and can be done to a sufficient quality; and 4) whether the costs of obtaining the information are justified, i.e., implementing mitigation or controls might be less costly than obtaining the information needed to determine if the safety issue can be resolved. This is done by examining the potential "paths to success," performing sensitivity analyses of the relevant parameters and inputs, and using value-of-information techniques to provide guidance on the cost-effectiveness of options. These "tools" of the strategy need to be used only to the extent required to make technically sound and scientifically defensible decisions.

A characterization implementation plan would then be prepared after integrating data and information needs from other program elements. The plan may involve conducting laboratory studies, improving prediction of tank contents, sampling and analysis of tank waste, and conducting direct and/or indirect monitoring for chemical species of interest or of particular physical parameters. Longer-term efforts to understand the waste's reaction phenomena, its energetics, and kinetics are expected to provide a much stronger technical basis for assessing the risk but are justified only if such information is needed to show that the risk of a disruptive event is or can be made to be acceptable.

The data obtained by implementation of the characterization plan will lead to revised analyses of the risks of those tanks not yet deemed sufficiently safe. Thus, by a few iterations through the recommended strategy, a well-defined path to closure of each safety issue in each tank would be obtained.

3.2.6 Take Actions

Waste tanks that do not meet risk acceptance criteria require actions to bring the risk of a disruptive event into the acceptable range. In general, the actions taken may range from mitigation, such as adding moisture to the tank to preclude or minimize the likelihood of a rapid exothermic reaction occurring, to imposing operational controls to reduce the likelihood of initiating the disruptive event, to doing nothing because the risks are accepted for a given time period . The actions chosen should reflect their effectiveness on reducing or better managing risk, cost, and the time required for implementation. The same actions do not have to be implemented on all tanks that do not meet the risk acceptance criteria. The actions most quickly available in reducing the risk of an organics-oxidants disruptive event are operational controls to minimize the likelihood of initiating the unwanted reaction and addition of moisture to reactive waste (if this can be shown to be feasible and does not create a greater or another identifiable hazard such as waste leakage from single-shell tanks).

3.3 Flammable Gas Illustration

In this section, a flammable gas burn in Tank S-106, using varying risk acceptance criteria, is used to illustrate the effect various risk acceptance criteria have on the decisions made and actions required to ensure that acceptable risk is achieved.

3.3.1 Tank Waste Description

Tank S-106 is currently not on the flammable gas Watch List, but based on current concepts (Brewster et al. 1995), the behavior of the waste suggests a potential for generation, retention, and episodic release of gases. The waste behaviors that indicate this tank may have a flammable gas safety concern are 1) a rise of about 50 cm in waste surface level since the last waste level adjustment (June 1982) and 2) the change in waste surface level as a function of barometric pressure that is one of the largest observed to date for a single-shell tank at Hanford (Hopkins 1995; Stewart et al. 1996). Without relevant measurements, it is not known if the gases generated and released are flammable or if the waste properties allow for episodic releases of significant volumes of the trapped gases.

This tank contains waste that is predominantly of the saltcake type (Agnew et al. 1996; Brevick, Gaddis, and Pickett 1995c). The waste in Tank S-106 has not been core sampled and analyzed, and gases in the tank dome space have not been sampled and analyzed. The tank is passively ventilated. A tank characterization report for this tank has not been issued. The tank has not been interim stabilized (i.e., it has not been salt-well pumped to remove as much free liquid as feasible). Thus, direct information regarding the tank contents and the composition of the gases in the tank dome space does not presently exist (Hanlon 1996b). Implementation of the recommended strategy for our limited scope illustration using Tank S-106 is therefore typical of applying the strategy to many of the existing waste tanks and their associated potential safety issues. The selection of this tank illustrates several factors facing the tank waste safety program.

Estimates of the safety risks for each tank must be made even in the absence of the information needed to make a definitive assessment of risk. Operational controls are often imposed as a result to reduce the likelihood of the occurrence of an initiating condition for a disruptive event. If these operational controls are not needed, they may impose an unnecessary cost and may actually delay other operations or treatment planned for the waste. Also, the effectiveness in reducing the risk may not be known. Application of the recommended strategy, as illustrated in the preceding sections for the organics-oxidants safety issue, creates a defensible basis for making decisions.

3.3.2 Risk Acceptance Criteria

The risk acceptance criteria considered for this illustration are given in Table 3.3.

3.3.3 Input Parameters to Risk Calculation

As indicated above, although Tank S-106 has not been sampled, there is considerable information about its contents from historical records, from tank grouping models, etc. This is the case for many of the Hanford tanks and represents a case that must be addressed. We cannot wait until all tanks have been sampled and analyzed to some statistically meaningful extent to determine whether they have unacceptable risks. Thus, this example addresses an important class of tank

Table 3.3. Risk Acceptance Criteria Under Consideration for the Flammable Gas Illustration

Criterion	Definition	Interpretation
I	No potential for flammable gas burn.	The likelihood (or chance) of having even a small flammable gas burn is zero.
II	The frequency of flammable gas burn is less than 10^{-6} times per year.	Flammable gas burns (including those that cause no damage) may occur at an expected rate of no more often than 10^{-6} times in a year (once in one million years).
III.a	The frequency of dome collapse resulting from a flammable gas burn is less than 10^{-6} times per year, as defined by the expected frequency of dome collapse less than 10^{-6} times per year.	A tank dome collapse as a result of a flammable gas burn may occur no more often than 10^{-6} times in a year, as defined by the expected or mean frequency less than 10^{-6} times in a year.
III.b	The frequency of dome collapse resulting from a flammable gas burn is less than 10^{-6} times per year, as defined by the 95th percentile of frequency of dome collapse less than 10^{-6} times per year.	A tank dome collapse as a result of a flammable gas burn may occur at an expected rate of no more often than 10^{-6} times in a year, as defined by the 95% confidence level of the predicted frequency being less than 10^{-6} times in a year.
IV	Offsite and onsite radiological dose from a flammable gas burn and dome collapse is acceptable.	The radiological dose consequence from a flammable gas burn is at an acceptable level.

problems and also demonstrates the importance of identifying risk criteria to support decision making.

In the absence of extensive tank-specific information, a regulatory-accepted formal process was used to obtain the needed expert judgments for all necessary parameter values and distributions used in the calculations. The procedure used was adapted from a methodology developed for the NRC as part of the NUREG-1150 risk analysis of several nuclear power plants (NRC 1989; Keeney and von Winterfeldt 1991). Estimates of the parameters were obtained from staff from PNNL, Westinghouse Hanford Company (WHC), and Los Alamos National Laboratory (LANL) who are knowledgeable about the specific parameters to be elicited. These individuals were selected because of their knowledge of historical records about the materials transferred into and out of the tank, the chemistry of the waste type, the contents of similar tanks, etc. Others from these organizations critiqued the information obtained and the calculations of risk using the information. The elicitation was led by nationally recognized experts on obtaining and using expert judgments for complex technical problems. Expert judgment can be used effectively and defensibly to start the process in the absence of definitive, specific information about the tank wastes. The results obtained using such information can then be evaluated to determine if certain data need better definition; if so, the optimum way to obtain the improved information can be determined and specified in an implementation plan for characterization. Specific information on waste properties, tank dome space gas composition, tank system information such as ventilation rates and structural information, experimental data from waste simulants or waste samples, and improvements in models may be required to reduce the uncertainties in the relevant information and data needed to calculate risk.

The nominal values for the input data obtained from the elicitation process are given in Table 3.4.

3.3.4 Calculating Risk

This discussion shows the effect of various risk acceptance criteria on decisions, not to quantitatively assess all parameters identified in Table 3.4 as input to calculating risk of a flammable gas burn. Thus, details of calculating this risk are not given. The risk for this event is primarily determined by frequency; the predicted consequences are minimal. The result is graphed in Figure 3.6, showing the cumulative probability versus the frequency of potential dome collapse per year.

Table 3.4. Input Data to Estimate the Risk of a Flammable Gas Event in Tank S-106

Name	Nominal Value	Description
Time at risk	3 years	The time at risk for a flammable gas burn (i.e., from now until *resolution* of the flammable gas safety issue for the tank in question via salt-well pumping; salt-well pumping is believed to preclude massive gas retention and rapid release
Spark frequency	10^{-2} per year	The expected number of sparks that could initiate a flammable gas burn per year.
Gas release frequency	10^{-3} per year	The rate at which gas release events of sufficient magnitude to lead to dome collapse if ignited occur in the tanks in question.
Duration of release	5×10^{-4} per year (4 hours)	The length of time that gas is released from the waste in a single gas release event. The release rate is assumed constant over this period.
Characteristic ventilation time	3×10^{-2} per year (10 days)	The time necessary for ventilation (passive or active in the case of mitigation) to remove a volume equal to the headspace volume.
Headspace volume	2.2×10^3 m^3	The volume inside the tank that is not occupied by solid or liquid waste.
Retained gas volume (STP)	5.5×10^2 m^3	The amount of gas retained in the waste at the time a release occurs.
Release fraction	0.5	The fraction of the retained gas that is released to the headspace.
Equivalent hydrogen fraction (flammability)	0.4	A description of the flammability of the actual waste gas relative to pure hydrogen.
Lower flammability limit of hydrogen in air	4×10^{-2}	The smallest concentration (mole percent) of hydrogen in air that will sustain combustion.
Pressure at which gas is held in the waste	2 atm.	Pressure, due to hydrostatic forces, at which retained gas is held in the waste.

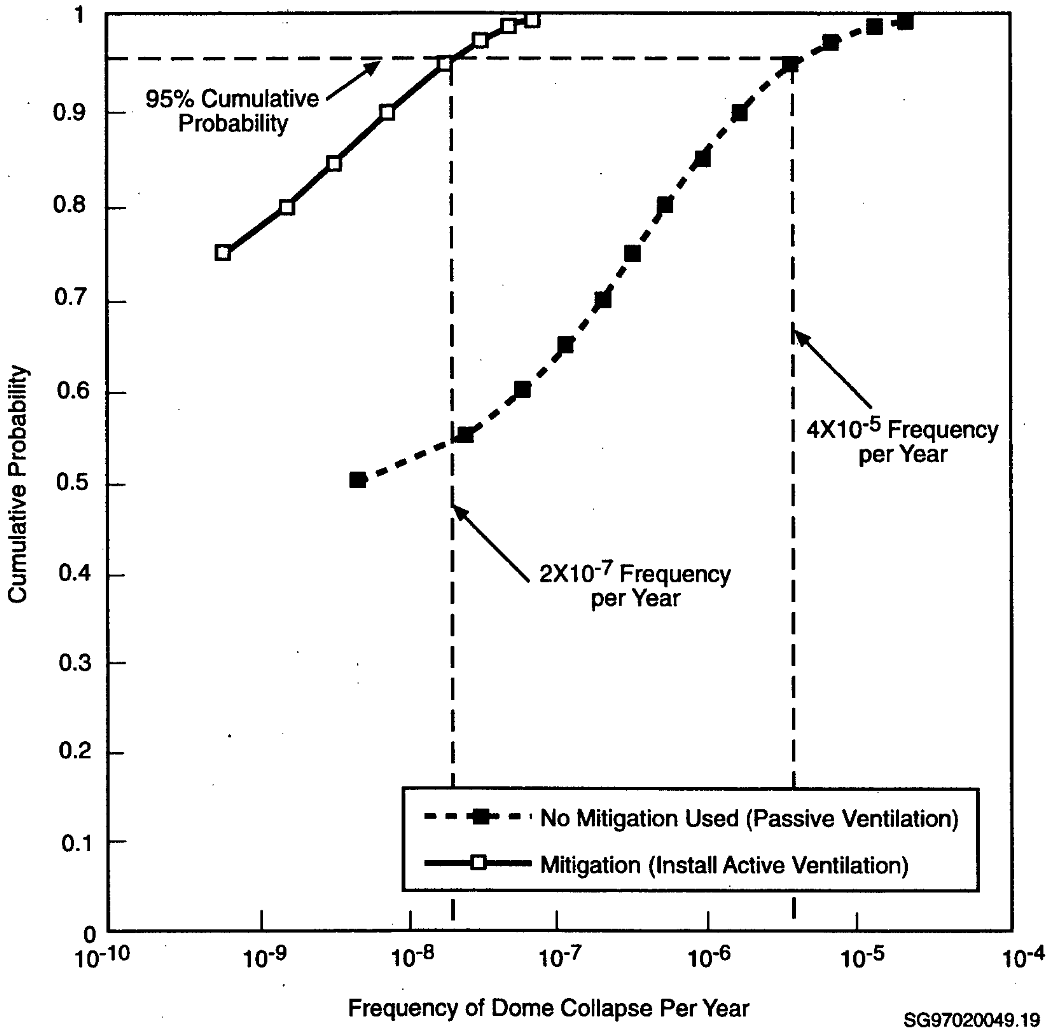

Figure 3.6. Frequency of Dome Collapse and Cumulative Probabilities for Critical Parameters Controlling a Flammable Gas Explosion

This figure displays the frequency of tank dome collapse versus cumulative probability as a function of frequency of a flammable gas explosion in Tank S-106 (Brothers et al. 1996). If the safety resolution goal (desired outcome) is to attain a less than one-in-a-million (10^{-6}) per year frequency of dome collapse with 95% confidence, then the goal can be achieved by installing an active ventilation system. That safety goal cannot be achieved using the "no-mitigation" approach where only passive headspace ventilation is applied. Thus, the analysis illustrates that a two order magnitude reduction in the frequency of dome collapse is achieved by implementing a mitigative (ventilation) action. Such information, along with the potential costs and risks of conducting mitigative actions, is provided to decision makers.

3.3.5 Making Decisions

The decisions to be made in this illustration are to either 1) resolve the safety issue through understanding (e.g., the existing information is sufficient to determine that the calculated risk and the uncertainty in that calculated risk are acceptable), 2) achieve acceptable risk through mitigation or controls, or 3) gather additional and/or more accurate information before selecting an action.

These three options are a type of triage, with resolution and showing that definitive risk acceptance criteria are met being based on information whose uncertainty does not preclude such a result; cases that either do not meet the risk criteria or that have an uncertainty in the result that does not permit knowing if the risk criteria have been met are passed on to the next stage of analysis and iteration through the recommended strategy to achieve acceptable risk.

The following results are obtained using the risk acceptance criteria given in Table 3.3 and the risk analysis results for Tank S-106 (based upon Brothers et al. 1996).

- **Criterion I**: If risk acceptance Criterion I is imposed, the recommendation is to *gather information*. The analysis shows more than a zero chance for a flammable gas burn in Tank S-106, thus this risk acceptance criterion is not met under current conditions based on the existing information. Consequently, the *resolution* decision cannot be made. Similarly, installing an active ventilation system as a mitigation action will not remove the potential or chance for a flammable gas burn as long as the waste produces flammable gas. Consequently, *this mitigation* action will not result in meeting the risk acceptance criterion. The risk is not acceptable, and other mitigation options must be considered and/or new information must be obtained that will reduce the risk in order to meet Criterion I. Except for retrieval of the tank contents or other modification of the waste contents as a mitigation action, it is unlikely that this acceptance criterion can be met. There is a remote chance that the gas produced by the waste is not flammable; thus, pursuit of additional information might result in a determination that the gas produced by the waste is not flammable. A better decision might be to recognize that Criterion I is an unrealistic criterion to apply to many (most) tanks.

- **Criterion II**: If risk acceptance Criterion II is imposed on Tank S-106, the recommendation is to *gather information*. The frequency of a flammable gas burn of any size is not shown by this analysis to be less than 10^{-6} times per year (Brothers et al. 1996). Therefore, resolution cannot be asserted. Because active ventilation does not affect the frequency of burns from small volumes of flammable gas, this proposed mitigation action is not effective. Additional information and analysis would focus on a more detailed evaluation of the factors contributing to the risk, especially with regard to the frequency and potential detection of burns of small volume. Strict controls on ignition sources might lead to an acceptable risk under this criterion.

- **Criterion III.a**: If this risk acceptance criterion is imposed, the recommendation is to declare the safety issue resolved for this time. The expected lifetime probability of dome collapse due to a flammable gas burn is calculated to be 8×10^{-7} times per year (see Figure 3.7). Therefore, according to this criterion, the risk from flammable gas is acceptable.

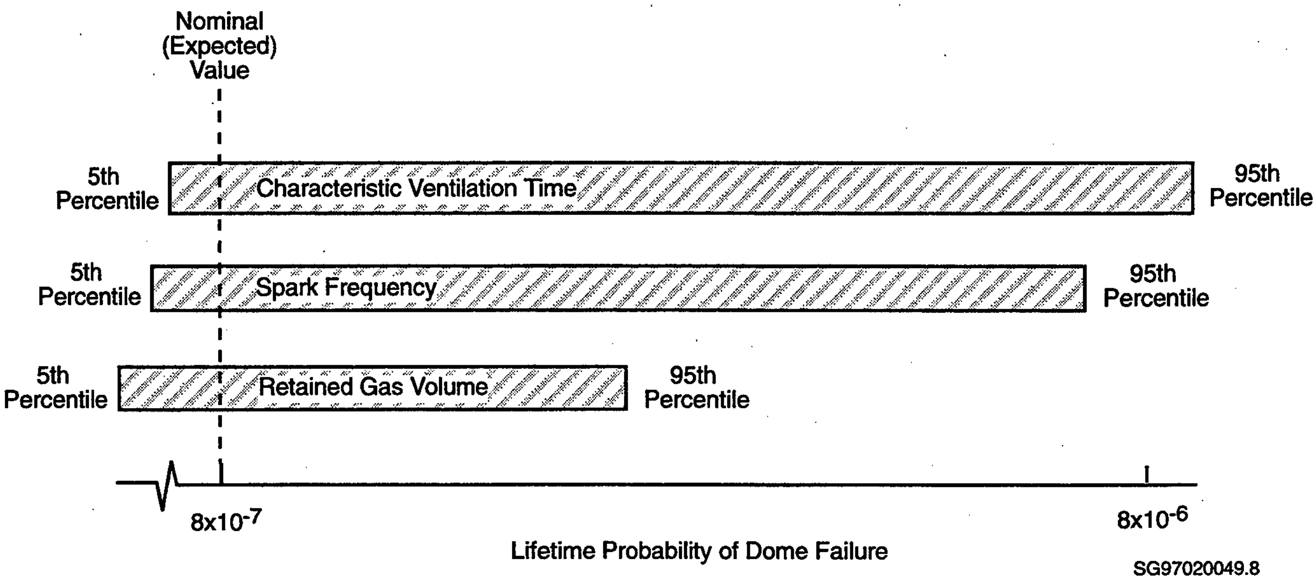

Figure 3.7. Sensitivity Analysis of Input Parameters for Calculating the Lifetime Probability of Dome Failure for a Flammable Gas Burn in Tank S-106.

No mitigation is necessary, and no further information gathering and analysis are warranted.

- **Criterion III.b**: If this risk acceptance is imposed, the recommendation is to *gather information* (if there are several tanks of this type to which this new information would be valuable) or achieve acceptable risk through *mitigation and/or controls*. The 95th percentile value for the frequency of dome collapse due to a flammable gas burn as related to the "retained gas volume" bar in Figure 3.7 is 3×10^{-6}. The difference between this value and the expected (nominal) value of the frequency (8×10^{-7}) is due to the large uncertainty in the information about this tank and its contents. This value must be reduced by a factor of three for an acceptable risk to be obtained; therefore, resolution is not demonstrated. The factor of three reduction is achievable by active ventilation (a mitigative action). However, it may also be possible to ascertain from new information that the certainty of this probability is less than the calculated 95th percentile value. The uncertainty in the risk is sensitive to the uncertainty in/about passive ventilation rates, retained gas composition, and spark frequency, and there are existing, relatively low-cost options for obtaining this information. The sensitivity analysis shows that it will be necessary to obtain new information on more than one of these parameters. While it is not possible to obtain new information on several of these parameters for less cost than the mitigation option for a single tank, a possible cost-effective option is to perform such studies on a few related tanks and then apply the results to reduce the uncertainty in the estimated risk in other tanks. Based on this example, performing a value-of-information analysis is recommended before making a decision on whether or not to install active ventilation in Tank S-106.

Note that a value-of-information analysis may still show that active ventilation should be installed. The advantage of performing the analysis is that the cost benefit, as well as the benefit from risk reduction, will be known and documented to aid in defending this decision.

A tank failure from a seismic event is predicted to occur with a frequency of 1 in 7500 years (1.3 x 10^{-4} per year) by some estimates (LANL 1996). Therefore, the acceptable level of 10^{-6} annual frequency for tank failure from a flammable gas burn is somewhat irrelevant because it might be more cost-effective to focus efforts and budgets on reducing the risk from failure of single-shell tanks due to more frequently occurring seismic events. This could be accomplished by accelerated salt-well pumping and transferring the waste into double-shell tanks. Likewise, the expected (and in some cases demonstrated) loss of tank integrity due to ongoing tank wall corrosion and the plans to remove liquid wastes from single-shell tanks places a fairly short-term time scale on the problem that should be considered in deciding what level of risk is acceptable. (For example, all single-shell tanks have already outlived their 30-year design life. The first-built double-shell tanks are also now exceeding their original design life of 25 to 50 years. [See Gephart and Lundgren 1996.]) If this tank is to be salt-well pumped within a few years, a risk of 3 x 10^{-6} per year may be acceptable. This illustrates how applying the strategy provides decision makers options with quantifiable risks without prescribing solutions.

- **Criterion IV**: If risk acceptance criterion IV is imposed on Tank S-106, the finding is that an acceptable risk exists. The expected offsite and onsite doses from a dome collapse accident were calculated to be essentially zero offsite, and onsite doses were less than 100 mrem for 10 workers. According to any historical version of Hanford risk-acceptance guidelines, this dose is acceptable, even at an annual frequency of one per year. A dome collapse accident at a frequency of one per year obviously is not acceptable to any decision maker. Therefore, it is probable that this criterion alone is insufficient for making defensible and acceptable decisions.

The recommended decisions that apply to each of the risk acceptance criteria discussed in this section are summarized in Table 3.5. For each decision that recommends the gathering of in formation, the information that would provide the most insight in addressing the ultimate resolution or mitigation decisions are listed.

3.3.6 Taking Actions

Information gathering may include further development of the model of the disruptive event (represented by the Structured Logic Diagram for this disruptive event), analysis of existing information needed to calculate risk to determine its validity and accuracy, experimentation on actual wastes or simulants, sampling and analysis of tank contents, and investigation of programmatic decisions and priorities that affect the flammable gas burn probability or consequences in Tank S-106. **A sensitivity analysis of various parameters (shown in Figure 3.7) shows that changes in the characteristic ventilation time have a major effect on the probability of dome collapse from a flammable gas burn in Tank S-106.** Each of the parameters considered and their relationship to determining the risk is documented in the Structured Logic Diagram. Thus, investigations on this parameter will aid in the decision process if risk acceptance Criterion III.b is imposed. **Likewise, changes in spark frequency have the second most significant effect on the probability of dome collapse**

Table 3.5. Summary of Decisions for Flammable Gas Burn in Tank S-106

Risk Acceptance Criterion	Decision	Parameter
I - No potential for flammable gas burn.	Remove waste from tank	• Time at risk
	Gather information	• Equivalent hydrogen fraction • Retained gas volume • Time at risk
II - The frequency of flammable gas burn is less than 10^{-6} per year.	Gather information	• Spark frequency • Retained gas volume
III.a - The frequency of dome collapse resulting from a flammable gas burn is less than 10^{-6} per year, as defined by the expected frequency of dome collapse less than 10^{-6} per year.	Resolve the safety issue	• Not applicable
III.b - The frequency of dome collapse resulting from a flammable gas burn is less than 10^{-6} per year, as defined by the 95th percentile of frequency of dome collapse less than 10^{-6} per year.	Gather information (or mitigate depending upon value of information analysis)	• Characteristic ventilation time • Spark frequency • Retained gas volume
IV - Offsite and onsite radiological dose is acceptable.	Resolve the safety issue	• Not applicable

from a flammable gas burn. Investigations on this parameter will aid in the decision process if risk acceptance Criterion II or III.b is imposed.

Changes in equivalent hydrogen fraction and retained gas volume have lesser effects on the probability of dome collapse in Tank S-106. However, information about both parameters relate to the nature of the waste in the tank and would provide insight into the flammable gas burn issue for all of the criteria that may be applied (Criteria I, II, and III.b). The remaining parameter, time at risk, is set programmatically and by scheduled operations. If Criterion I is imposed and information is gathered and analyzed about the equivalent hydrogen fraction and/or retained gas volume shows that the gas produced by the waste is flammable, then programmatic issues must be addressed that prioritize the schedule for removal of tank contents within the context of the total risk at the Hanford Site.

Note that within the scope of performing the analysis on a single tank, information gathering may not appear to be justified. Economies of scale cannot be analyzed on an example of a single tank for a single issue. If the tanks can be grouped by similarities in their waste contents, or by their potential for a particular disruptive event, then knowledge obtained for one tank can be defensibly used to predict the magnitude and uncertainty of information needed for other less characterized tanks in the same group. It is anticipated that over many tanks for a single issue, and over several issues, there will be a cost benefit realized from such synergistic learning. The focused learning process provided by the recommended strategy is of overall benefit to solving site issues and supporting taking definitive actions on Hanford's waste.

3.4 Summary

The discussions have illustrated the implementation of the recommended strategy for two specific safety issues. The organics-oxidants safety issue illustrates the implementation of the strategy and the results of that first iteration for Hanford's waste tanks. The flammable gas issue for Tank S-106 was used to illustrate the importance of selecting and using various risk acceptance criteria because the resolution of tank safety issues, supported by decisions and recommended actions, depend on such criteria.

These two illustrate that the strategy can be implemented and used to address real issues. The strategy is neither too theoretical nor complex to be understood and implemented by the Resolution Team approach recommended and the results can be validated by peer review.

It is important to minimize the complexity of risk analyses both to minimize the time and costs required to perform quantitative risk assessments and to communicate the results as simply and convincingly as possible. The following examples illustrate the three elements of the recommended strategy that are designed to respond to this requirement:

- Identification of controlling parameters: if the parameters that control the primary events are known sufficiently to control the event probability or consequences to incredibly low values, the full risk calculation is not necessary. For example, if the amount of reactive waste is too small to cause an unwanted waste release, it is not necessary to develop and calculate pathways of exposure to the public.

- Using iterative problem analysis methods: the recommended strategy progressively develops the complexity of the problem description and analysis until the risk is known with enough certainty to take actions.

- Using risk screening criteria: if small-scale events (e.g., a contained in-tank fire) can be shown to be sufficiently improbable, protection from large-scale versions of the same event will be covered by the simpler analysis.

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Appendix A

Letter from the U.S. Department of Energy to Pacific Northwest National Laboratory Requesting Development of a Technically Sound Strategy

ACTION BDS				REPLY DUE					DATE 4-25-96		
DIST.	RCA	WJA	JFB	TJB	KCB	GHC	TRF	MLK	WJM	CMN	EWP
LTR.			✓						✓	✓	
ENCL.											

DIST.	GRP	JTAR	GLR	BDS	JWS	GMS	RAW	GLW	CC		
LTR.				✓					✓		
ENCL.											J

Department of Energy

Washington, DC 20585

April 15, 1996

PNNL-
cc96-0499

Dr. William J. Madia
Director
Pacific Northwest National Laboratory
P.O. Box 999
Richland, Washington 99352

Dear Dr. Madia:

The U.S. Department of Energy (DOE) must develop a technically sound strategy that defines the actions leading to the transition of the Hanford Site tank wastes from the current state of significant uncertainty to a state of greatly reduced uncertainty. The Pacific Northwest National Laboratory (PNNL) has been asked to create an alternative characterization component of that strategy. DOE expects to apply a modified characterization strategy to the resolution of the safety issues associated with the storage of the waste in tanks and to assist in the final disposal of the wastes.

The potential impact of a technically flawed strategy is significant. Underestimated risks can result in unnecessary exposure of workers or the public to hazardous materials. Overestimated or ill defined risks can unnecessarily constrain processing actions and greatly increase the costs of tank waste remediation. Delays and increased costs resulting from improperly structured efforts can erode public confidence as well as support.

Many millions of dollars and significant amounts of work have been expended to date in the task of formulating and implementing characterization and safety resolution strategies. This speaks to the magnitude of the challenge. To this end, PNNL has been asked to draw upon the best minds within the Laboratory and throughout the Nation and the world, and to come forth with a technically defensible strategy that is not constrained by past approaches and yet takes advantage of the best thinking that has taken place to date.

Please call upon me if there is anything that I can do to facilitate your work on this critical task. I understand the time constraints are a concern. However, we expect the modified characterization strategy to significantly impact work at the Hanford Site starting not later than fiscal year 1997.

Sincerely,

Thomas P. Grumbly
Assistant Secretary for
Environmental Management

W. J. MADIA
APR 25 1996

Printed with soy ink on recycled paper

Appendix B

Report of the *ab initio* Team for the Hanford Tank Characterization and Safety Issue Resolution Project

Report of the *ab initio* Team for the Hanford Tank Characterization and Safety Issue Resolution Project

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June 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
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Executive Summary

The justified acquisition of new tank characterization data, the processing and modeling of information, and the validation of the models are combined in a plan for gathering reliable chemical and physical "intelligence" about Hanford tank wastes. This intelligence drives action-oriented choices coupled with risk-based decisions in a new General Strategy to address current tank waste characterization and safety issues and future remediation efforts. Characterization is a continuous task complete only when the final waste form or state is produced at Hanford. The interrelationships of the principal elements in this General Strategy are discussed in this report.

The strategy is based on a common operational model used throughout the chemical industry. It recognizes that the principal technical difficulty in the successful characterization of waste and the resolution of safety issues originates in the diversity of the wastes and their heterogeneity. Elementary sampling theory indicates that the compositions of the gaseous dome spaces and the liquid supernatant solutions can be determined by the analysis of small samples. The theory also indicates that similar attempts to completely characterize the sludges, slurries, salt-cakes, and crusts are so severely restricted by the requirement for many *randomly* selected samples, that the approach is impractical. The new strategy recognizes this essential problem and is designed to circumvent the problem by developing and taking advantage of a wide range of opportunities for waste characterization. At this level, the strategy is scientifically defensible and self-consistent.

The new strategy is iterative, and justified characterization is an integral part of it. The approach recognizes the dynamic chemical reactivity of the tank wastes. It will provide chemical intelligence, in the same sense as military or industrial processing intelligence does. The most important attribute of characterization in the context of this report is that it is a dynamic continuous process that can be carried out regardless of the waste storage, treatment, or disposal option that is under consideration, and whether or not a given option is carried out by a government contractor or private industry. Actions taken within the context of the strategy will, in chemical engineering parlance, functionally provide "transfer information." This process continuously improves technical understanding of the behavior of the wastes, leads to an improved safety situation, and maximizes the probability for successful remediation work.

Five different examples of the application of the new strategy are included in the report. They were chosen to illustrate the scope of the strategy in addressing problems of different complexity and to draw attention to perennial issues such as the possibility of criticality excursions, explosions of flammable gases, waste blockage in pipes, the presence of surprise molecules, and plans for sludge washing procedures. The examples describe a guiding logic that can address tank waste characterization and attendant safety issues, technically justify newly planned characterization activities, and link that justification with risk-based decisions and actions.

B.2

Contents

Figures

Tables

1.0 Approach

Components of this report is presented at two levels. The relationship between the two levels and how they apply to Hanford tanks is shown in Figure 1. The inner shaded area represents the domain (information space) of characterization needs related to the Hanford tanks. This information space is plotted radially as some cumulative parameter consisting of elements such as existing historical records, chemical and physical analyses, modeling results, risk analyses, costs, and remediation action needs. Given the large diversity between the physical and chemical state of the tanks and the extent of knowledge about individual tanks and groups of tanks, it is safe to assume that the shaded area will have an irregular shape.

We have deliberately used an abstract graphic analogy to describe the highly variable nature of the tanks' information space including characterization needs. As more data are obtained, issues resolved, and actions taken, the shape of this information space will change. Therefore, to develop an effective approach that will ensure that present and future tank characterization needs are met, we must create a broadly applicable strategy that encompasses all 177 tanks. This is called the General Strategy and is depicted by the checkered line in Figure 1.

Our goal has been to design a General Strategy that applies to all Hanford tanks with the highest scientifically defensible level of detail. Thus, the correct strategy would follow the tank characterization needs contour in Figure 1 as closely as possible without creating an outlier (symbolized by the tank icon). The separation between the "intelligence needs" (shaded area) and the General Strategy (checkered line) is a measure of scientific defensibility of the approach used in this report and of its conciseness; if the two lines were to cross, the outlier will be created. If the strategy strayed too far from the problem (solid line), it would not be concise enough. An example would be the gathering of excessive characterization data beyond the minimum needed to resolve a given problem or take an action. That area is entitled "unjustified knowledge" (wasted effort) in Figure 1. Such an excursion from justified data can be very costly and time-consuming. Therefore, the strategy must be sufficiently robust to encompass the safety and characterization needs of all 177 tanks.

The second level of information in this report is represented by selected examples of specific safety or characterization issues that can be analyzed using the logic developed in the General Strategy. Several examples are discussed in Section 3.0 to the level of detail determined only by the scientific defensibility of the arguments to illustrate use of the General Strategy. Because of the time constraints imposed on this project, only a few examples were examined; these are presented at different levels of detail. These examples illustrate another way of looking at the structure of this report, with the individual examples being

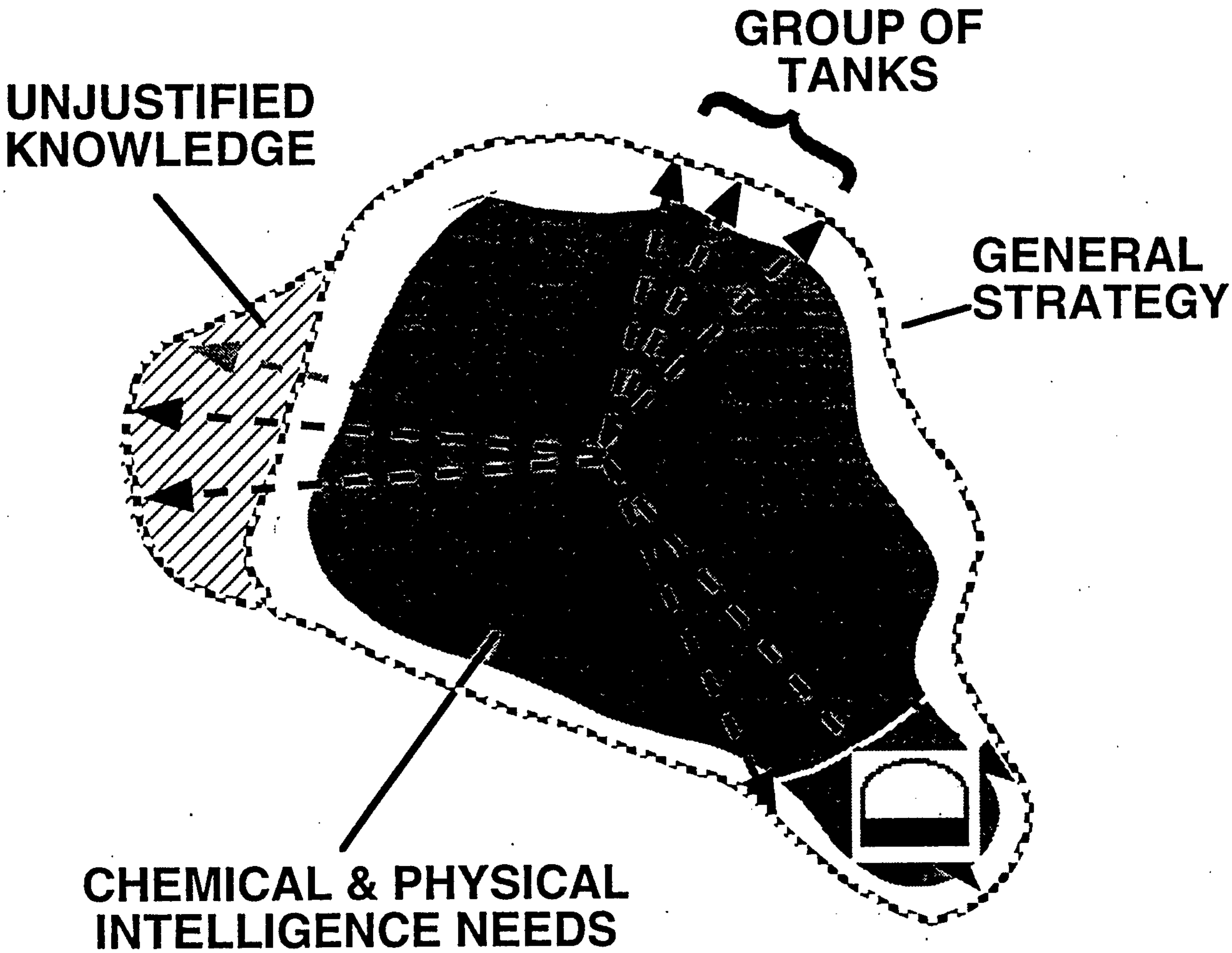


Figure 1. Graphic Analogy Depicting Variable Nature of Hanford Tank Waste Characterization Needs to Resolve Characterization and Safety Issues. The shadow area represents characterization needs expressed in "abstract" information space. The dashed arearepresents Unjustified Knowledge. The checkered outline depicts the General Strategy that encompasses all Hanford tanks but does not stray away from the justified needs.

presented at different levels of detail; they all have their origin in the General Strategy. Selecting issues, asking the relevant questions, and then systematically answering them illustrate the methodical approach that should be used in examining any tank related issue. Thus, we are using the term "General Strategy." This approach represents a considerable paradigm shift in relation to the current characterization and safety issues resolution strategy. For example, rather than trying to respond to such questions as

- "When is characterization completed so Hanford can get on with cleanup?"
- "How many core samples should be collected from each tank?"

a different set of more technically justified and scientifically defensible questions are asked, such as

- "What specific characterization information is needed to enable decision making and initiate actions to solve a particular problem?"
- "What sampling protocol provides an acceptable level of confidence in knowing average tank waste characteristics?"
- "What characterization strategy is needed to resolve safety issues that may occur during interim waste storage or treatment processes?"

Another important aspect of the General Strategy is that it is *dynamic*. This means that with progress in any aspect of the work, the knowledge base (i.e., the shape of the shaded area) becomes better defined and the degree of uncertainty (e.g., manifested by widely changing shapes as new knowledge is obtained) will be reduced. This is more fully explained in Section 2.0. It can be generally stated that as the waste is acted on and chemical/physical information is gained, the uncertainty decreases while the safety of the tank waste improves.

2.0 General Strategy

Hanford waste tanks are, in effect, slow chemical reactors in which an unknown but large number of chemical (and radiochemical) reactions are running simultaneously. Over time, the reaction dynamics and compositions have changed and will continue to change. A critical strategy issue is knowing which reactions and reaction products should be characterized, monitored, or otherwise identified on an as-needed basis to ensure tank safety and provide adequate knowledge to store or process waste. The Hanford tanks have been without proper industrial-type process controls since their installation decades ago. Similarly, well-known explosion hazard management approaches, used in monitoring potentially hazardous conditions in the mining and petroleum industry, are not used in the management of potentially hazardous tanks. Tank monitoring, special sampling, or other in-tank actions (such as waste mixing or evaporation) are driven by immediate operational needs and compliance requirements rather than by scientifically defensible decisions, or by the optimization of data collection and phenomenological modeling to support both present and future waste safety, stabilization, and/or processing needs. It is understood that specific characterization needs will require development of new methods or sensors. Such an effort must be carefully scrutinized so that it does not become an "unjustified" research project.

There are two types of energy input into these chemical reactors: the heat from the radioactive decay of primarily ^{137}Cs and ^{90}Sr (both with half-lives of approximately 30 years), and the chemical heat from slow oxidation reactions of organic compounds which generate products, such as sodium formate, oxalate, and carbonate, and (volatile) hydrogen rich products. An important and positive aspect of the present situation is that the total energy available from both the chemical and nuclear reactions decreases with time. This situation could be used as an argument for inaction, e.g., letting the waste remain in its existing state. Unfortunately, all single-shell tanks (SST) have long outlived their original design lifetimes. Several of them have already failed structurally and leaked some of their contents (~1 million gallons is equivalent to 1 MCi of radioactivity) to the underlying soil. While none of the double-shell tanks (DSTs) have leaked, the oldest ones are now reaching their design life. Waste contained in the SSTs represents a potential release source for ~132 MCi of radioactivity (decay value corrected to 1996) and 190,000 tons of nonradioactive chemicals. The contents of the DSTs represent a potential release source for ~82 MCi of radioactivity (corrected to 1996) and 55,000 tons of various chemicals. All 177 tanks contain ~50% of the current radioactivity and ~60% of the chemical waste found at Hanford. Thus, an expedient stabilization/remediation action on this stored waste should be a high priority issue at Hanford. This is the most important technical program driver for the selection of a remediation plan tailored to ensure adequate health and environmental protection.

Given the basic uncertainty about the level of technical knowledge relating to the tank waste, the possibility of an uncontrolled release of energy (e.g., of a chemical explosion) has been a major concern of Hanford Site contractors, federal/state agencies, and the general public. This concern is greatly amplified by the potential consequences (both real and perceived) of radiation releases to the environment, should such an event occur. This fear has been the major driver behind the existing waste characterization effort (e.g., relying nearly exclusively upon core sampling). Missing has been the pursuit of other in-tank waste characterization and even pilot-scale waste processing opportunities (using existing or new facilities) from which new, critical, chemical, and physical information could be obtained for more technically based decision making.

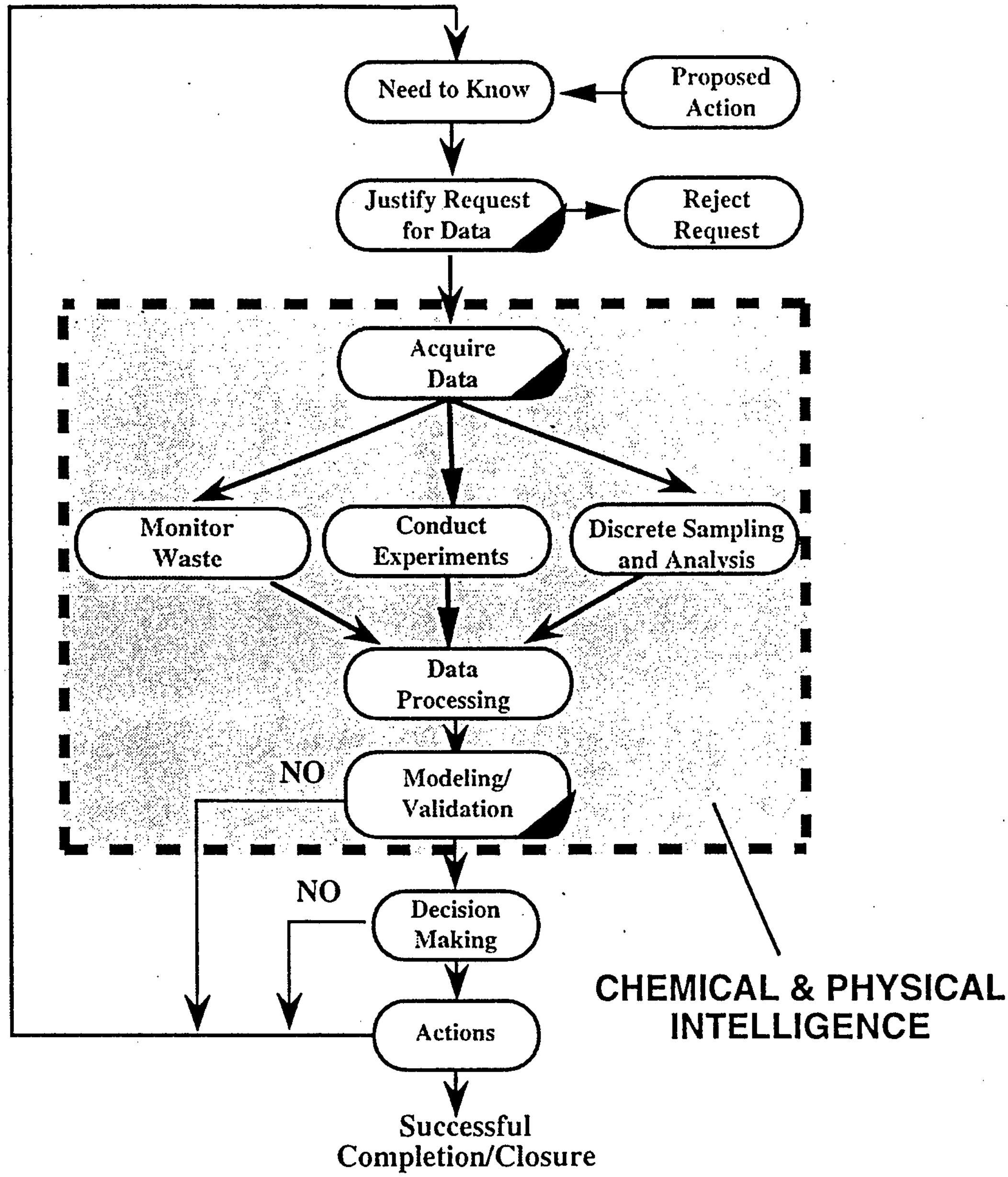
2.1 Overview

The *ab initio* team examined the relationship between characterization, safety/risk analysis, decision making, and large-scale remedial actions applicable to all tanks. All of these elements are part of the same model and cannot be viewed or implemented separately; otherwise, data are collected without a meaningful purpose or actions are undertaken without technical justification. Such actions result in lost time, money, and confidence in the operational programs. Collectively, the aforementioned elements form an iterative loop (see Figure 2) in which justification for new data, characterization actions, validation/refinement of the model(s), and risk analysis take place on every iteration. Thus, none of these elements can be "completed" before achieving an acceptable final state of any given tank (identified in Figure 2 as "successful completion/closure"). This is especially true for waste characterization since that segment is an intricate part of the entire "cradle-to-grave" tank remediation process--from today's ensuring of tank safety, through tomorrow's waste processing control and final waste-form deployment. Thus, as discussed in Section 2.3, such questions as "when will tank characterization be finished?" or "how many core samples must be taken from each tank?" are meaningless.

In the following sections, the meaning of the individual boxes (in boldface type) in this scheme are described in greater detail (Figure 2; and Table 1 describes the terms used in Figure 2).

2.2 Justification of Request for New Data

The amount of existing knowledge differs from tank to tank and so will the justification for new data. Therefore, the key starting point for the loop in Figure 2 (applied to any tank or for resolving any issue) is the element **[Justify Request for Data]**. This "justification" is required for starting the process. This step must be rigorously and consistently applied in a scientifically defensible manner. Otherwise, costly and time-consuming waste characterization campaigns are begun without technical merit. Violation of this principle leads to interminable, unnecessary, and expensive "studies" of the tank waste, often masquerading as "characterization." While such studies generate much data, these data are of little use for resolving critical tank safety and characterization issues. Such data are termed "Unjustified Knowledge" in Figure 1. Such non-justified data-collection activities should *not* be undertaken. This step will be the single most important factor in gaining cost control and defensibility for waste characterization actions. It also allows correct assignment of priorities for remediation tasks under necessary budgetary constraints.



— Other Information

Figure 2. Logic Diagram of the General Strategy Defining the Position of "Chemical & Physical Intelligence" in the Remediation Scheme

Table 1. Terms Used in Figure 2

Proposed Action	• Proposed diagnostic or processing step
Need to Know	• Identify possible information/data need • Question(s) raised from previous iteration through diagram
Justify Request for Data	• Request compared to screening criteria/guidance • Screen "need-to-know" data for applicability to solve issue
Reject Request	• Unjustified data/information request
Other Information Sources (ovals containing shaded corner)	• Historical site data/information • Scientific literature • International experience • Other DOE sites • Industry and university experience
Acquire Data	• Identify and execute approach to data collection • Establish acceptable data uncertainties • Identify information acquisition frequency
Monitor Waste	• Continuous, or time-continuing, data collection
Discrete Sampling and Analysis	• Discontinuous, or batch, sampling and analysis
Conduct Experiments	• Initiate laboratory experiments to gather critical data
Data Processing	• Signal processing and analysis • Data management • Derived data • Error analysis • Chemometrics
Modeling/Validation	• Conceptual (physical) modeling • Numerical Modeling • Predict phenomena and waste behavior • Evaluate phenomena and waste behavior
Decision Making	• List options for actions • Estimate risk for options • Prioritize options on a technical basis • Identify need for additional iterations (if needed)
Actions	• Carry out recommended specific major physical action(s) on the waste

2.3 Chemical Intelligence

It is obvious from photographs of the interiors of the tanks or from core samples that the content is extremely heterogeneous. The tanks contain many chemical components derived from a wide variety of waste decades. The *number of phases could be as high as the number of components in the tank.* This, in turn, means that the total area of the boundaries between these phases, the so-called "interphases," is very large. Many components in the tanks that drive chemical reactivity are accumulated at such interphases.

The distribution of any given component I between two phases α and β is given by the Gibbs partitioning law:

$$(C_i \text{ in phase } \alpha)/(C_i \text{ in phase } \beta) = K \quad (2)$$

where K is the partition coefficient.

If "characterization" of the tank is taken to mean "*to know the concentration of every component in every phase*," the total number of "characterization steps," CS, could become

$$CS \approx P^2 \approx C^2 \quad (3)$$

(Note: Here, we are using the term "concentration" instead of the correct term "activity.") Another alternative would be to determine the concentration of each component in only one phase and determine the corresponding partition coefficients (K) for all other phases and interphases for a given temperature and pressure. The number of required characterization steps would then be approximately equal to the square of the number of components. Thus, for example, for the 20 components listed as "Average Chemical Composition of Tank 241-SY-101" (Stewart et al. 1994), it may be necessary to perform approximately 400 (i.e., 20^2) analytical determinations for complete characterization. If some of the significant components were to be adsorbed at the interfaces, then every adsorption coefficient at each interphase would have to be determined. The values of the partition coefficients would be valid only for the temperature at which they were determined. It is obvious that either approach calls for an unrealistically large number of samples and analyses. It is, therefore, safe to conclude that a complete characterization of a tank, let alone 177 tanks, is absurd and thermodynamically infeasible.

Is this the end of the "characterization" story? An impossible task? Certainly not. The key word in the preceding statement is "*complete*." If it is replaced with "justified," the characterization task suddenly becomes manageable and "characterization" assumes its proper meaning:

> Characterization is the act of developing a dynamic model or understanding of the chemical, physical, and spatial properties of a system adequate to initiate an action or resolve a question about the system.

In this context, characterization is seen as *gathering chemical and physical intelligence*, analogous to *military intelligence*, which provides operational information about the chemical state of the system under consideration. Chemical and physical intelligence is framed in Figure 2 by the dashed line.

From the analytical point of view (referring to Figure 2), measurements are made either by **[Discrete Sampling and Analysis]** (e.g., batch chemical analysis) or by continuous **[Monitoring Waste]** (e.g., via in situ chemical sensors and/or ex situ sensor systems). The raw data obtained by these two routes are transformed into useful information through application of advanced **[Data Processing]**. This information can be used to construct a physical description and a numerical **[Model]** of the system. This model represents the best working hypothesis available about the system at any given time. It must be self-consistent **[Validated]** and is updated, as needed, as new information becomes available. A violation of the internal self-consistency of the model triggers another request for new data that can be a physical/chemical measurement of the tank waste or a search for another piece of external information, i.e., **[Other Information Sources]**. As noted earlier, any request for the new data must be technically justified (Figure 2).

The most critical step is to develop defensible criteria to justify a characterization request. This inevitably places the task of obtaining physical and chemical intelligence inside a "do" loop, which links it to **[Decision Making]** and remediation **[Actions]**. In this context, it is erroneous to view "characterization" as a separate task that has to be "completed" before any large-scale action on the waste is undertaken. Such a position creates an excuse for inaction and leads to unnecessary and unjustified "characterization" expenses.

The only time characterization is completed is when a successful **[Successful Completion/Closure]** of the tank is achieved. The justification step ensures that the loop does not become interrupted between the **[Modeling/Validation]** and **[Decision Making]** steps. It is clear that improvements in routine **[Monitor]** and/or **[Discrete Sampling and Analysis]** would only marginally improve the quality of the Model. This depends critically on the quality of its inputs; in other words, the quality of the analytical data. This, in turn, depends on the quality of the *sampling* operation, the location of the sampling/monitoring sites, and the representativeness of that sampling intelligence to the whole waste system. Another important aspect of the General Strategy is the application of the common chemical engineering concept of the *transfer function*. It is a ratio of the perturbation input to the system output, which predicts the response of a complex system to an externally imposed perturbation. According to this theory, the validity of the Model would be automatically tested by each successive iteration. It becomes important when a major action (e.g., waste sluicing or mixing for homogenization, etc.) in a tank is taken. In such a case, the response of any measured parameter (e.g., gas evolution, temperature distribution, or analysis of a selected chemical component) compared to its value predicted by the model can validate the model. Thus, a major **[Action]** on a tank can be viewed as a perturbation that should be used for the model's refinement on the next iteration. With the exception of tank 101-SY, none of the tanks has been perturbed to a large extent to allow such **[Model Validation]**. (The mere transport of a portion of waste from one tank to another is not considered a defined perturbation input). Such actions are undertaken until the model is validated for predicting, within an acceptable level of uncertainty, waste behavior to solve critical safety or characterization issues. Such validation should also take place during pilot-scale operations so as waste is processed, chemical and physical intelligence is gained that can be applied to other tanks having similar waste characteristics or facing related safety issues.

2.3.1 Sampling Strategies

Under the proposed Characterization Strategy, when a request for information is issued for a given tank, the request must first be justified on the basis of the accuracy required of the estimates of each physical property or concentration of each chemical component to ensure that it will lower the calculated risk in *taking some specific* **[Action]**. The first source of information is the historical data available on the tank. If the source is sufficiently reliable, then the information would be issued and the request satisfied. If historical data are unavailable, incomplete, or inaccurate, the next source might be to physically take samples from the tank and submit them for analysis. However, depending upon the required accuracy of the information, the concentration of several analytes, and the physical characteristics and degree of heterogeneity of the tank waste, *tank sampling may not be able to provide the information within the required confidence levels*. Since this can be determined prior to sampling using Sampling Theory, an informed decision can be made as to whether or not a sampling plan should be implemented. The decision would be based on a scientifically justifiable basis, as described below.

The potential value of the waste sample depends upon the tank contents being sampled (see Figure 3). For example, tank head space is well mixed (homogeneous). A few samples should be representative of all head space gases at a given time in a tank. Though subject to less active mixing, a limited number of supernatant samples should also provide relatively representative samples of the waste's upper liquid medium. Rapid to slow mixing of the vapor and liquid phases provides a degree of randomness to the samples periodically withdrawn from the tank's fixed riser locations. However, this is not true for the solids and high viscosity waste in the tanks, such as salt cake, thick slurries, and sludges. Here, nonrandomly taken samples may be valuable for determining the ratios of selected analytes or the presence of surprise molecules, or for collecting waste samples for performing waste processing studies. However, such nonrandom samples have little value for establishing average chemical compositions which present the characterizing strategies we are seeking. Moreover, the areas immediately below the risers are the most disturbed areas of the waste and, therefore, the least representative of the tank contents. Thus, as noted earlier, different "sampling strategies" based upon waste perturbations/actions are needed to characterize solid or highly viscous wastes.

With this in mind, it can be stated that conclusions about tank contents based on the sampling of Hanford tanks done to date, particularly the sludges, slurries, and salt cake, are not scientifically justified. However, physical and chemical information obtained from core samples may be very valuable if used for a specific justified purpose.

The initial sampling plan developed in the late 1980s specified that two complete core samples be obtained from *randomly selected locations* within a tank. (The obtaining of two core samples from each SST was specified in the first version [May 1989] of the Tri-Party Agreement [Hanford Federal Facility Agreement

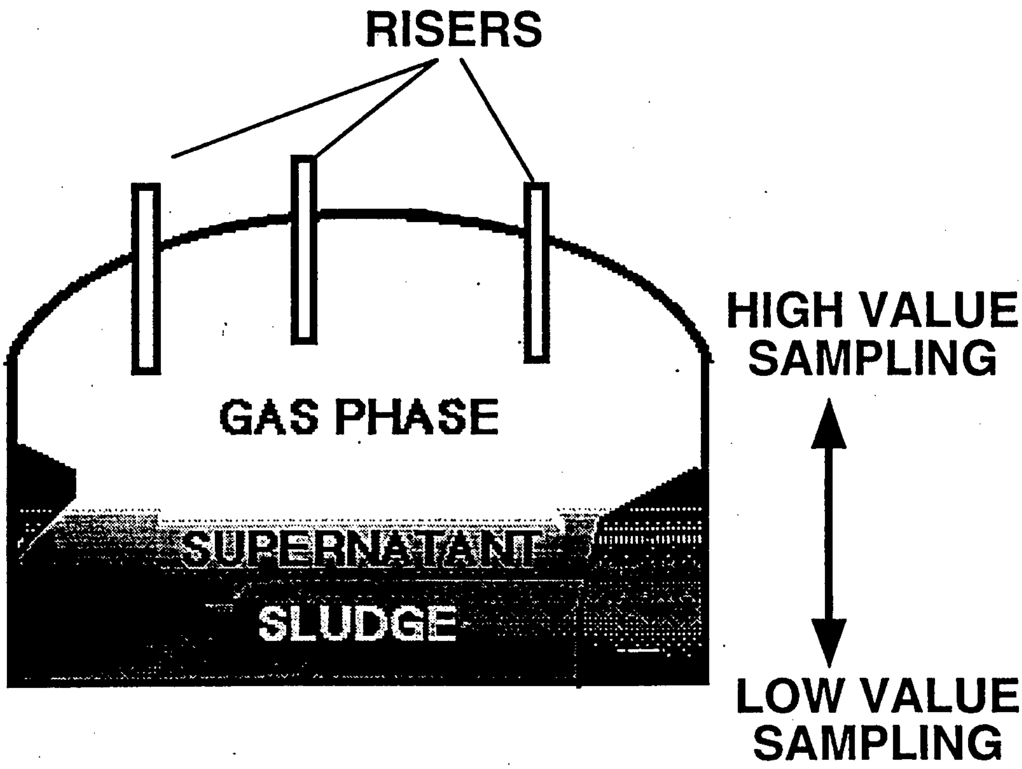


Figure 3. Value of Sampling Shown as the Function of the Depth of the Waste. Random samples of the gas and liquid phase can provide information about average concentrations of the components in those phases. The value of nonrandom samples, for example in the sludge, is more restricted, providing useful information only about ratios of analytes, presence of "surprise molecules," and processing tests.

and Consent Order 89-10, Ecology 1989]. While tank waste sampling is less quantitative and more flexible in the present Tri-Party Agreement, interpretation of sampling requirements has changed little.) Core segments would be homogenized to form composite samples, followed by chemical analysis on two aliquots from each sample. The numbers, two core samples and two aliquots, were chosen because they are the minimum number needed to apply Analysis of Variance (ANOVA) to the data. However, given the small number of degrees of freedom (total assays), the confidence intervals associated with ANOVA estimates are necessarily very wide, making the information obtained for thick slurries, sludges, and salt cake essentially useless for risk-based decision making.

The requirement for random sampling of solid phases cannot be met since core samples can only be obtained at fixed riser locations. This is true if the number of statistically required samples is greater than the number of available risers. Additionally, obtaining complete sample recovery from the cores (also required) is usually not achieved.

After this initial sampling plan was reviewed by the National Academy of Science Panel on Hanford Single Shell Tanks, a decision was made to acquire seven to eight samples from two tanks (241-B-110 and 241-U-110) and perform a more complete statistical analysis on data from these tanks. These studies were completed using accepted statistical methods. The results from U-110 show that spatial variability for some analytes is exceedingly large, and for other analytes the analytical variability is also exceedingly large, with no apparent pattern in the magnitudes of variability. For B-110, a significant result was that among the types of variability, sampling variability generally was largest, indicating that current core sampling methods have difficulties producing repeatable measurements.

While the methods used to study 241-B-110 and 241-U-110 were scientifically defensible, the results obtained are questionable for at least two reasons. First, the *primary assumption of random sampling is invalid* as tanks can only be core-sampled at fixed riser locations. Second, *complete core samples cannot be obtained* routinely.

A recent study has attempted (for the first time) to determine the minimum number of core samples required to estimate the concentration of many (592) analytes within specified confidence levels. The study used data from nine tanks from which two or three core samples were analyzed. The study concluded that in order to keep the estimated width of the 95% confidence levels associated with analyte concentration estimates (arithmetic mean) within 50% of the relative half-width, from two to more than five core samples (14% to 38% of the analytes, respectively) would be required. A 50% relative half-width means that the 95% confidence limits for an analyte with an estimated average concentration of 500 ppm would be 250 ppm to 750 ppm, a rather large uncertainty. While the study is commendable since accepted statistical methods were employed, the reported results on the minimum number of core samples, the number of homogenized segments, and the replicate analytical measurements represent extreme lower limits for several reasons:

- Sampling may not be performed randomly.

- Complete core samples cannot be acquired consistently.

- The estimates of analyte concentration variability used in that study were obtained from only two or three core samples per tank and are, therefore, highly uncertain.

- Fifty percent (50%) of the relative half-width would lead to a large uncertainty in the total amount of material which would be calculated from the estimated mean concentration.

It is recognized that, in many cases, a low-accuracy estimate may be sufficient to resolve a particular safety issue.

As noted earlier, there are a few basic reasons to obtain a tank waste sample. The first is to obtain some *actual waste* in order to test waste processing methods and to detect unexpected "surprise" molecules and/or their by-products that could pose an explosion or a health or reprocessing hazard. The sample may or may not be representative of the unsampled tank waste, but it is most likely closer than waste simulants. The second reason for sampling is to obtain an estimate of the average (arithmetic mean) concentration of one or more analytes. Using the estimated concentrations and the total volume of the waste, the total amounts of each analyte could be estimated. This type of sampling requires a formal sampling protocol that must rely on Sampling Theory. The average concentration estimate for each analyte must be accompanied by confidence interval estimates at a specified level of probability (usually 95%) if the concentration information is to be used in a formal risk assessment. Confidence intervals are calculated using the sample standard deviation, S(Total), the square of which is the total variance,

$$S^2(\text{Total}) = S^2(\text{Sampling}) + S^2(\text{Analytical}) \quad (4)$$

where S^2(Sampling) is the sampling variance and S^2(Analytical) the analytical variance. The sampling variance is itself a function of the variance of each step in sampling, including sample segmentation and homogenization. It is obvious that this type of sampling falls within the proposed sampling strategy. However, it should be understood that sampling theory may require dozens of completely random samples from heterogenous layers to bring the confidence levels of the concentration estimates within levels required by risk assessment calculations.

The proposed new strategy demands that a request for new information obtained via tank sampling be justified. Therefore, statistical Sampling Theory must be employed to provide an estimate of the accuracy associated with obtaining the information. For vapor-space sampling of the tank headspace, the sorbent trap and continuous monitoring methods in use at Hanford provide reasonably accurate information. *For sampling waste crust or any other fraction involving a range of particle size distributions, sampling to determine the average concentration of an analyte within reasonable confidence levels via core sampling is futile.* Even ignoring the requirement for complete and random sampling, the number and size of the samples required, as well as the several grinding and mixing steps involved, make the effort intractable. A review of sampling theory used in the mining industry shows that the required sampling protocol gets quickly out of hand as 1) the particle size and density distributions widen, 2) the within-particle concentration heterogeneity increases, and 3) the probability of finding the analyte in a given size particle decreases. The analytical equations covering several types of materials are not included in this report for reasons of brevity. A simple real-life example, which is vastly less demanding than that required for sampling the Hanford tanks, should serve to show the futility involved.

> *Example: A sampling protocol was developed to determine the concentration of aflatoxins in shipments of peanuts. Peanuts contaminated with mold could have concentrations around 112 mg/kg but the law allows a maximum of 0.02 mg/kg. Ignoring the analytical error, keeping the sampling error below 20% required that 82 kg of peanuts be randomly sampled from a shipment.*

This case is trivial in comparison to tank waste since all peanuts have approximately the same density and shape. Clearly, 82 kg is a lot of material. However, since only a small amount of sample (~1 gram) is used for a single assay, the protocol also requires crushing the 82-kg sample to a predetermined particle size and thorough mixing and sectioning to obtain a 20-kg portion. The process of grinding to smaller particle sizes, mixing, and sectioning would continue until a multitude of 1-gram samples were ready for replicate analysis. A well-known reference textbook (*Chemical Analysis*, H. A. Laitinen and W. Harris 1975) states that for "the general case of a complex mixture of several components, each containing the desired constituent at a different level and each existing in a wide range of particle sizes, rigorous statistical evaluation of indeterminate error is impractical."

One look at a photograph of the crustal material in a Hanford tank shows the heterogeneity of the material and, therefore, the futility of trying to estimate analyte concentration averages within a useful level of accuracy. The only realistic approach is to dissolve and mix the waste during retrieval and either analyze the slurry in real-time using on-line analyzers or mix and analyze the retrieved waste in a holding tank prior to processing.

Sampling slurries or sludge of the type found in Hanford tanks are somewhat more tractable, providing that a sufficient number of random and complete samples can be obtained and processed according to a rigorous protocol. If estimates are available for the variance among core samples and among homogenized segments of the cores and the analytical variance, then the number of core samples, assays per segment, and replicate assays can be estimated at a given total variance (error):

$$S_T^2 = \frac{S_c^2}{n_c} + \frac{S_s^2}{n_c n_s} + \frac{S_a^2}{n_c n_s n_a} \qquad (5)$$

where S_c^2, S_s^2, and S_a^2 are the estimated variance between core samples, homogenized segments of the cores, and the analyses and n_c, n_s, and n_a are the number of core samples, segments, and replicate analyses, respectively. This method was used by Jensen, Cromar, Wilmarth, and Heasler (1995) but their estimates are to be considered as extreme lower limits for reasons stated earlier. The proposed strategy would use formulas that include the *costs associated with core sampling*, homogenizing core segments, and replicate assays and are able to minimize the total cost for each tank. The optimum number of core samples, segments per core, and replicate analyses (rounded off) is

$$n_c = \frac{\sqrt{S_c^2/C_c}}{S_T^2}\left(\sqrt{S_c^2 C_c} + \sqrt{S_s^2 C_s} + \sqrt{S_a^2 C_a}\right) \qquad (6)$$

$$n_s = \sqrt{S_s^2 C_c / S_c^2 C_s} \qquad (7)$$

$$n_a = \sqrt{S_a^2 C_s / S_s^2 C_a} \qquad (8)$$

where S_T^2 is the desired total variance and C_c, C_s, and C_a are the costs associated with core sampling, segment homogenization, and analysis, respectively. The significant result here is that n_s and n_a are independent of the desired overall variance S_T^2. This means that if a more accurate analyte concentration estimate is needed, the number of core samples must increase.

Calculations made using cost and variance quantities appropriate for most Hanford tanks are quite discouraging, especially when the desired confidence levels are in the range necessary for a scientifically defensible risk assessment. Moreover, since S_c^2 is the largest variance and C_c the largest cost by far, sampling to obtain a useful value of S_T^2 is not economically feasible. For example, if the half-width of the 95% confidence interval for phosphate analysis in tank T-105 is to be only 50% of the estimated concentration, the number of complete core samples would be 4. However, if the desired half-width was 25%, the number jumps to 8 and, at the more acceptable 10%, 32. Nitrate samples on the same tank go from 5 (50%) to 12 (25%) to 58 (10%). For other analytes and tanks, the situation can be much worse. Again, it should be stressed that these estimates may be far too low due to nonrandom sampling, incomplete sample recovery, and other factors. Here again, accurate estimation of waste constituents may only be available using on-line analyzers during retrieval or from analysis of holding tanks containing mixed retrieved waste. The only other alternative is use of a large, heavy-duty robotic arm capable of obtaining complete random core samples at any location in a tank.

2.4 Relationship Between Characterization, Risk Analysis, Safety, Policies and Regulations

The General Strategy model illustrates the interrelation between characterization, risk, actions, and levels of confidence in choices made (Figure 4). It does not predict whether greater or smaller numbers of tank samples will have to be obtained and analyses performed to achieve tank closure. Those decisions are an outcome of the decisions made and remedial actions taken on any given tank or tank group. Neither does this model predict the rate of progress of any remediation plan. That will be determined by the number and aggressiveness of the adopted Choices.

Let us assume that an intermediate level of understanding **[Model]** of the tank has been reached and a **[Decision]** has been made to proceed with a certain **[Action]** option on the tank. Each of those options will have a different element of risk. Even the *decision to take no action carries some risk. There is no risk-free decision*. It is possible to argue that the decisions (actions) having higher risk will also have a higher potential pay-off in terms of the chemical/physical intelligence gained. This, in turn, translates into impacting the time and expense of tank waste remediation. On a short time scale, a successive action may carry a higher level of risk than the previous action. Overall, however, the level of risk should decrease as the know-how of the operators and the level of the technology and knowledge about the system increases. How informed those decisions will be depends on the level of uncertainty in the Chemical and Physical Intelligence (Figure 4). This is represented in Figure 4 by the origin and the length of the **[Choices]** arrows. These choices will have to be made in the framework of the existing political, economic, and technological realities.

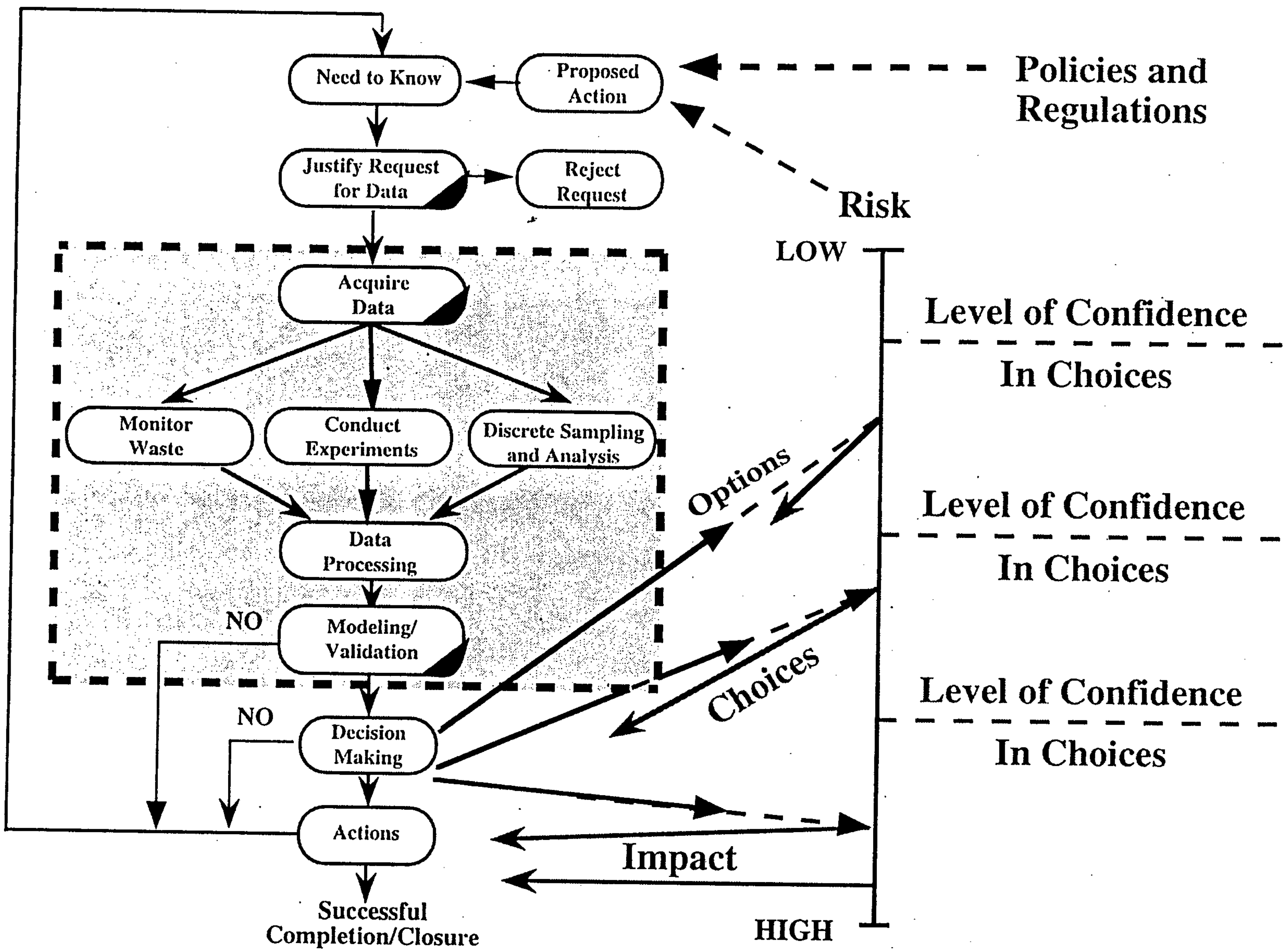


Figure 4. General Relationship Between Chemical and Physical Intelligence, Options, Choices, and Actions

Nonetheless, we believe that the greater long-term cost/benefit and risk avoidance will be achieved through establishing a decision-making framework driven by defensible scientific and technical realities and by first asking and then addressing the right questions (see Section 1.0).

It is encouraging to see that, according to this model, the uncertainty and risk decrease and the entire situation becomes progressively safer. We expect there will be some hesitancy to gaining new chemical and physical intelligence by means of actions other than traditional core sampling. However, it is expected that acceptance of future actions will increase once tangible characterization progress for such actions have been demonstrated. This is analogous to the experience and confidence gained from installing and operating the mixer pump in tank 101-SY.

Another way of expressing the relationship between the confidence limits uncertainty in chemical intelligence, safety, and remediation progress is shown in Figure 5. It is expected that the state of **[Successful Completion/Closure]** will be reached at different balances of tank contents. In other words, the final waste form and the final state of the tanks have to be decided on an individual tank or tank group basis. To achieve a tank closure, some tanks will likely have the entire contents removed (see the lower-most curve in Figure 5). In other tanks, acceptable tank closure may occur with a small to large portion of their waste remaining in place. In this instance, tank closure refers to resolution of all safety, waste stabilization, or isolation issues. It does not refer to closure as defined under the Resource Conservation and Recovery Act (RCRA).

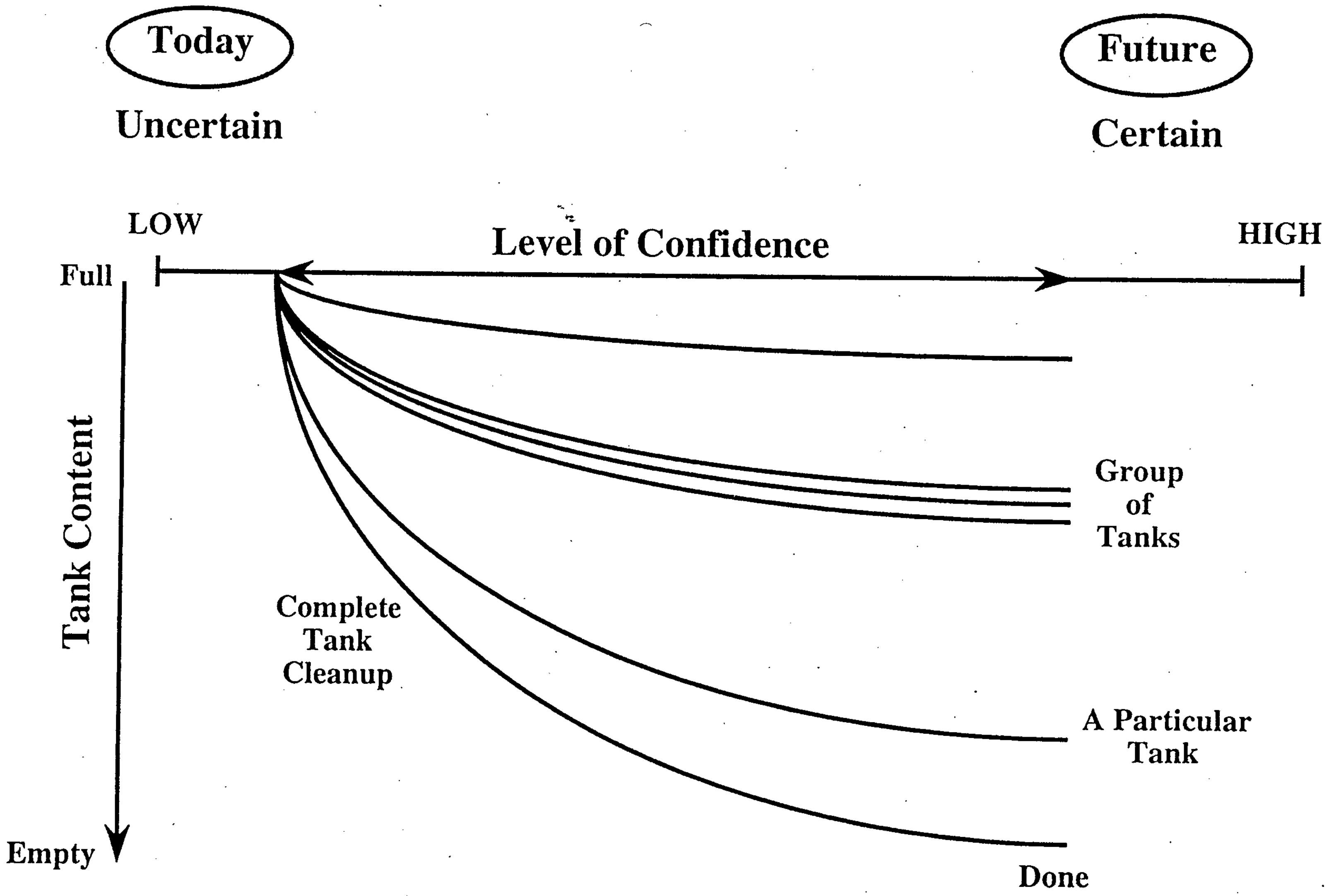


Figure 5. Expected Increase of Level of Confidence With the Progress of Remediation (for individual tanks and groups of tanks

3.0 Examples

As radiolysis and solution chemistry take place in Hanford's tank waste, new molecules and by-products are created that also undergo further chemical transformations. The chemical composition of these wastes is both complex and dynamic.

Evidence that chemical reactions are occurring is shown by the presence of decomposition products such as hydrogen, ammonia, nitrous oxide, nitrogen, trace hydrocarbons, lower molecular weight ketones, and butyl alcohol in the vapor phase; and the formates, oxalates, and other remnants of nitrogen-containing components in the liquid phase.

Over the years, several waste characterization issues related to potential safety vulnerabilities have arisen because of the presence and evolution of this waste chemistry.

Sections 3.2 through 3.6 address five examples of many safety and characterization issues that have existed or now exist in the Hanford tanks. This is not an exhaustive list. Rather, the outline and examples are intended to demonstrate the use of the General Strategy (Section 2.0) to analyze a potential problem and describe action-oriented alternatives for its resolution. Examples were selected to range from general discussions of issues (1st order [1.0] discussion of nuclear criticality) to the very specific (4th order [3.1.1.2] potential presence of an energetic nitroalkane). Each order demonstrates the relative degree of characterization needed to solve a given safety issue. Such characterization may come about from using existing data, relying upon external ("other") information sources, or collecting and analyzing new data. The iterative nature of the General Strategy enables it to be used for planning. This feature is clearly evident from the "flammable gas" example (3.3) in which four trips around the loop are described.

The outline from which these five examples are drawn is also one of many possible combinations of how a particular safety issue could be broken down into logical subparts.

Examples developed are noted in **bold** type and are discussed in detail in this section. The indentations in the outline below indicate the degree of detail to which the General Strategy can be applied:

Criticality (see Section 3.1)
- Distribution
  - Fractionation

Hazardous Gas
- **Flammable** (see Section 3.2)
- Toxic
  - Noxious

Energetic Chemical Conditions
- Ferrocyanide
  - Organic

- **Nitroalkane** (see Section 3.5)

Processing

- Waste Transfer
  - Compatibility
  - **Pipe Blockage** (see Section 3.4)
  - Corrosion
- Combined Waste Retrieval
- **Sludge Washing** (see Section 3.3)
- Phase Separation
  - Solid/Liquid
  - Liquid/Liquid
  - Evaporation

3.1 Criticality Assessment Example for Tank 102-SY

Characterization of Tank 102-SY is needed to establish that 102-SY is subcritical by a wide margin of safety **[Need to Know]**. A criticality event, depending on the severity, could breach containment and release radionuclides. Also associated with criticality is a prompt burst of neutrons and gamma rays, which could potentially expose nearby workers to nuclear radiation.

The most important factor in reaching nuclear criticality is the presence of fissile nuclides in sufficient concentrations to promote a nuclear chain reaction. An important consideration is determining the presence of any concentrating mechanism enabling fissile nuclides to associate or fractionate to a particular phase (e.g., sludge phase). Also, certain elements are very good absorbers of neutrons and, thus, will prevent a criticality excursion when present in sufficient concentrations. These elements are commonly referred to as neutron poisons.

The first characterization effort will utilize existing knowledge of a) tank contents, b) chemical and physical processes that produced the waste, and c) physical and chemical properties of the waste constituents. If this approach does not resolve the issue, a follow-up discreet sampling approach would follow from the next iteration through the Grand Strategy diagram (Figure 4).

3.1.1 Fissile Content and Distribution [Acquiring Data]

The total Pu-239+240 content of Tank 102-SY has been established previously at a value of ~60 kg (4,440 Ci) in Dicenso et al. (1995). The isotopic composition of the plutonium (Pu) is 93 wt% ^{239}Pu and 6 wt% ^{240}Pu (72.58 Ci/kg). The minimal critical mass concentration of weapons-grade plutonium, independent of form, is 2.6 grams/liter (see Nuclear Safety Guide, American Standards Association Sectional Committee N6 and Project 8 of the American Nuclear Society Standards Committee 1961). All Pu present will be distributed between the supernate and sludge phases.

On the basis of its hydrolysis chemistry, essentially all of the Pu is expected to be in the sludge phase as its insoluble +4 hydroxide; if sufficient complexing ligands (CO_3^{-2}, EDTA, DTPA, etc.) are present in the aqueous phase, some fraction of the Pu could be complexed and, hence, reside in the aqueous supernate phase. However, the 1994 "Grab Sample" indicates that the Pu solubility in the aqueous phase is low, with less than 0.02% of the Pu activity being present in the supernatant phase at that time.

A conservative approach is taken here in regard to the highest concentration that could be present in either the supernate or sludge phases. It will be assumed that all of the Pu can be in either phase, and the highest Pu concentration will be selected for the criticality evaluation. In addition, an extra margin of safety is provided because the presence of neutron absorbers (poisons) in the waste inhibit achievement of criticality.

Previous process knowledge and documented records show there is no chance that Pu could be isolated from the other actinide and lanthanide elements as a separate layer (or several layers) within the sludge phase. When cation hydroxides are precipitated using a large excess of sodium hydroxide, all of the actinide elements, fissile nuclides, most of the fission product elements, cladding elements, process addition elements (e.g., Fe), and corrosion product elements are co-precipitated as hydroxides. No chemical mechanism is known that would redistribute the co-precipitated hydroxides during aging of the tank sludges.

The only way Pu could be isolated in a pure layer would have been to add essentially all of the present Pu inventory to tank 102-SY as a neutralized small-volume process stream. A gross error, such as dumping a significant fraction from a Pu product tank to waste neutralization, would be required to accomplish this effect. There is no indication of such an event in historical process records **[Data processing]**.

3.1.1.1 Supernate Phase

The supernate volume in tank 102-SY is approximately 600,000 liters. If it contained all of the Pu, its concentration would be 0.10 gram/liter, a value considerably less (by a factor of ~25) than the minimum critical mass concentration value of 2.6 grams/liter required to accomplish a critical excursion.

3.1.1.2 Sludge Phase

The sludge volume in tank 102-SY is approximately 460,000 liters. If it contained all of the Pu, its concentration would be 0.13 gram/liter, a value considerably less (by a factor of ~20) than the minimum critical mass concentration value of 2.6 grams/liter required to accomplish a critical excursion.

3.1.1.3 Neutron Absorbers

Significant neutron absorbers (poisons) exist within the sludge phase (see Table 2) and provide additional insurance that nuclear criticality cannot be achieved in tank 102-SY. Much smaller concentrations of these poisons would be present in the supernate phase.

Table 2. Nuclear Poisons in Sludge Phase

Element	Nuclide	Thermal Neutron Cross section (barns)	Mass (metric tons)	Mass Ratio (Element/Pu)
Europium	^{154}Eu	1400	3.9 E-06	6.4 E-05
Europium	^{155}Eu	4000	2.5 E-06	4.1 E-05
Thorium	^{232}Th	7.4	2.8	4.6 E+01
Uranium	natural	2.7	0.86	1.4 E+01
Iron	natural	2.5	29	4.7 E+02
Plutonium	^{239}Pu	714	6.1 E-02	1.0

3.1.2 Input Data Reliability and Possible Consequences [Modeling/Validation]

This example of the criticality evaluation of tank 102-SY is based on characterization data contained in report WHC-SD-WM-ER-366, Rev. 0 (Dicenso et al. 1995), which is believed to be the best data currently available. If the reported plutonium content of tank 102-SY is grossly low by several orders of magnitude, the possibility of a criticality event occurring when the sludge fraction is stirred is significantly increased. The "worst case" scenario would be the initiation of a criticality excursion in the sludge or supernatant phases, resulting in an instantaneous release of 10^{17} fissions, enough energy to convert 1 liter of water to steam. This level of energy release would not be expected to do any physical damage to either the tank containment or the off-gas system; however, it would release a burst of neutrons and hard gamma rays from the emitting tank and would release fission gases (I, Xe, Kr) to the dome space above the liquid phase. Since the tank is located below ground and has a thick (8-10 feet) earth shield over the structure, no significant exposure to persons in the immediate vicinity would be anticipated. There would be a "burp" of gases, followed by a collapse of the gas void to create a mild shock wave that would be absorbed by the tank structure.

This type of accidental solution criticality excursion is discussed in detail by Tuck (1974, pp 67-68) and confirms the anticipated "no physical damage" scenario described above. Additional information on solution-based criticality accidents of this type may be found in Stratton (1967).

3.1.3 Decision/Action

Historical process records, tank records, and the available knowledge of the chemical and nuclear properties of the tank constituents indicate that tank 102-SY is subcritical by a wide margin with respect to Pu concentration. Furthermore, the presence of nuclear poisons add additional insurance to the safety margin.

The criticality issue for 102-SY should be considered closed. This evaluation should be performed again for any future additions of wastes to this tank or for other similar tanks **[Action]**.

3.2 Flammable Gas Safety Example

This characterization example discusses the resolution of flammable gas hazards by use of the General Strategy. It concerns all tanks and all intrusive activity where the flammable gases may reach concentrations that can be ignited and, thus, present hazards to site workers and the general public.

The radiolysis of both water and organic materials is strongly dependent on the chemical composition of the waste; therefore, the quantity and composition of the gaseous radiolysis products are also strongly dependent on the chemical composition. Typical components in the released gases are hydrogen, nitrogen, ammonia, and nitrous oxide, with small amounts of methane in some cases. Oxygen and the carbon oxides are also known, but not well-quantified, reaction products. The major categories of flammable gas generation can be subdivided into two categories:

- gas generation from thermo-radiolysis of inorganic constituents
- gas generation from thermo-radiolysis of organic constituents.

The largest fraction of the tank waste is the inorganic salt, which, with the present composition maintained, contributes only approximately 25% to the volume of the flammable gases. The flammable gas volume of inorganic origin is not expected to be strongly time-dependent because of the large masses involved. The approximately 75% of the flammable gas derived from the thermo/radiolysis of organic compounds is time-dependent because of the depletion of the carbon/hydrogen bonds in the decomposition sequence.

Unfortunately, it is common practice to correlate organic compound quantity (total organic carbon, hereafter denoted by %TOC) with the amount of flammable gas. However, there is no direct relationship between TOC and flammable gas generation. Hydrogen-depleted organic compounds, such as sodium oxalate, show up as %TOC but do not contribute to flammable gas generation.

It is important to understand that the chemical and radiological processes taking place in the stored waste may generate a mixture of gases that has sufficient quantities of oxidizer to burn without mixing with air.

3.2.1 Current Characterization Strategy

In some cases, the waste rheology is such that the generated gases are continuously released from the wastes, while in other cases they are partially retained and periodically released from the waste. At the present time, there is a better understanding of the steady flammable-gas generation and release mechanisms than of the retention mechanisms. The basic intelligence that needs to be established for each tank waste/tank configuration is 1) the potential and magnitude of the hazard of a flammable gas burn in the dome's head space (such a possibility is, albeit indirectly, related to the rate of flammable gas generation), 2) the retention of any flammable gas in the waste, and 3) the flammable gas release mechanism. The following discussion is based on the General Strategy (see Figure 2).

[Need To Know]

The need-to-know information for safe storage is whether the flammable gas concentration is below acceptable levels (flammability limit with a fourfold safety factor, i.e., 25% of the lower flammability limit)

- during steady-state conditions
- during intrusive activities
- in periodic release conditions.

Further information would be needed about whether or not the severity of the flammable gas condition would change under processing conditions, such as waste mixing, sludge washing, and processing scenarios.

The flammable gas issues are closely related to the "organic safety issue." It concerns the acceleration of the same or a similar chemical reaction to a slow but propagating chemical reaction under special conditions.

[Justify Request for Data]

The safe storage conditions of the tank farms require knowledge about the hazards relating to the composition and quantity of flammable gases because of the potential for producing excessive mechanical stresses on tanks or excessive releases of hazardous contaminants that could be a consequence of a gas burn in the tank dome space or in a subsurface gas pocket.

This information is needed under all three conditions which were listed under the "need to know" paragraph for safe storage (steady-state conditions, intrusive activity, periodic release conditions).

FIRST ITERATION

[Acquire Data]

The characterization data acquisition for the General Strategy and for the different conditions of the flammable gas release mechanisms requires several iterations be performed through the strategy process. The iterations are for the different conditions. The first iteration is the establishment of the potential flammable gas hazards in the tanks as they presently exist, before access or any other activity is attempted or before additional knowledge regarding waste behavior is collected.

Before any access to the tank is permitted, the presence and concentration of the flammable gas has to be established. This can be a single discreet sample or "in tank" dome space monitoring for short periods using appropriate instrumentation. Thus, the first iteration can use either of the two primary data-collecting methods. Although previous measurements may be available for a specific tank, because of the possible non-steady-state nature of flammable gas occurrence, the previous data, while relevant, are not acceptable for this initial access step.

[Discrete Sampling and Analysis]

The 25% lower flammability limit of the dome space is established.

[Data Processing]

The data processing for this first iteration serves both screening and comparative purposes. The discrete sample measured 25% lower flammability limit will address questions concerning how hazardous a tank's dome flammability situation is for the installation of monitoring equipment and for normal tank farm management activities. These new data would also serve as a check on the quality of the dome space chemical composition data obtained from **[Other Information]**. If the older data are considered reliable, such a comparison would yield information on the steadiness and variability of the gas releases.

Are the measured values above 25% lower flammability limit? If the measured values are within the error band of the 25% lower flammability limit, remeasurement is necessary. How many new measurements are to be taken should be established based on an error analysis of the measurement technique.

[Modeling/Validation]

Are the measured values in the range of any previous data points?

[Other Information Sources]

- Any indication of surface level changes?
- Any indication of thermal gradients in waste layers?
- Sludge level in waste.
- Dome space volume.
- Ventilation rate, if any.
- Hanford Defined Wastes (HDW) (Agnew)\organic model indications.

[Decision Making]

If there is a significant variation between prior measurements and the current lower flammability limit value, the tank may be subject to periodic release type behavior and should be prioritized for installation of permanent continuous lower flammability limit monitoring prior to any further access to the tank. If the percent lower flammability limit value is within the range of prior values and below 25% lower flammability limit, controlled access to the tank for non-intrusive activity can be permitted, while the permanent continuous percent lower flammability limit monitoring is installed. The decision making should also consider input from **[Other Information]** knowledge for the monitoring prioritization. The more the indications are for periodic-type releases, the more caution should be applied for action relating to a tank in regard to administrative controls. If periodic-type releases are indicated, all activity regarding the tank should be under flammable gas administrative control. Typical options are the plans for the installation of ventilation systems, implementation or change of data-taking frequencies, and avoidance of any intrusive activity until additional information is available.

Examples of other options include

- Establish whether flammable gas control conditions apply to any future activity.
- Establish any additional data-taking needs or frequency changes.
- Establish whether intrusive activity should be planned.
- Review previously installed equipment for operability under flammable gas controls.
- Establish prioritization for the installation of continuous % lower flammability limit monitoring.
- Establish instrumentation/hardware needs for safe operation (e.g., ventilation systems, etc.)
- Establish input for the second iteration for the characterization strategy diagram **[Justify Request for Data]** block.

SECOND ITERATION

[Justify Request for Data]

While the information generated in the first iteration may be varied, there are assumptions made here to indicate the type of behavior that leads to the second iteration. However, as stated in the first iteration, the initial concern is what precautions need to be made to access the tank even for the installation of monitoring equipment, if it is not installed at the starting time, to generate data on the basis of which tank waste behavior can be evaluated.

[Acquire Data]

The most direct and least ambiguous information regarding any phenomenon is the measurement of the actual parameter or property of concern; any derived information is always subject to additional errors and uncertainties. Thus, the historical record of flammable gas concentrations versus time behavior is a valuable measure of the flammable gas steady state or periodic change concentration measurement.

The periodicity of concentration in the dome space can be correlated with the dome space versus ambient pressure because flammable gas release volumes of concern result in pressure changes in the dome space. Concentration and pressure values can also be compared with other monitored, derived, or historical data, such as waste temperature profile change, level change, and historical release volume information.

Periodic gas releases are also known to cause waste level drops. Besides indicating the occurrence of a release, waste level can be used to estimate the volume of the gas released. Based on past gas release histories, the type of gas release being discussed results in sludge mixing. Thus, the waste and dome space temperature profile can be used as an indicator of the occurrence, magnitude, and, perhaps, even the spatial location of a periodic gas release.

If none of these parameters show significant changes, one can reasonably make assertions concerning the steady state or periodic gas releases.

In the **[Other Information]** category, the past history of the tank and the information available from the fill records can be used to establish whether the specific tanks were contaminated with the type of organic chemicals that are known to result in flammable gas generation under the chemical and radiological conditions of the tanks (S. F. Agnew 1995).

The past temperature and radiation history of the waste are also important parameters for the estimation of the residual flammable gas generation contribution of any organic complexants which were originally present in the waste. The decomposition rate and even the reaction product composition are strongly affected by both temperature and radiation field strength.

The gas release by itself is an insufficient determinant of the potential hazard resulting from a gas release. Other factors also influence the determination of the magnitude of the hazard or, in some cases, can determine the acceptable mitigation forms if any are needed. Some of these are measurable or derived values relating to sludge height, free dome space, ventilation rate, breathing rate, mixing ratio, and time in the dome space, etc. Thus, it is insufficient to establish whether the flammability can reach the 100% lower flammability limit. It is also important to establish the consequence of the pressure and temperature rise in an exothermic event on the structural integrity of the waste storage tank and any current radiation protection system (HEPA filters, etc.).

Under all conditions, it is necessary to have a first indication of the dome space gas composition, regardless of the mechanism of gas release. The gas composition information will be needed for the **[Modeling/Validation]** and the **[Decision Making]** steps to establish a gas composition library under various release and operating conditions.

[Monitor Waste]

It is assumed that the necessary monitoring instrumentation has been installed under the **[Decision Making]** and **[Actions]** steps of the first iteration. That is,

- percent lower flammability limit in dome space, continuous data logging
- precision ΔP measurement between dome space and ambient, continuous data logging
- waste level, continuous data logging--determine the error range from all factors for level measurement accuracy

- dome space and waste temperature profile, continuous data logging
- barometric pressure (for potential predictive information generation) or preferably dome space absolute pressure.

[Discrete Sampling and Analysis]

- Composition of dome space gas is determined.

[Other Information]

This information would include

- past history of tank level measurements
- past history of temperature profiles
- known information relating to original organic complexant inputs
- free volume of dome space
- dome space ventilation rate (forced or free)
- dome space mixing rate.

[Data Processing]

There are more complicated steps at this time relating to the processing of the obtained data than in the first iteration. The steps are both analytical and predictive.

- Variation of dome space percent lower flammability limit versus time: Can any periodicity be established from the generated information?
- If any variation occurred in dome space percent lower flammability limit, are there any comparable indications of change in the other **[Monitoring]** generated parameters, such as waste surface level, temperature profile, or dome space pressure? If "yes," then the correlation needs to be analyzed for potential classification of the tank as a Gas Release Event producing tank. The generated data also need to be compared with the **[Other Information]** for the relationships between the theoretical understanding of waste behavior and the obtained information.
- If no variation in the dome space percent lower flammability limit has occurred, what are the confidence levels acceptable for the establishment of steady-state release conditions compared to the known dome space ventilation rate? Is it possible to increase the steady state percent lower flammability limit levels by some tank farm action or modification of an action, which needs to be administratively controlled?

- Is the generated information regarding the flammable gas release rate comparable to the theoretical estimates of the water or the water plus complexant hydrogen-generation rates? This evaluation can also be used to estimate gas retention possibilities, which should trigger additional analysis or iteration.
- If periodic release is indicated, what is the volume estimate of such releases?
- If periodic release is indicated, what is the duration of a release?
- What is the frequency of the periodic release?
- What is the ratio of the rate of steady-state release to the rate of periodic release flammable gas mixture?
- Evaluate other potential causes of waste level change, e.g., solid consolidation after salt well pumping, rain water intrusion, leakage, level measurement instrument faults, etc.

[Modeling/Validation]

The **[Modeling/Validation]** steps at this iteration may be performed for several different decision-making steps and may need to be grouped accordingly.

- Based on the generated data, can the steady state or the periodic release mechanism for a particular tank be established, i.e., is a steady-state flammable gas release condition confirmed by all relevant measurement parameters? Or is the periodic flammable gas release condition confirmed by all relevant measurement parameters?
- Are the confidence levels of the measurements acceptable for decision-making or does additional information need to be generated?

[Decision Making]

The basic decision-making process at this iteration relates to whether sufficient information is available for the segregation of tanks into steady-state or periodic flammable gas release behavior tanks. This segregation is not directly related to whether there is retained gas in the waste. For example, there may be gas retained in a "salt cake" matrix, but it cannot be released at a rate or in a quantity that would generate a condition above the percent lower flammability limit in the dome space of the tanks. If such accumulation occurs, it would not be determined at this iteration, but in a successive one.

- What type of administrative controls are needed for what type of actions regarding access and activity in the tanks? For example, are controls needed for 1) normal non-intrusive operations, 2) dome space intrusive operations, and/or 3) waste intrusive operations?
- What type of safety rules need to be established for preventive safety? Does the tank or tank farm need to operate under a specific set of regulations?
- What type of activity can be performed in the tank, while maintaining the continuous monitoring of the dome space for percent lower flammability limit?
- What additional data needs to be generated to better establish the quantity and periodicity of a non-steady-state gas release?

- Does the tank qualify to be added or removed from a "special list" of issue tanks?
- Can an operational "window" be established when a lower hazard level exists compared to time durations when a higher hazard exists?

[Actions]

The actions can be administrative decisions to accept the information as adequate for resolution of tank administrative controls or to require additional data generation. When the data indicate a periodic gas release or (in a derived manner) gas accumulating in the tanks, the action would be to prepare a request for additional data.

THIRD ITERATION

[Justify Request for Data]

If the previous iteration indicates that the gas release rate is periodic, then additional information is needed to establish an operational basis for mitigation measures for the tank. This type of intelligence will include information that may require a waste intrusive characterization activity and, therefore, will include additional measurements which are based not only on **[Monitoring]** but also on **[Discrete Sampling and Analysis]**. However, the intelligence obtained in the previous iterations also needs to be added to the **[Other Information]** now available.

If the gas release rate is periodic, it means that in some part of the waste there are solids which are capable of retaining flammable gases up to a limiting condition, at which time they may be released at a relatively high rate into the dome space, where the existing ventilation would not prevent reaching the 25% lower flammability limit value.

Another phenomenon could be occurring, i.e., the retention of a flammable gas volume in the crust of the salt cake, which may stay trapped and not be subject to periodic releases (similar to the SY-101 crust). Such a condition may present a hazard upon breaching the gas-retaining layer by waste intrusive activity or by the initiation of waste processing. This latter case can be considered a limiting condition for the first case with different waste solid rheological properties. Under most conditions, after reaching a limiting value, the flammable gas would be released from this trapped mode, but in a much slower manner, either by diffusion or by slow leakage through cracks. The only relatively fast release that can be postulated for this type of retained gas is during sluicing or other retrieval modes, when due to dissolution, the salt cake could release the trapped gases relatively rapidly.

However, this type of trapped gas still causes hazards for waste intrusive activity that may release only a small part of the total flammable gas, but which could be deflagrated by the waste intrusive action itself.

Another aspect of the data justification is whether the iteration needs to be performed for all of the tanks, for tank groupings, or even only for tanks that exhibit bounding periodic releases. Thus, the extent of the iteration is a factor to be decided and justified for further characterization.

[Acquire Data]

In all cases, the **[Acquire Data]** step in successive iterations assumes that the data needed in the previous iterations are already available. In this case, the basic data acquisition relates to the quantification and better definition of flammable gas retention and of periodic releases.

[Discrete Sampling and Analysis]

- In situ void volume profile of waste
- Retained gas sample from waste profile
- Waste viscosity profile
- Waste specific gravity profile
- Major organic constituents of sample
- Radiation dose of waste (or layers)
- Composition of the release gas during a periodic event.

[Other Information]

- Estimation of the flammable gas generating complexant half-life
- Any simulant-based data relating to flammable gas generation.

[Data Processing]

- What is the magnitude of the hazard on the tank structure due to a burn of the flammable gas volume?
- What is the effect of the tank ventilation on the magnitude of the hazard?
- Correlations between the measured parameters.
- Indication whether there is retained gas which is not subject to periodic releases without intrusive activity.
- Can any predictive information be generated which applies to future behavior of a single or multiple tanks?
- Estimation of the total retained gas volume.
- Estimation of the fraction of release to the total volume retained before release.

[Modeling/Validation]

- What is the uncertainty of the data and or correlations obtained to this point?
- Can the generated intelligence be expanded to other waste types, other tanks, etc.? What are the limitations of the generated data in a predictive mode?

- What is the intrusive activity effect on the gas release?
- Evaluate indication of a non-gas release event producing gas retention.

[Decision Making]

- Can administrative controls alone be applied for ensuring safe operation?
- Are mitigative actions necessary to ameliorate the hazard?
- What routine activity can be performed without additional iteration of data generation?
- What are the bounding conditions for planned future activity and are those activities covered by the available information?

[Actions]

- Establish operational safety limits for the intended activities.
- Establish whether additional iterations are needed.
- Mitigate the flammable gas generation hazard.

FOURTH ITERATION

[Justify Request for Data]

The justification for additional data identifies the retained but non-gas release event that produces gas in the previous iteration. Such retained gas may be a hazard during intrusive activity, such as core drilling for samples. In all cases, the core drilling equipment should be designed for the most conservative National Fire Protection Association (NFPA) and National Environmental Council (NEC) classification for operation in flammable gas and, particularly, for hydrogen-containing environments. In typical substrates, which may require core drilling rather than push mode drilling, the rheology of the waste is expected to be more rigid than for waste substrates, where push mode sampling is expected to be successful. In such wastes, it is possible that the intrusive operation may disturb a pocket of waste retaining flammable gas, perhaps resulting in a local gas release that does not propagate away from the area of disturbance. Cases may exist in salt well pumped sludge tanks or in salt cake tanks, where there is a significant gas volume trapped in the waste even though a near-continuous gas release is occurring by diffusion or controlled leakage through cracks. Under these conditions, the monitored gas release would be near steady state.

A possible behavior simulating this type of gas retention is the floating crust in SY-101, which is assumed to contain large quantities of gas. The composition of this gas may not be the same as in the continuous or gas release event gases because of the significantly different diffusion properties of the gases. Thus, the floating salt cake may be depleted in hydrogen.

If this type of gas retention exists, it would also be expected to be subject to periodic release behavior during salt well pumping or retrieval, which would either change the overburden pressure or dissolve part of the gas-retaining waste.

[Acquire Data]

The data acquisition in this case would start by the review of the data generated during the previous iterations. It is important to determine if conditions allow gas retention within the waste. It is possible that the sampler of the retained gas can be utilized for the discrete sampling and analysis to determine the presence of nonreleasing flammable gas accumulation. However, the composition of the gas released during the steady state may also be different from that collected from discrete sampling events. Thus, there is a unique value in continuous monitoring. Gas composition estimates could also be obtained by retrieving and dissolving crust samples to see what type of residual composition exists in crystalline material after long-term gas storage. These are just a few examples of opportunistic characterization steps proposed in the new strategy.

[Discrete Sampling and Analysis]

The discrete sampling of tanks for trapped, but not released, flammable gases (i.e., retained-gas sampling) is performed only for the selected list of tanks.

[Other Information]

The information obtained from the previous iterations.

[Data Processing]

The data processing determines, based on the retained gas volume and the previously generated continuous flammable gas monitoring data, whether there is an indication of retained gas which is not subject to periodic gas release events. Based on retained gas sampling, the quantity and the composition of the retained gas can be determined. Due to the different diffusivity coefficients of the generated gases and the potential of differential releases from substrates where this type of phenomenon may occur, both the composition and the quantity determinations are important. (A similar analogy can be used for some of the large floating crusts in other gas-generating tanks.) If the gas composition is not in the flammable range, the consequences of such retained gas release are not relevant for this issue evaluation. If there are flammable gases above a certain level which could result in flammability hazard in the dome space during a release, additional data may be needed.

[Modeling/Validation]

The modeling and validation steps need to compare the measured gas retention and release properties of this phenomenon to the other type of gas retention and release knowledge. There may be a need for new data generation concerning future activity relating to the waste, e.g., the flammable gas release rate upon dissolution or dilution of the gas-retaining waste. Such operations may be represented by retrieval-type activity or waste transfer. Need for this type of additional data acquisition can be handled by an additional iteration, which would be a gas release rate measurement from a discrete sample during dissolution. (This type of behavior is expected to be relevant only for salt-cake-type waste.)

[Decision Making]

The type of decision making relates to the following questions:

- Does tank waste behavior require different control or mitigation than that used for other types of flammable gas tanks?
- Is the retained gas flammability hazard different than that of the other type of retained gases?
- Does the type of gas composition affect local intrusive activity?
- Does the type of retained gas composition affect tank-wide intrusive activity (salt well pumping, retrieval, etc.)?

[Actions]

Examples of actions could be

- treating the tank as a non-gas-retaining tank in all activities
- treating the tank as a gas-retaining tank for all or some activities
- performing additional iteration(s) to determine changes in gas-retaining behavior upon processing the waste.

The above examples of iterations discuss typical properties and examples of the characterization steps; they do not cover all possible characterization steps, data acquisition steps, data evaluations, or any other steps. They were generated as examples of handling a particular safety-issue resolution-identification methodology.

3.2.2 Alternative Flammability Characterization Issue Resolution

The problem of managing explosive atmospheres (flammable gases) is not unique to the nuclear waste storage tanks. It has been a long-standing problem of mining, petrochemical, marine transportation, and other industries. In those cases, the probability of explosion is often higher although the consequences compared to Hanford tanks probably would be less severe.

There are two aspects to this problem. One is understanding the mechanism and mitigation of the generation of explosive gases. The second is the technology of monitoring and safety. The first one has been addressed in Section 3.3.1, the second one will be discussed here.

The radiolysis and accompanying chemical reactions result in the formation of a variety of gases, some of which are flammable and others which are not. Moreover, all gases can be temporarily retained in the rheologically complex medium that is the condensed part of the waste, and they can be released at unpredictable and often irregular intervals. These are the infamous "burps" that have been observed in some of the Hanford tanks.

Although the presence of most components of this complex and time-varying gaseous mixture can be rationalized, the amounts, rates of release, and ratios of these components cannot be. *Likewise, the total volume of the evolved gas bears little or no correlation to the property of concern, i.e., flammability.* This is because some gases such as N_2 or vapors of most chlorinated hydrocarbons and water act as diluents or explosion retardants. The solubility of different gaseous components in the supernatant is also a largely unknown and complicating factor.

Furthermore, even if there were a valid correlation between the volume of evolved gas and flammability, serious doubts exist about the quality of this information. Yet the economic and safety consequences of the decisions based on this type of information are far-reaching. It can be safely stated that the industries mentioned above (e.g., petrochemical), being publicly accountable and business-oriented entities, could not afford to approach their specific flammability problems at the low level of technical sophistication exercised at the Hanford Site. The main difference lies in the fact that at Hanford the "flammability" is judged from an indirect and probably irrelevant and low-quality experimental observation, while in other industrial situations the "flammability" is measured *directly* by relatively inexpensive and time-tested instrumentation. In the following sections, we explain how this is done and suggest how a similar approach could be adopted to facilitate the direct resolution of characterization and safety issues pertaining to flammability in the Hanford tanks.

3.2.2.1 Principles of Flammability Sensing

Reaction between a fuel (F) and oxygen (O_2) releases thermal energy (ΔH) and combustion products (P):

$$F + O_2 \xrightarrow{k} P \qquad \Delta H \tag{9}$$

For hydrocarbons, the products would typically be CO_2 and H_2O for complete combustion, but compounds containing other elements would lead to a more complex mixture of products. The velocity with which this reaction proceeds ranges from very slow (e.g., rotting) to fast (e.g., burning) to extremely fast (e.g., explosion). It depends on the value of the rate constant, k, and on the concentrations of the oxidant and the fuel. Sensing of "flammability" or "explosion limit" is based on the very same reaction, although the amount of heat evolved for the same amount of fuel depends on the rate of the combustion. This is why such sensors provide *direct* information about "flammability." The trick is to perform the reaction under *controlled and reproducible conditions* that allow quantitative extraction of information. The experimental parameter that provides this information is the reaction heat, ΔH, which is readily converted to an electrical signal. In most practical situations, these sensors are used as threshold indicators of some predetermined value, for example, 25% lower explosion limit (25%LEL). It is customary to call such devices "alarms" rather than sensors, which provide information on a continuous scale of concentrations.

One advantage of the "alarm" mode as opposed to the "sensor" mode of operation is that the precision and accuracy requirements do not have to be very stringent. Typically, an accuracy of $\pm 10\%$ of the preset value is sufficient.

It is important to note that the given concentrations of the fuel and of the oxidant alone do not necessarily lead to a flammable condition. The presence of inhibitors and retardants on one hand and promotors and initiators (also accelerators) on the other is very important. Again, a good "flammability sensor" provides *direct* information about flammability, rather than concentrations or even the ratio of the concentrations of the oxidant and fuel. The presence of promotors and/or inhibitors also affects the performance of the "flammability sensors." In the flammability sensors, the controlled combustion takes place typically at the surface of a mixed oxide which contains a specific amount of catalytic metals. It is known that certain compounds may "poison" (i.e., slow down) the rate of combustion at the sensor surface causing erroneous results. Therefore, sensors that perform flawlessly, e.g., in a mining environment, have to be optimized for application in other environments. This tailoring and evaluation of the sensors for a specific sensing application is one of the most critical elements in their correct deployment. Correctly prepared flammability sensors have been used in the mining industry for many decades and have a solid record of protecting human lives. It is important to realize that the concentration of oxygen in mining operations is higher than would be encountered in the dome space of a storage tank. This presents a higher explosion risk in a mining operation compared to the tanks. On the other hand, a decision to "ventilate" a tank resulting from invalid information about the headspace gas composition may lead to an *increased* risk of explosion should the conditions in the dome correspond to an "oxygen starved" state of the combustion reaction. Again, a correctly operating "flammability sensor" would provide direct information about the available margin of safety.

3.2.2.2 Suggested Action

An approach to resolution of the flammability characterization issue is suggested that is consistent with the General Strategy. The **[Need to Know]** is unquestionable. The first step is the rough prioritization of the tanks on the basis of the composition and rate of change of the gas in the dome space. (This is not the same as flammability!) Much of this information, i.e., **[Other Information]**, is probably available in the historical records of gas phase analyses of individual tanks. Special attention needs to be paid to the tanks that have a low relative humidity, since water vapor is a powerful retardant. This information needs to be supplemented by obtaining "grab samples" and performing batch analysis and laboratory **[Experiments]**. The latter should be done from the viewpoint of obtaining direct information about flammability of the grab sample. The techniques for doing this exist and are widely known. Some grab samples could be used to determine the optimum operating conditions for the "flammability" monitors and sensors that will be deployed later. The grab samples should be obtained in **[Justified]** time intervals in order to obtain some assessment of the dynamics of the gas evolution in any given tank. **[Data Processing]** will merge the existing information with the experimental and analysis data. This information feeds directly into the **[Model]** for any given tank. On the basis of the model, **[Decisions]** will be made about the priority of any given tank for 1) continuous monitoring, 2) frequency of the information acquisition, and/or 3) any mitigation or remedial action.

In the Second Iteration of the loop, the prioritization of the **[Need to Know]** for individual tanks should be made. This will, in effect, generate the technically defensible "Watch List Tanks." According to this list, the identified tanks will be instrumented with monitors, i.e., flammability sensors, for which the calibration protocol will be specified. That will depend on the "chemistry" of any given tank and the resiliency of the sensor toward "poisoning" in the course of continuous operation in a given atmosphere. Frequency of batch analyses will be established. As the continuous monitoring proceeds, the incoming information will be fed into the **[Model]**.

It must be realized that the resolution of the flammability gas issue is only a portion of the overall tank waste problem. The information gathered from the management of the flammability issue of any given tank thus becomes a part of the larger model of that tank's behavior, which must be seen in the context of the overall remediation goal. Thus, the flammable gas resolution contains the three linked elements: control - mitigation - resolution.

3.3 Sludge Washing Example

Sludge washing is an important step in the sludge retrieval/processing option for the waste tanks. Sludge washing involves dissolution of the salt cake by water (steam) addition, separating the salt solution from the sludge, and then washing the sludge with alkaline water solution to remove interstitial salts and to dissolve some of the soluble ingredients. A key issue in sludge washing is the ability to effect near-quantitative separation of solids and liquids. Waste characterization is necessary to provide the technical basis for the design of process flow sheets and to define equipment requirements for sludge washing.

[Need to Know]

The proposed characterization approach (Figure 2) provides a general strategy for eventually obtaining the necessary information to

- design the sludge washing processes
- construct equipment and facilities
- estimate the costs for sludge washing.

The results of this study show that for any given tank, the characterization approach will require several iterations through the steps outlined in Figure 4. After identification of tanks containing similar wastes (information obtained from historical and initial analytical data), these closely related tanks will then be more extensively characterized to form a suitable feedstock group by identifying what additional data are needed to fill data gaps. **[Justify Request for Data]**

The method for deploying the characterization strategy diagram uses the following two iterations as examples:

(a) First, review all existing information on waste tank contents and identify groups of tanks having closely similar waste characteristics.
(b) Second, determine if the present database is sufficient to develop detailed chemical process flowsheets, which must include material balances and process cycle times. If the database is incomplete, determine from the strategy diagram what additional data are needed and initiate appropriate actions to obtain the required data.

3.3.1 Iteration 1--Identify Tanks with Similar Wastes

The existing tank information base, **[Other Information]**, was reviewed with respect to physical and chemical properties of the wastes in all of the tanks. This information base included historical records of the processes that produced the wastes, and current core-sampling data, which suggest selection of four of the ferrocyanide waste tanks as a tank group with closely similar properties: tanks 241-C-108, 241-C-109, 241-C-111, and 241-C-112.

Process records indicate that initially these tanks had a high sodium nickel ferrocyanide content, $Na_2NiFe(CN)_6$, ranging from about 9 to 24 wt%. Recent core samples indicate that the ferrocyanide has decomposed significantly, perhaps by as much as a factor of ten. This decomposition produces hydrous oxides of iron, nickel, and the water soluble salt sodium formate. The wastes now exist as amorphous wet solids consisting of about 75 to 85 wt% precipitated sodium salts (nitrate, nitrite, and formate), 10 to 20 wt% of water insoluble sludge, and about 5 wt% water. Radionuclides make up less than 1% of the mass of the sludges.

It is concluded that the wastes in these four tanks are close enough in their chemical character to be processed together, using the same basic processing flowsheet and equipment. One would expect that reasonable adjustment of process controls to a modest variance in parameters (e.g., dissolution times, liquid/solid separation rates) could be used to successfully complete this processing. It must be noted that at this time not all the specific characterization information needed to design the salt dissolution and subsequent liquid/solid separation systems is available. However, a general consensus exists from process chemists evaluating sludge washing treatment as to the general chemical approach required for the process system.

3.3.2 Iteration 2--Detailed Process Flowsheets

To develop proper flowsheets for sludge washing, detailed chemical and physical data are required. The types of data needed are listed in Table 3. These data can only be acquired by careful characterization of tank residues. Sludge characterization information currently available is totally inadequate for this purpose; the core samples available at present are only qualitatively useful.

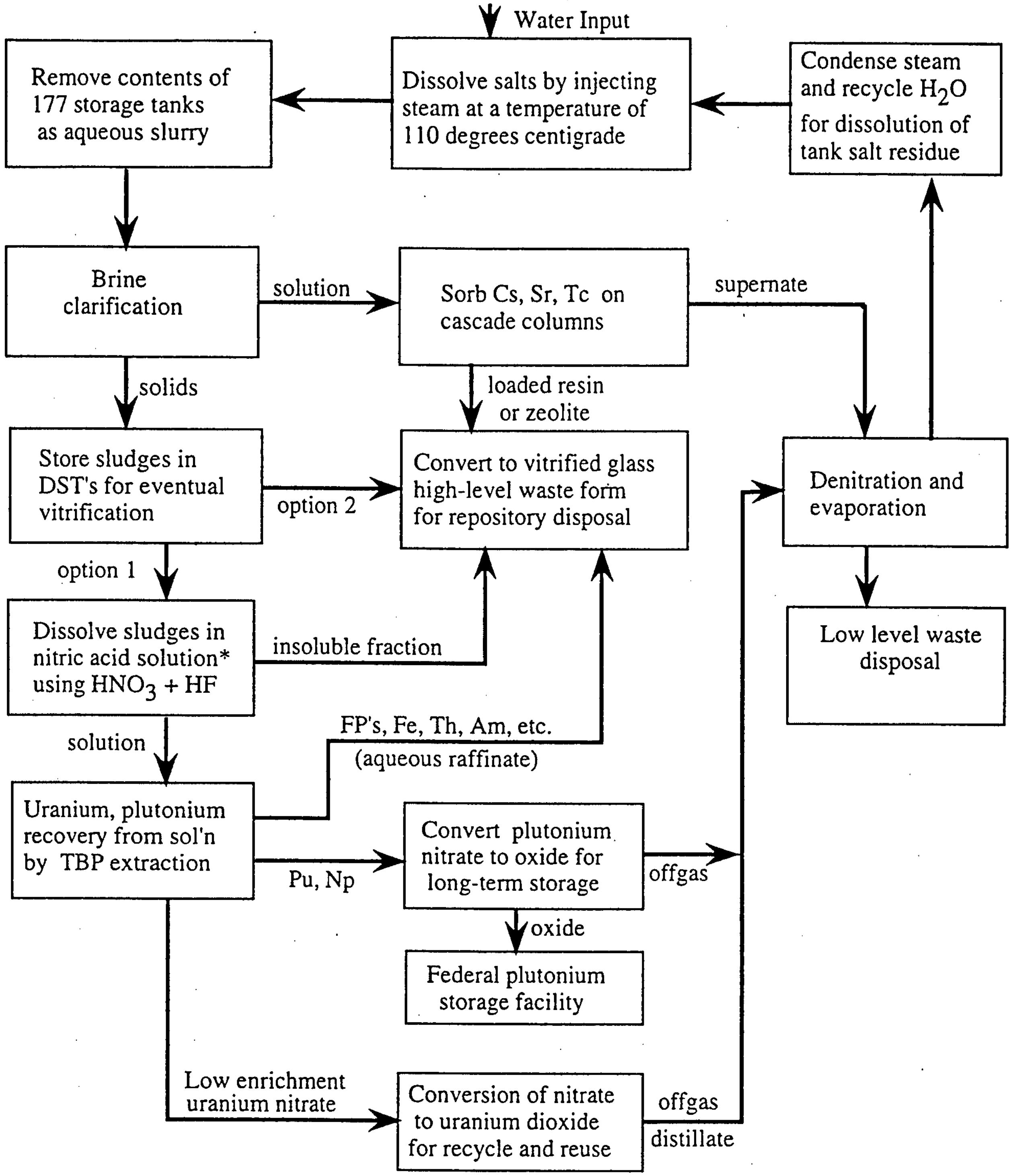
Table 3. Chemical and Physical Property Data Requirements for Sludge Washing Flowsheets

Dissolved Salt Solutions	Sludge
Chemical composition	Chemical composition
Anions present	Anions present*
Cations present	Cations present*
Radionuclide composition	Radionuclide composition*
Density vs. concentration	Density vs. concentration
Viscosity vs. concentration	Viscosity vs. liquid content
Organics present (complexants)	Organics present (precipitates)
Salt solubility characteristics	Rheologic properties
	Settling rates
	Ionic strength effects
	pH effects
	Particle size distribution
	Centrifugal force needed to effect liquid removal
	Filtration characteristics of insoluble fraction (colloids?)

*These analyses should be performed on the solution obtained from acid dissolution of the washed sludge; see prototype flowchart for position of "interim acid product for analysis." (Figure 6)

Attaining truly representative samples from core sampling will be prohibitively expensive and probably infeasible as well. To obtain the operations data needed for effective sludge washing, a small pilot plant is required to adequately establish the physical and chemical properties of the insoluble sludges. It would be best to adopt a "characterize as you process" concept in a pilot plant specifically set up for evaluation of sludge washing requirements.

The pilot scale unit would use feedstocks from one or more locations in each of the tanks to establish the range of chemical compositions and physical properties that has to be accommodated. Pilot plant operations will provide relatively large and representative samples of sludge. These samples would provide the critical technical information describing the sludge, such as its chemical composition, chemical properties, viscosity, pumping characteristics, settling rate, etc. (see Table 1). In addition to the requirements shown in Table 3, other chemical characterization data, would be required for the operations that follow sludge washing, such as removal of radionuclides from the dissolved salt brines, additional solids processing, solids dissolution, etc. Sludge washing development must be well coordinated with chemical processing activities that will follow that initial treatment step, as shown in the prototype flowchart (Figure 6). This type of information-gathering "on-the-fly" is typical of a normal industrial *process control.*



*NOTE: This is the place to obtain samples to perform detailed chemical analysis of sludge contents.

Figure 6. Prototype Flow Chart for Sludge Washing

There is a special need to evaluate the characteristics of the various types of inorganic sorbents and organic ion exchange resins for retention of Cs, Sr, and Tc from alkaline solution. This fundamental information will be critical to the basic concept of sludge washing, since most of the ^{137}Cs and much of the ^{90}Sr and ^{99}Tc will be present in the aqueous brine phase. This characterization should have a high priority in the sequence of events since it will directly affect the success of this concept.

Additionally, the organic complexant content of the brine phase must be carefully evaluated relative to its effect on the retention of Cs, Sr, and Tc in the various possible exchangers, since this reaction will compete with adsorption on potential process sorbents.

It is evident that some level of prioritization of characterization work should be established to efficiently program the sequence of characterization events. It would seem prudent to delay characterization intended to support sludge washing activities until it is reasonably certain that washing will be carried out. This is because a "learn as you process" situation with a small pilot plant operation will be a significant undertaking, both in effort and expense.

3.4 Waste Retrieval and Transport Using Pipes Example [Need to Know]

In this section, examples are given as to how safety concerns associated with moving waste through pipes can be addressed in an effective manner. Issues addressed include leakage of material from pipe joints and fittings, catastrophic release of the waste via pipe rupture, and blockage of the pipe during waste retrieval or transport. The first two issues represent safety concerns. The last issue represents a process upset as the disruption may result in a costly process shutdown.

3.4.1 [Justify Request for Data]

It is likely that some tank waste will be retrieved from Hanford tanks via direct pumping of waste or pumping a slurry of waste and water added by high pressure jetting to dislodge crusted material at the surface. In any case, the waste will move through pipes of various diameters to a holding tank or directly to a processing unit.

Following retrieval, waste or waste slurries will be transported from a holding tank to one or more processing units through pipes. During retrieval or transport, a number of conditions may occur that would raise safety concerns or cause process disruptions that may need to be addressed in the domain of characterization. Due to the abrasive and chemical nature of the waste, leaks may occur at elbows, joints, flanges, pumps, or other fittings. Also, due to the possibility of having large chunks of waste in the flow, periodic pulsation caused by temporary blockages may even rupture the pipe, causing release of the waste. Finally, deposits of insoluble waste may lower the diameter of the pipe, eventually leading to permanent blockage of the pipe and costly processing disruption.

To circumvent these upsets, a request may be made to provide information in real-time on leaks, rupture, or pipe blockage. For the request for information to be justified, a contingency plan would have to be developed and tested that could respond to each particular upset as it was detected. For example, it makes little sense to provide a monitoring device to detect pipe rupture if an **[Action]** plan to deal with the released waste was not available. If a monitoring device could detect the onset of a pipe rupture, then a plan would be needed to lower the flow or otherwise change conditions so that the rupture would not occur. If no contingency plan was available, then the characterization effort would represent a waste of resources.

The justification procedure would continue with an examination of the particular hazard that would occur following a release of waste into the environment or a pipe blockage. If the nature of the waste was such that the hazard did not present a serious enough safety concern or a process upset, then the request for information would be rejected.

3.4.2 Acquiring Data [Other Important Sources]

Provided that the **[Request for Information]** was approved, the primary source of information would be a complete compendium of all historical information, **[Other Information]**, on the tank waste in question. It may be determined that the waste did not contain a crust or other layer that would result in large-diameter pieces that would cause a pulsating flow. In this case, the need to detect the onset of pipe rupture would be unnecessary, and the action of retrieval or transfer could proceed directly. Another case would be the determination that by controlling certain conditions, such as temperature or water added, or by adding solubilizing agents to the waste, it would not form a scale in the pipe. Then **[Monitoring]** for restricted flow and potential blockage would be unnecessary. The information necessary to keep the operating parameters within required tolerances would result in a successful characterization effort and allow an action (retrieval or transfer) to commence.

3.4.3 Acquiring Data [Monitor Waste]

If an active monitoring program was needed to provide the requested information, the characterization effort would rely on in-house expertise and outreach to industry or university sources to provide the required monitoring technology in the most cost-effective manner. The direction of choice here is to use available sources of information rather than to develop specific chemical sensors for individual analytes. Therefore, passive monitoring methods would be examined first. For example, to monitor the flow of material through the pipe, the power to the pump could be monitored in real-time and the data analyzed by signal processing and pattern recognition methods. A restricted flow caused by scaling or blockage could be detected as an increase in the power necessary to achieve constant flow. A pulsation effect caused by temporary blockage by large particles could be detected by **[Data Processing]** such as Fourier analysis and pattern recognition.

Another approach to passive monitoring is the use of acoustic sensors and pattern recognition data analysis. This approach has been used to detect and even identify the onset of failure of power-generating turbines used in remote locations. A central computer simply places a call to the remote (unattended) power station and the acoustic signature is acquired and compared to stored signatures representing normal operation and a variety of failure modes (e.g., bearing failure in the turbine). The technology is inexpensive and also could be used to monitor multiple points along the length of a transfer line as well as at pumps, valves, and other restricted flow components.

To determine leaks in a pipe, the acoustic frequency would be raised to the ultrasonic domain. High-pressure leaks are associated with high-frequency sound signatures that can be acquired via acoustic sensors and recognized via advanced signal processing methods.

A host of other monitoring methods is available for detecting and identifying problems associated with pipes, pumps, and transfer lines. These methods range from moisture tapes and time domain reflectometry that detect specific chemicals or vapors to laser light scattering and ultrasonic imaging that can provide detailed information on physical properties of transport line contents (such as particle size distribution in real-time).

3.4.4 Data Processing and Interpretation

Most of the passive monitoring methods and many of the active monitoring methods that could be employed in the waste characterization effort considered here involve the use of advanced signal processing and pattern recognition. Therefore, it is proposed that a significant base of expertise in these areas be developed within a central characterization effort to accommodate future needs at Hanford.

3.4.5 Modeling

As in the last section, a considerable amount of **[Modeling]** would be required to make full use of the data acquired for each application. Data from tests associated with retrieving and transporting simulated waste sludge and slurries could be used to build models that could detect the onset of leaks, ruptures, and blockages. These models could also be extended to provide other properties that may be useful for waste processing, thereby providing information to multiple users and saving money.

3.4.6 Decision and Actions

The primary purpose of the proposed characterization strategy is to provide sufficient and reliable information on an issue so that a **[Decision]** for action can be made within acceptable risk. Requiring that the request for information be justified, as discussed earlier, will ensure that actions will be taken and the characterization effort will not waste effort and resources. A careful evaluation of the full use of existing information and then, if necessary, the use of low-cost passive monitoring methods will ensure that action can be taken in the most cost-effective manner. This strategy would circumvent costly attempts to measure several analytes at several spatial points along a transfer line. It must be understood that the transport or processing of the waste can create conditions which will require additional characterization. For example, the rheological properties of the original waste may be significantly altered due to particle size breakdown or particle agglomeration.

3.5 Surprise Molecule Example

The wastes are dynamic chemical reaction systems that continually produce new substances as the organic complexants and organic solvents undergo radiolysis and chemical conversion (Meisel et al. 1992, 1993; Camaioni et al. 1994; Barfield et al. 1995). The principal products of many of the reactions have been defined in the past few years, but the complexity of the wastes ensures that many surprise molecules that have not yet been detected are also formed simultaneously. Little attention has been given to this problem because, for the most part, the principal products of the reactions of the organic constituents have less thermodynamic energy than the substances that were originally present. For example, sodium glycolate is converted predominantly to energy-poor sodium oxalate (Burger 1993; Camaioni et al. 1994). However, the technical literature provides incontestable evidence that the radiation chemistry of the compounds known to be present in the wastes also provides other products, some of which are more energetic than the original complexants and some of which are health hazards (Neta 1976; Spinks and Woods 1990). Although only low yields of the by-products are expected, the large quantities of organic materials in the tanks create a situation where, in absolute terms, quite large amounts of material can form. Even more serious consequences can arise if these substances become concentrated during interim storage or in a subsequent processing operation. Clearly, the presence of a by-product that accumulates in the waste can have a serious impact on the safety of interim storage or the success of a planned waste treatment operation. On the other hand, these by-products may disappear as rapidly as they are formed or be completely innocuous and have no material effect on the storage or the conduct of any operation. The General Strategy that is presented in this report provides a method to distinguish between these alternatives and to address the safety issues about surprise molecules that are significant for the safe storage of the wastes and to promptly resolve unimportant issues by the efficient and effective examination of each technical question.

This section presents an example of how a "surprise molecule" might come to exist in the tank waste and how the question raised by such a hypothesis would be pursued by using the General Strategy. **[Need to Know]**. This example is illustrative of

- the dynamic nature of the waste
- some consequences of prolonged storage of the waste
- the importance of chemical models in the study of the wastes
- the facility with which the General Strategy can resolve surprises.

Nitromethane is used as an example. However, it is pertinent that this nitro compound is only one of many surprise organic molecules that may exist in the organic tank wastes. The radiation chemistry literature indicates that hydrocarbons of the kind that are known to have been discharged to the wastes will be converted to nitroso and nitro compounds, nitrite and nitrate esters, dimeric compounds, and homologous series of alcohols, ketones, sodium carboxylates, and nitriles.

3.5.1 [Justify Request for Data]

Among the reasons for investigating a proposal that nitromethane might be found in the waste are the following:

1. The chemical kinetic model developed to model hydrogen generation in SY-101 showed that nitrogen oxides are produced simultaneously (Meisel et al. 1992, 1993). As already mentioned, reactions of the nitrogen oxides in the waste with the organic radicals, including the methyl radical, produced by radiolysis can form nitroso and nitro compounds. Other more subtle chemical transformations can also generate nitromethane. One pathway, a reaction sequence involving hexone [RCOCH3 with R=(CH3)2CHCH2], tank radiation, and the alkaline chemicals in the waste, is shown in the following equation:

$$RCOCH_3 + \text{radiation} \rightarrow RCOCH_2\bullet + NO_2 \rightarrow RCOCH_2NO_2 \rightarrow \\ RCOCH_2NO_2 + NaOH \rightarrow Na(RCO_2) + CH_3NO_2 \qquad (10)$$

2. It is known that low-molecular-weight mononitroalkanes (e.g., nitromethane) and their metal salts are condensed-phase explosives.

3. If such nitroalkanes or their salts can form and congregate (e.g., due to low solubility in the supernate), a tank hazard could exist. It is important to realize that even though a surprise molecule may be formed in low concentration, the large quantity of the tank waste could lead to the presence of large amounts of such a substance.

3.5.2 Acquiring Data [Other Information Sources]

The first and most economical source of information is provided by the data previously obtained from tank characterization activities by a search for evidence of the molecules of interest (i.e., nitromethane, its sodium salt, and sodium 3-methylbutyrate). Examples of such data include the spectroscopic studies of gaseous samples withdrawn from the dome, as well as solid and liquid samples. The investigation of the infrared or Raman vibrational spectra and the information obtained by gas chromatography-mass spectrometry of tank waste samples may provide important information concerning the presence of these molecules.

3.5.3 Acquiring Data [Discrete Sampling and Analysis]

If the existing data set proves to be inadequate to answer the questions posed, appropriately devised analytical experiments could be applied to core samples that are already available.

Clearly, if the reaction scheme outlined in the equation is operative, then the work should focus on studies of tanks that are high hydrogen producers or contain molecules that, like hexone, could react to form nitro compounds. If formed, their presence can be detected by sensitive analytical methods.

However, many of the initial by-products will be unstable in the alkaline waste solutions or in the presence of radiation and will undergo decomposition to harmless substances as rapidly as they are formed. The important next question is: what are the lifetimes of these compounds (e.g., the nitro compounds and their salts) under the chemical and radiological conditions in the waste? The technical literature provides information about the radiolysis of nitroparaffins in organic phases as well as in alkaline solution, but not about the chemistry in very alkaline sodium nitrite and sodium nitrate waste solutions or in complex heterogeneous sludge or salt cake. Therefore, experimental lifetime studies, which could be conducted in several different ways (for example, by implanting the molecule of interest in the waste and exposing the mixture to a radiation field), may efficiently resolve the issue.

3.5.4 Data Processing and Interpretation

The experimental plan would determine that

- The test nitroalkane degrades rapidly to other innocuous lower-energy molecules and that there is consequently no explosion hazard as a result of nitroalkane formation.
- Nitroalkanes can persist under the waste tank conditions.
- Nitroalkanes degrade but to other surprise molecules (such as sodium fulminate) that are troublesome.

Experimental protocols of this kind would provide definite information about the formation and occurrence of a surprise molecule in the waste and about its stability.

3.5.5 Modeling

If the latter two options prove correct, it would be appropriate to investigate the systems more thoroughly, possibly devise chemical kinetic models of the system, and use the models predictively to estimate the concentrations of the nitroalkanes that can exist under waste tank conditions.

3.5.6 Decisions and Actions

If the nitroalkanes do appear and do not degrade to harmless compounds, then it would be necessary to iterate, with the next cycle addressing questions about quantifying the nitroalkane and characterizing its solubility properties in the waste since a dilute soluble compound does not present a deflagration or explosion hazard. The role of the compound in interim storage would be resolved.

By-product molecules may also interfere with retrieval operations. The technical investigations that would be needed to address this issue are beyond the scope of this study.

4.0 Summary and Recommendations

The actions recommended by the *ab initio* Team are as follows:

- Validate the proposed strategy through an independent peer review process.
- Initiate development of a detailed operating plan (Phase II) for a selected tank or group of tanks.
- Terminate the present mode of "characterization" activities and integrate action-oriented chemical intelligence-gathering approaches into the Phase II strategy.
- Incorporate the definition of the final state of the selected tank or group of tanks into the definition of Successful Completion (Figure 5).
- Involve the academic community in order to ensure the future supply of trained engineers and scientists.

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Appendix C

International Perspectives on the Hanford Strategy for Characterization and Risk Evaluation of Military Waste

Appendix C

International Perspectives on the Hanford Strategy for Characterization and Risk Evaluation of Military Waste

This appendix summarizes some key points learned/heard by the authors from discussions before an international audience of nuclear waste researchers, scientists, and officials following a presentation of the recommended strategy by S. D. Colson, Pacific Northwest National Laboratory (PNNL) at a Gordon Research Conference on Nuclear Waste and Energy held in September 1996. More than 70 scientists, engineers, and academicians attended the conference representing the United States, Canada, France, Japan, Russia, Sweden, Germany, Spain, Belgium, the Czech Republic, the Netherlands, and Switzerland.

The goal of presenting this topic at the conference was to seek an international perspective and feedback on the strategy and to learn from other nations' experiences. Key points made by conference participants after the presentation are given here, followed by a short narrative from the discussions.

C.1 Key Points

- From the nature of the discussion, it was clear that the audience easily grasped the essential elements of the strategy and how it can be applied to waste storage and remediation problems.
- France's use of the Probability Safety Assessment approach to safety resolution is similar to the proposed Hanford strategy.
- Human error is a factor that needs to be included in any Probability Safety (now Risk) Assessment, as it can be the largest contributor to risk.
- Several participants expressed concern about the lack of a sound U.S. policy for Hanford tank waste disposal and the associated lack of progress toward resolving tank waste issues.
- Tank responses to various perturbations are likely not all linear (e.g., a linear correlation between tank waste stimuli and system response). Highly nonlinear and sometimes unexpected responses are likely.

C.2 Discussion Narrative

The presentation was received favorably and stimulated lively discussion. An overall concern expressed was the lack of progress (i.e., waste destroyed or immobilized rather than placed in temporary storage) in Hanford Site cleanup, particularly in light of the amount of money spent.

Noted here were the tradeoffs in the risks associated with the tanks today versus years ago. Waste heat and free energy have diminished with time, but because of the chemical reactions going on in the tanks for the past 40 to 50 years, we face new safety issues (e.g., flammable gases) and possible "surprises." However, it was pointed out that two recent developments suggest we can get on with remediation work and focus limited resources on essential problems: 1) the U.S. government is limiting funding, which is forcing more careful prioritization of work; and 2) several "hypothetical" safety issues are being put to bed. Identifying and prioritizing actual waste management and environmental risks are growing realities that will drive many funding allocations and work execution decisions. The DOE is moving toward a risk basis for making these decisions, which is one of the strengths of the presented strategy.

Audience members were complimentary of the recommended risk assessment and probability analysis, which resembles work done in France, where a major concern is quantifying and comparing potential impacts on humans of waste treatment options and safety resolution approaches. A corporation responsible for vitrifying French high-level waste used a similar Probability Safety Assessment to calculate risk and decide if further safety actions were necessary. Reviewers of the French strategy found that human factors (failures) were not included in the initial risk analysis proposal and can be the most important factors. Inclusion of human factors was recommended for addition to the strategy reported by Colson.

Concern was raised about the apparent (but unintended) linear response implied in one of the view-graphs in the part of the Colson presentation emphasizing the importance of obtaining characterization data when acting on the waste. Without questioning the importance of such measurements, the general consensus was to expect surprises and unanticipated waste responses in the tanks. Both linear and nonlinear responses should be taken into account. Complex thermal, radiochemical, and physical processes will continue to impact waste behavior. Modeling performed to predict waste responses to natural or human-induced changes must represent actual tank waste conditions. Waste simulants have limited usefulness. The strategy description needs to make these points clear.

The point was brought out that the consequences of decisions should be thoroughly thought through before they are implemented. Reference was made to two sludge ponds at Oak Ridge National Laboratory's K-25 site. Resource Conservation and Recovery Act (RCRA) regulations drove the cleanup of these ponds, with a goal of attaining nickel concentrations at or below 48 ppm. Oak Ridge experienced two surprises during cleanup: 1) a contractor's lifting strap on a container broke, and the container killed a worker; and 2) the resulting 48,000 carbon steel drums of waste are now rusted from the inside out, and it will cost $90 million to $146 million to stabilize them. This emphasizes the importance of inclusion of both the work process and the end state of the waste in applying the reported strategy to the consideration of risk reduction from proposed actions.

It was noted that since Hanford's inception, scientists have recognized waste generation and release problems as well as a longer-term waste disposal problem. This led to the question: If a Probability Safety Assessment for the resolution of a safety issue comes out with an "acceptable" value, then Hanford won't take any action, but if the risk is, for example, unacceptable (e.g., 10^{-2}), will some mitigative action take place? In short, in another 50 years and if waste reprocessing is not completed, will many of Hanford's tanks be doing what they're doing now? In response, it was noted that the "take no action" decision was only with respect to mitigation of a safety issue. Current safety concerns are greatly restricting access to the tanks and consuming scarce economic resources. Resolving safety issues will allow work on waste disposal to go forward at an accelerated pace.

The comment was made that Hanford tanks are analogous to small, individual chemical plants and an analogy was drawn to the fact that Probability Safety Assessment has been taken seriously and used as standard practice by the chemical industry since toxic methyl icocyanate gas was released from a Union Carbide plant in Bhopal, India in 1984.

One attendee maintained that hydrogen generation is the most important tank safety issue and that waste and vapor sampling have given a good idea of the hydrogen generation rate. Single-shell tanks have minimum supernatant, and in some cases, there is a linear response between the amount of liquid and gas generation. To process waste, characterization must not be done solely for the purpose of safety. Integration of characterization needs must cross multiple processing and safety issues and is a vital element of the proposed strategy. Processing cannot begin until you know **what** the end result of the processing is.

In response to questions about the number of borosilicate logs to be formed from Hanford tank waste, an attendee pointed out that recently completed analyses suggest chromium concentrations are twice that previously expected. This could result in nearly doubling the number of logs (from ~33,000 to ~60,000) projected under the preferred tank waste cleanup alternative proposed in the recently completed tank environmental impact statement (DOE 1996). Using existing vitrification technology approaches and waste loading, that could raise the cost of log creation and storage by an additional $30 billion. This observation underscores the high sensitivity and potential impacts of uncertainties in Hanford's tank waste characteristics that go well beyond the resolution of safe interim storage issues.

The statement was made that despite tank cleanup privatization goals, not all tanks should be cleaned up. State and environmental requirements dictating this are unreasonable. The short- or long-term risk posed by a tank should dictate if and how it should be cleaned. The amount of actinides (e.g., select isotopes of plutonium, thorium, americium) present is a major factor in determining long-term risk. Radioisotopes of cesium and strontium, forming >99% of radioactivity now contained in Hanford tank waste, will decay away in a few hundred years. The presented strategy could provide a risk and cost benefit basis for the establishment of technically sound cleanup goals

Questions arose about the United States's attitude toward dumping low- and medium-level waste that does not contain long-lived actinides, given that most radioactivity is from cesium and strontium. It was suggested that attention should be given to the separation and isolation of actinides; as for example, is being done at Chelyabinsk. High-level waste is still being pumped 300 meters underground at two Former Soviet Union (FSU) reprocessing sites and is an acceptable practice by FSU standards. This, of course, is not acceptable in the United States, as well as in other nations. Another (non-United States) attendee familiar with Probability Safety Assessment suggested that the FSU scientists consider the application of a strategy such as the one presented for the evaluation of the potential consequences of underground dumping.

Based on evaluation of existing technical input from PNNL and Argonne National Laboratory, one individual suggested that two of three safety issues related to Hanford tanks are nearing resolution: 1) ferrocyanide because of its chemical breakdown over the years, and 2) organics--chemical byproducts (oxalate or formate) having lower energy states are now detected rather than higher energy organics originally discharged into the tanks. However, flammable gas remains as a safety issue.

An appropriately used deterministic approach (A + B = AB) will work for ferrocyanide and possibly for organics. However, flammable hydrogen will continue to form because of hydrolysis as long as radionuclides are present. Appropriate administrative controls (e.g., tank ventilation) are needed to deal with the hydrogen. But excluding issues of tank corrosion and the generation of flammable gases, it was suggested that by this criterion alone, Hanford's tanks are becoming safer over time. On the other hand, tank integrity (carbon steel sides) deteriorates with time, increasing the risk of uncontrolled release of the tank contents to the environment. Such risk is viewed as unacceptable by U.S. standards (see above). It was noted that the strategy presented called for the identification of controlling parameters (e.g., the amount of reactive fuel) to see if the risk from a particular proposed phenomena could be determined to be incredibly low for a given set of tanks or globally for all tanks.

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Appendix D

Locations of Specific Tank Farms and Tanks on the Hanford Site

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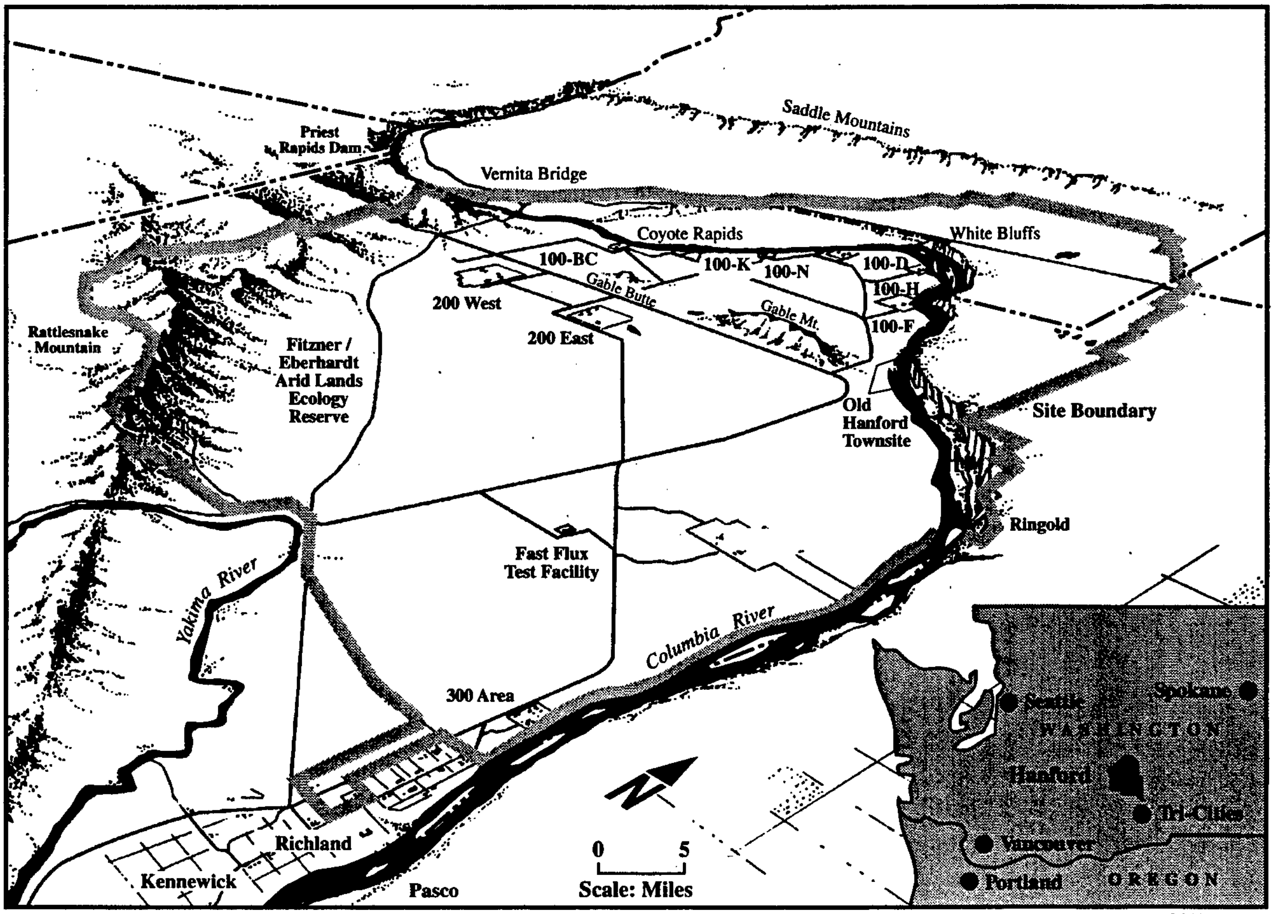
Locations of Specific Tank Farms and Tanks on the Hanford Site

This appendix contains maps of the 200-East and 200-West Areas showing the various tank farm locations and idealized layouts of the tank farms showing the numbered double- and single-shell tanks.



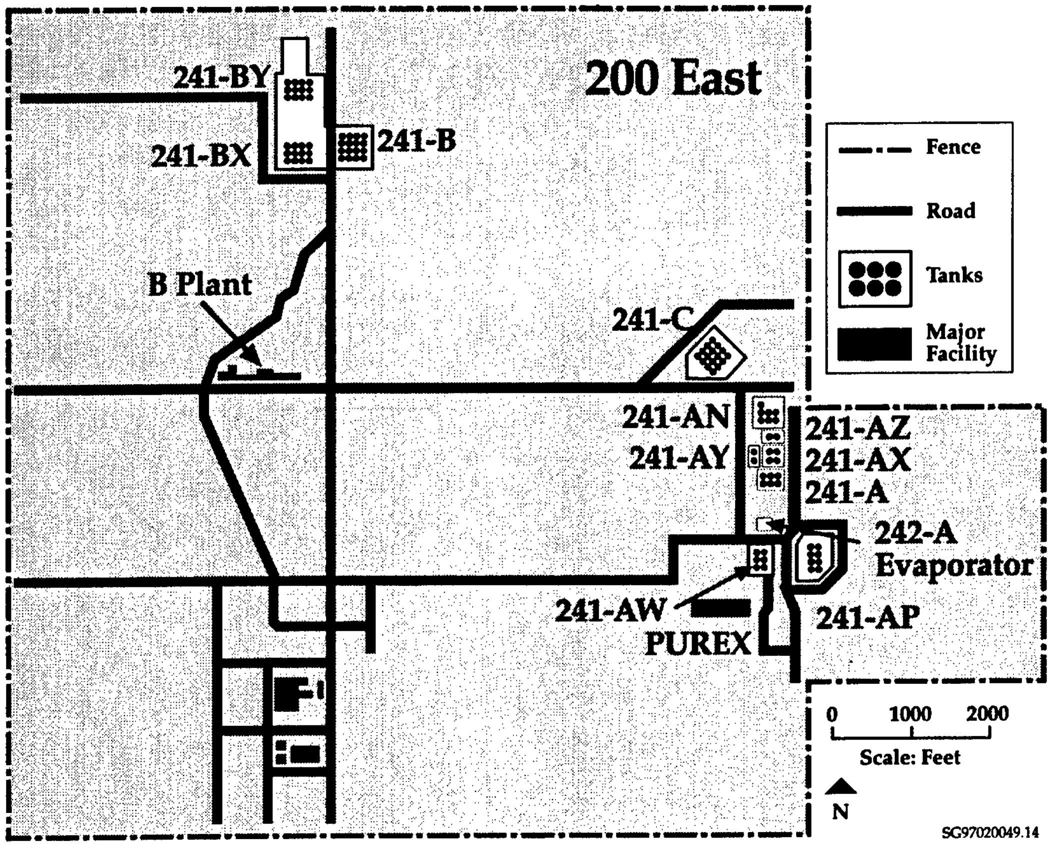


Figure D.1. 200-East Area Showing Tank Farm Locations

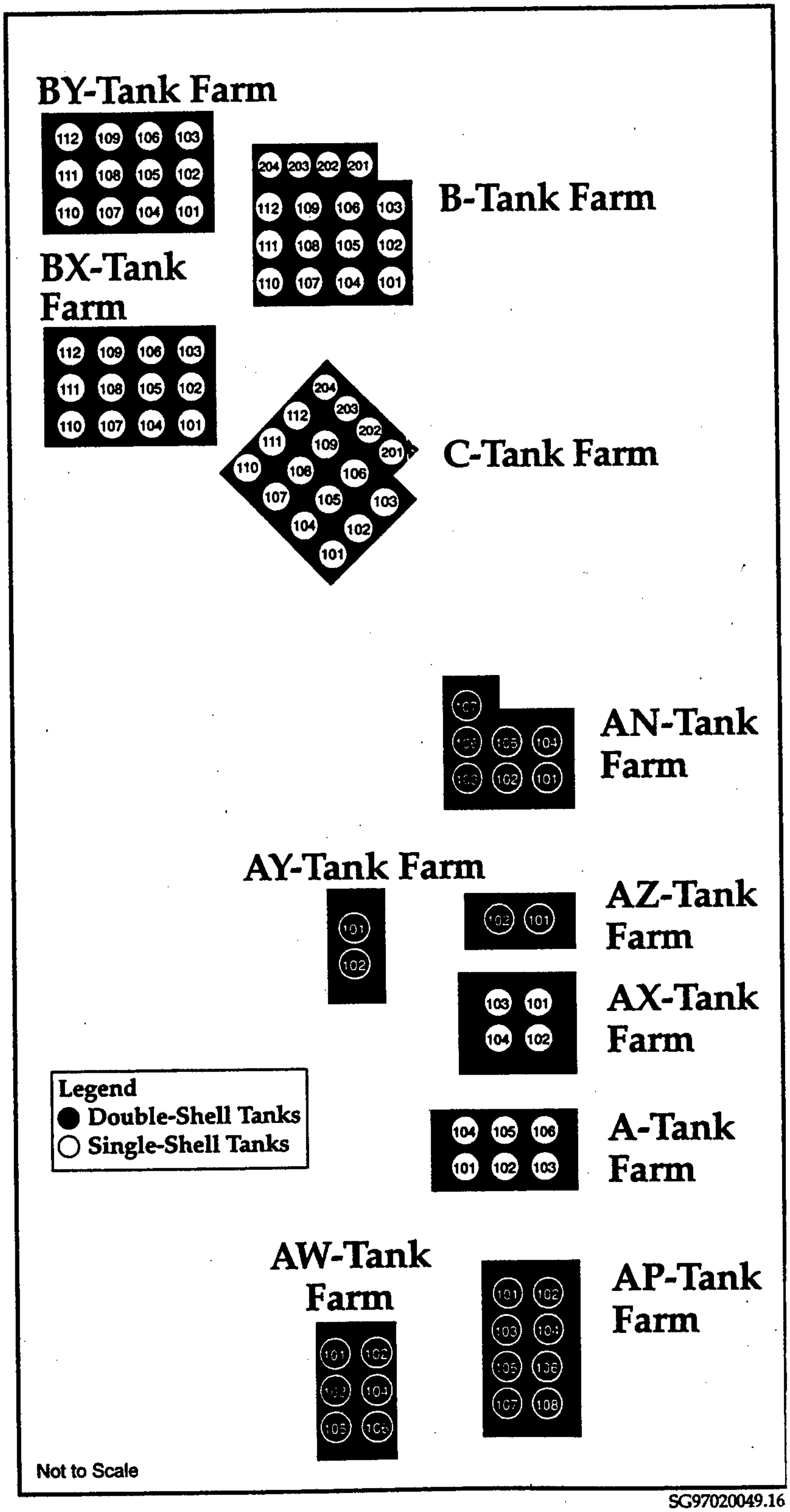


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Figure D.2. Specific Tanks and Tank Farms with an Idealized Layout of 200-East Area

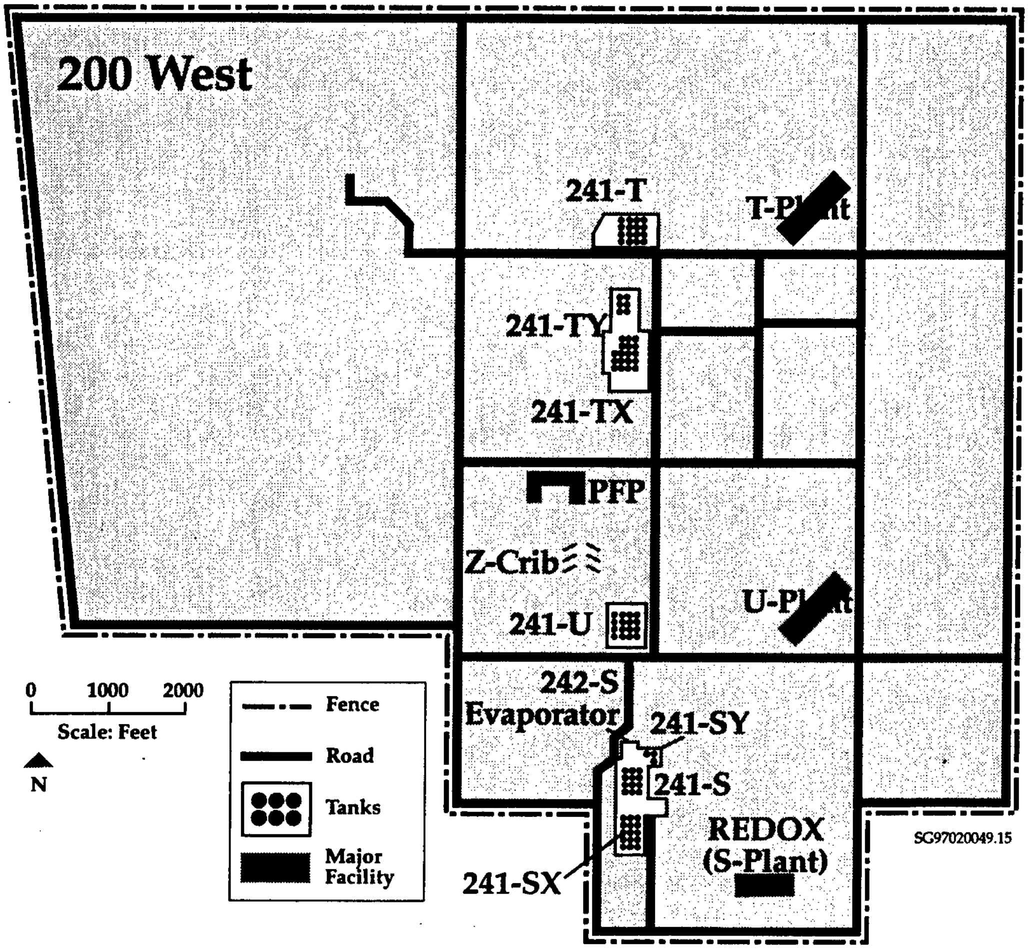

Figure D.3. 200-West Area Showing Tank Farm Locations

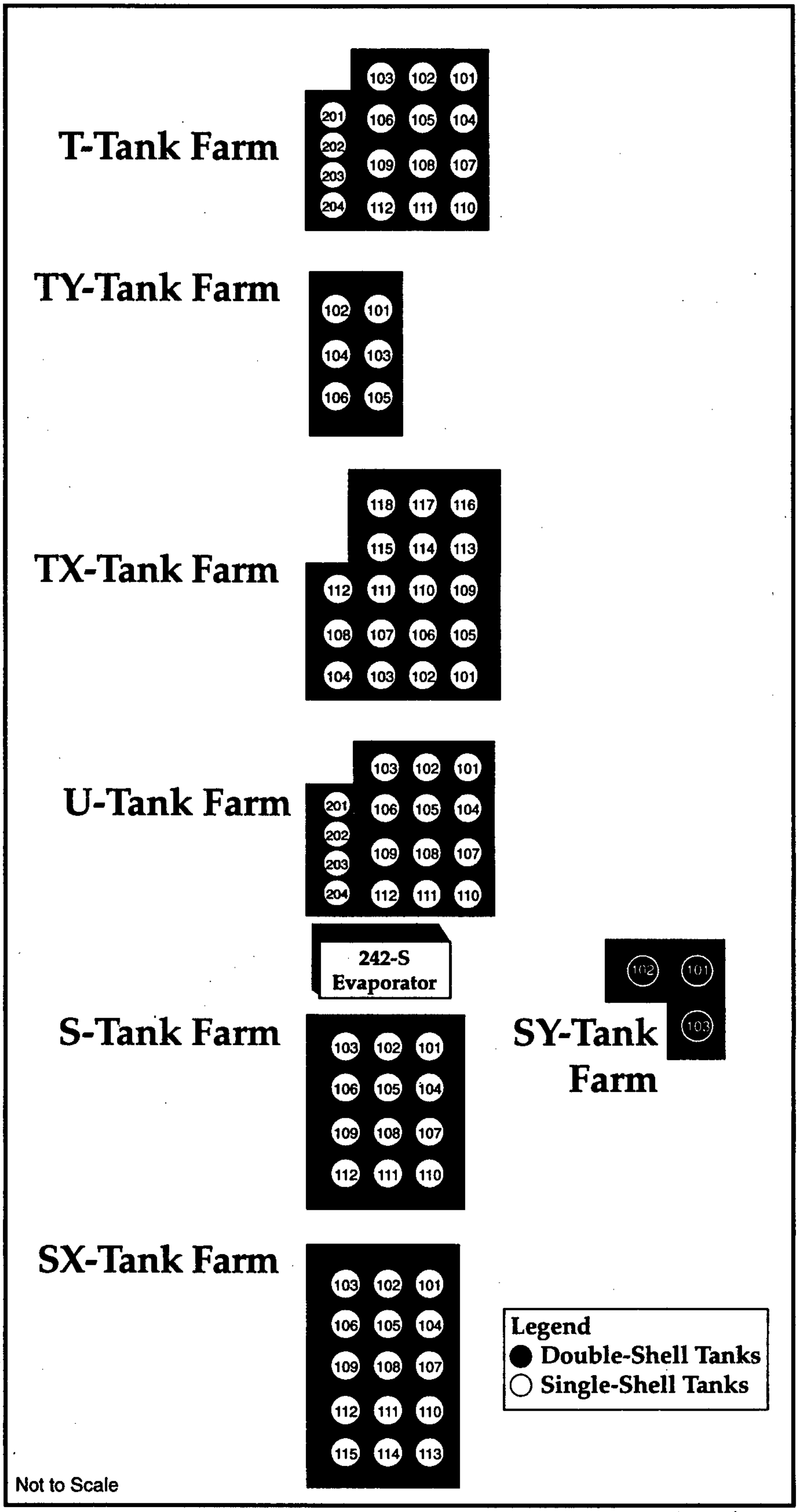

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Figure D.4. Specific Tanks and Tank Farms with an Idealized Layout of 200-West Area

Appendix E

Resumes

Steven D. Colson

Associate Director
Chemical Structure and Dynamics
Environmental Molecular Sciences Laboratory
Pacific Northwest National Laboratory

Education

B.S.	Utah State University, Chemistry	1963
Ph.D.	California Institute of Technology, Chemistry	1968

Experience

Dr. Colson became the Director for the Hanford Tank Characterization and Safety Resolution Project in January 1996. Dr. Colson became Associate Director of the Molecular Science Research Center for Chemical Structure and Dynamics in 1989. Prior to this, Dr. Colson spent 21 years at Yale University, as a Professor of Chemistry. He is particularly interested in the combination of optical and mass spectrometric methods to address fundamental problems in physical chemistry. General research interests include: photochemistry; photophysics; molecular dynamics; electronic structures of molecules, radical, and molecular ions; processes at the molecule/surface interface; and intermolecular interactions in molecular solids.

Other Experience

1967-1968	Postdoctoral Fellow, NRC, Ottawa
1968-1973	Assistant Professor, Yale University
1973-1980	Associate Professor, Yale University
1980-1989	Professor, Yale University
1989-present	Associate Director, Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory
1996	Manager, Hanford Tank Characterization & Safety Issue Resolution Project, Pacific Northwest National Laboratory
1970-1973	National Academy of Sciences Committee Advisory to U.S. Army Research Office
1977-1980	Director of Graduate Studies, Chemistry Department
1980-1982	Associate Editor, The Journal of Chemical Physics
1984	Chairman, Gordon Conference on Visible/UV Multiphoton Ionization and Dissociation Processes
1985-1987	Petroleum Research Fund Advisory Board
1988	Guest Professor, University of Ulm, West Germany
1990	Senior Alexander von Humboldt Award, Munich, Germany
1990	Adjunct Professor, Washington State University
1990	Affiliate Professor, University of Washington
1991	Chairman, 21st International Free Radicals Symposium,
1992	National Research Council, Committee on Critical Technologies
1995	Board of Visitors, Washington State University College of Sciences

Dr. Colson is the author of more than 100 publications in chemistry related periodicals.

Roy E. Gephart

Program Manager
Environmental Technology Division
Pacific Northwest National Laboratory

Education

B.A.	Geology Miami University, Oxford, Ohio	1971
M.S.	Geohydrology Wright State University, Dayton, Ohio	1974

Experience

Twenty-two years of geohydrologic and management experience within the hazardous waste industry. This includes thirteen years with Hanford's prime maintenance and operation contractors and nine years with the Pacific Northwest National Laboratory. Professional experience has focused on geohydrologic studies of groundwater flow and contaminant transport, project/program management, science/technology/policy issues associated with environmental cleanup, technical communication, and expert testimony. Author of 50 publications on the above subjects.

Program Manager: Pacific Northwest National Laboratory, Richland, Washington, 1987 to present. Responsibilities and experience have focused on strategic planning for cleanup of waste sites, assessment of science and technology needs for waste cleanup, program management of information and risk analysis system research, and technical communication addressing scientific and policy issues affecting the remediation of the U.S. Department of Energy's (DOE's) sites. Examples of experience include: (a) program manager for the initial CERCLA/SARA planning and waste site characterization activities at Hanford, (b) one year assignment at DOE-Headquarter (Office of Environmental Management) assessing national environmental cleanup issues for DOE, (c) manager for Information Analysis Technology, (d) worked with multi-discipline team that established the Laboratory's Environmental Management Operations, (e) co-leader for the Laboratory's successful development in 1996 of research proposals for the DOE's Environmental Management Science Program, (f) worked technology development and transfer opportunities with Savannah River Technology Center, Canada, and the State of Washington, (g) technical communication liaison with external scientific to general audiences on issues of Hanford waste generation/disposal history and science/technology needs, and (h) project manager for collaborative research with the University of Washington and University of California Irvine for prototype physics experiments being installed at the Nike site on the Arid Lands Ecology reserve.

Staff Hydrogeologist: Westinghouse Hanford Company (previous prime contractor was Rockwell Hanford Operations from 1977 to 1987), Richland, Washington, 1982 to 1987.
Conducted groundwater conceptual modeling, data base development, and programmatic planning in addition to being principal hydrology author of prelicensing reports and environmental assessments. Duties included report collaboration with engineers, earth scientists, and program managers, requiring a broad working knowledge of geology, hydrochemistry, and hydrologic field testing. Headed up or contributed to several interdisciplinary team assignments such as the Exploratory Shaft Project, national

mission plans for nuclear waste disposal, and establishing project positions relative to outside reviews. Technically represented the Basalt Waste Isolation Project before many organizations including the National Academy of Sciences, Nuclear Regulatory Commission, U.S. Geological Survey, Washington State overview committees, and environmental groups.

Hydrology Unit Manager: Rockwell Hanford Operations, Richland, Washington, 1979 to 1982.
Managed hydrologic studies for the Basalt Waste Isolation Project. Supervised 17 hydrologists and technicians, responsible for $5 million annual research budget. The unit's work tasks included conducting and documenting numerical model analyses of groundwater flow and solute transport, deep (1500-meter) hydrologic testing, hydrochemical sampling and analyses, surface-water inventories, and subcontract proposal writing and administration.

Hydrologist/Senior Hydrologist: Atlantic Richfield Hanford Company and Rockwell Hanford Operations, Richland, Washington, 1974 to 1979.
Conducted geohydrologic studies and supervised hydrologic projects. Field activities consisted of performing and interpreting shallow aquifer pump tests, installing piezometers, hydrochemical interpretation, and conceptual model development using hydrologic, geologic, and geophysical data. Also documented environmental impacts resulting from proposed water disposal and nuclear waste management activities. Management responsibilities included work planning, scheduling, budgeting , and contract administration for five earth sciences' personnel, responsible for $2.5 million research budget. In 1977 was initial organizer of Pasco Basin hydrology studies for the Basalt Waste Isolation Project.

Graduate Research Assistant: Geology Department, Wright State University, 1972 to 1974.
Taught geology laboratory courses, collected and analyzed gravity and seismic refraction data, interpreted groundwater pump tests, and completed a water supply study for New Carlisle, Ohio.

Geologist: U.S. Geological Survey, under summer appointment, 1971.
Field-mapped coal formations in the Appalachian Plateau near Middlesboro, Kentucky.

Affiliations

American Geophysical Union (Hydrology Section)
American Institute of Hydrology (certification #302)
American Institute of Professional Geologists (certification #6857)

Honors and Awards

Rockwell Hanford Operations Engineer of the Year, 1980
Graduate Assistantships, Wright State University, 1972-73
Acceptance to National Association of Geology Teacher's Cooperative Field Training Course, 1971
Ben Weeks Memorial Scholarship, Miami University, 1970

Valeria L. Hunter

Senior Research Engineer
Pacific Northwest National Laboratory

Education

B.S.	Chemistry Spelman College Magna Cum Laude, Dean's List	1984
B.ChE.	Chemical Engineering Georgia Institute of Technology Most Outstanding Chemical Engineering Student-1984 Atlanta University Center Dual Degree Program In Engineering	1984
M.B.A.	John M. Olin Graduate School of Business Washington University Consortium for Graduate Study in Management Fellowship	1990

Experience

Pacific Northwest National Laboratory **1990-present**

Systems Management Group/Engineering Technology Division: Expertise in Project Management, Decision Analysis, Systems Engineering, and Facilitation Skills as applied to the projects and tasks identified below:

Project Manager for Organic-Nitrate Safety Issue Data Requirements Specification. Project budget $700K over 2 years. Staff of PNNL, WHC contractors, and Decision Science Associates, Fauske and Associates, Inc., and G&P Inc. subcontractor personnel developed risk based methodology to identify data requirements for characterization of tank waste with respect to the organic-nitrate safety issue, and subsequent program strategy and support to revised organic Safety Analysis Report. Presented methodology and results to the congressional appointed Defense Nuclear Facilities Safety Board Staff. Prepared *A Value of Information Approach to Data Quality Objectives for the Hanford High-Level Waste Tanks* which was presented at Waste Management '95.

Task Manager for Decision Analysis of Low Level Waste Vitrification Technology Selection and Development. Managed budget of $150K. Supported selection of LLW vitrification system components for optimum design, integration with commercial vendor procurement and testing activities, design of decision and evaluation process, coordination with TWRS stakeholder values, and integration with the decision process for key TWRS decisions.

Supported the Department of Energy Plumes Focus Area Technical Team in developing a method for determining the portfolio of research projects and allocation of dollars for laboratory research, focusing primarily on matching site needs to existing laboratory research; and laboratory project technical review and recommendations. Project review included criteria development, determining the appropriate expert panel, and final reporting.

Performed decision analysis of High Level Waste Vitrification Melter Selection. Support to melter assessment process design, criteria development, and evaluation process. Managed expert panel, including international, national, and Hanford members; and process observers including DOE-RL and other stakeholders (Washington Department of Ecology, State of Oregon, Yakama Indian Nation, etc.) during the assessment process.

Performed decision analysis of Organic Destruction Process Selection. Developed criteria and weighting process. Managed panel of technical experts, technology advocates, and WHC and DOE clients culminating in a three day selection workshop. Documented selection process and decision making.

Task Manager for Tank Waste Remediation System Characterization Data Quality Objectives, Decision Logic, Structure, and DQO Strategy. Managed task budget of $200K. Prepared *Draft DQO Strategy and TWRS Decision Logic and Structure*.

Task Manager for Hanford Mission Planning Tank Waste Decision Logic. Managed a task budget of $100K. Performed systems analysis of double-shell tank pretreatment facility options. Identified significant processing risks associated with all options. Co-authored *Tank Waste Disposal Redefinition Strategy*. Prepared *Public Involvement in the Hanford Double Shell Tank Waste Disposal Program*, and presented at the 1992 Air & Waste Management Association Meeting.

Task Manager for Schedule, Cost, and Occupational Dose Impacts Task of Single Shell Tank Waste Characterization Program. Managed an annual task budget of $200K and a staff which included two subcontractors. Co-authored presentation to the Hanford Single Shell Tank Team of the National Academy of Sciences.

Rockwell/Westinghouse Hanford Company **1985-1988**

Plant Startup Engineer: Certified Engineer-In-Training, United States Department of Energy Security Clearance, Level 3 (Q). Provided process engineering support to major design and construction project (Grout Treatment Facility), including design reviews, test procedure preparations, reviews and performance; and plant startup. Developed and performed operability testing quantifying a major process variable in a new permanent waste disposal process after presenting test proposal and obtaining approval from the DOE Richland Operations. Developed computerized inventory tracking system for raw materials used in waste disposal process.

Process Engineer: Provided general process engineering support to the operation of two tank farms containing six and seven one million gallon tanks, respectively. Monitored trend analysis of tank system performance, including ventilation and liquid level. Provided minor design changes. Developed standard operating procedures. Developed instrument calibration schedules.

Jiri Janata

Associate Director
Materials and Interfaces
Environmental Molecular Sciences Laboratory
Pacific Northwest National Laboratory

Education

MSc.	(Summa Cum Laude), Chemistry Charles University, Prague, Czechoslovakia	1956-1961
Ph.D.	(Summa Cum Laude), Analytical Chemistry Charles University, Prague, Czechoslovakia	1962-1965

Experience

1962-1966	Assistant Lecturer in Analytical Chemistry, Charles University, Prague, Czech Republic
1966-1968	Postdoctoral Research Associate, University of Michigan, Ann Arbor, Michigan
1968-1973	Senior Research Scientist, Petrochemical and Polymer Laboratory, Imperial Chemical Industries, Ltd., Runcorn, England
1973-1975	Visiting Assistant Professor Department of Chemistry, University of Utah
1975-1976	Senior Research Scientist, ICI Ltd. (as in 1968-1973)
1976-1981	Associate Professor, Department of Bioengineering, University of Utah
1981-1983	Professor, Department of Bioengineering, University of Utah
1983-1985	Professor and Chairman, Department of Bioengineering, University of Utah
1986-1987	Visiting Scientist, UKAEA Harwell, England (sabbatical)
1987-1991	Professor, Department of Materials Science and Engineering, University of Utah
1992-present	Research Professor, Department of Materials Science and Engineering, University of Utah Research Professor, Department of Bioengineering, University of Utah

Honors

Editorial Board: Biosensors; Sensor Technology; Talanta; Advisory Board of Analytical Chemistry; Associate Editor of Field Analytical Chemistry and Technology; Visiting Fellow, Wolfson College, Oxford University, 1986/1987; Alexander von Humboldt Senior Scientist Prize 1987; Visiting Professor, EPFL Lausanne, 1990; Outstanding Research Award, University of Utah 1990 (declined); Heyrovsky Medal, Czechoslovak Academy of Sciences, 1990; Finalist medal, "Science pour l'Art 1992," Moët Hennessy & Louis Vuitton, 1992; Chairman, Gordon Research Conference, Electrochemistry, January 1995; Outstanding Achievement Award, Electrochemical Society, October 1994; Visiting Professor, Tokyo Institute of Technology, 1995; Member of National Research Council, Panel on Aviation Security, 1995; Listed in "Who is Who in the World;" and Chairman, Gordon Research Conference, Nuclear Waste and Energy, September 1996.

Dr. Janata has written 150 publications, 1 book, and received 15 patents.

Larry G. Morgan

Manager, Technical Operations
National Security Division
Pacific Northwest National Laboratory

Education

B.S.	Rose-Hulman Institute of Technology, Chemistry	1964
Ph.D.	Oregon State University, Physical Chemistry	1978

Experience

Dr. Morgan specializes in physical and inorganic chemistry with emphasis on those areas related to the nuclear fuel cycle, nuclear waste management, and materials sciences. His professional experience includes both basic and applied research. At Pacific Northwest National Laboratory (PNNL), his experience includes program/project/task management, technical contributor, and line management. While at PNNL, Dr. Morgan has been a major contributor in the following areas:

- **National Security.** Dr. Morgan is the Manager, Technical Operations, National Security Division (NSD) at PNNL, a position he has held since December 1991.

- **Environmental Restoration and Nuclear Waste Management.** Dr. Morgan is currently on special assignment as a Task Leader and principal contributor for the Hanford Tank Waste Characterization and Safety Issue Resolution Project. This project was charged to develop an independent, technically sound and defensible strategy for waste characterization and safety issue resolution. He is also responsible for the interface for external peer review of the project by the National Science Foundation. Dr. Morgan was appointed to DOE-HQ's High Level Waste Tanks Task Force in 1990 and continued that assignment until the Task Force was dissolved after achieving its objective. The Task Force provided both technical and management guidance for DOE High Level Waste activities at the Hanford Site, Idaho Falls, Savannah River, and West Valley. During this assignment, Dr. Morgan provided briefings to DOE-EM, DOE Site Contractors, the Defense Nuclear Facility Safety Board, the Advisory Committee on Nuclear Facility Safety (created as an independent group by the Secretary of Energy, DOE), Washington State Nuclear Waste Advisory Council, the Technical Advisory Panel created by DOE-HQ to assess technical aspects of High-Level Waste and safety-related issues, and PNNL's Waste Tank Science Panel (created for DOE by PNNL to assess potential safety issues in high-level waste tanks at the Hanford Site).

  In addition, he has been a task leader and technical contributor for studies related to the evaluation of what is required for characterization and ultimate disposal of single-shell tank sites at DOE's Hanford Site. These studies included critical evaluation of the chemistry assumptions used in existing computer models to simulate the generations, chemical pathways, and ultimate location of chemical species and radionuclides, reviews of analytical requirements, reviews of performance assessment needs and requirement, and assessment of characterization needs with respect to applicable regulatory requirements.

Through 1988, Dr. Morgan was the Manager, Salt Repository Project Support at PNNL. Projects conducted at PNNL supported the U.S. DOE Salt Repository Project in its evaluation of a geologic salt formation as a suitable geologic formation for the ultimate disposal of nuclear wastes. He was also the project manager for the Waste Package Program (WPP) and the Modeling Task Leader for the WPP. Dr. Morgan was principal co-author of the Salt Repository Project's Site Characterization Plan's sections addressing the issue resolution strategy for substantially complete containment, radionuclides release from the engineered barrier system, preclosure conditions, and overall performance design criteria.

- **Hanford Environmental Dose Reconstruction Project**. Dr. Morgan was appointed the Task Leader of the Source Terms Task of the Hanford Environmental Dose Reconstruction Project in 1988 and continued that assignment until 1991. The Source Terms Task provided quantitative estimates of all significant emissions of radionuclides from Hanford Site operations since 1944. The task was a multidisciplinary task involving reactor physics, chemical processing of irradiated fuel, emission and waste management controls and technology, chemical behavior of radionuclides in the environment, and sensitivity and uncertainty analysis. The Hanford Environmental Dose Reconstruction Project estimated the radiation doses that populations could have received from nuclear operations at the Hanford Site since 1944. The project was managed and conducted by PNNL under the direction of an independent Technical Steering Panel.

- **Other Technical Areas**. Prior to his current assignment, Dr. Morgan has contributed to programs in actinide chemistry, alternative nuclear fuel reprocessing methods, tritium properties, molecular spectroscopy, materials development, and assessments of the release of hazardous and/or radioactive materials to the atmosphere. He has served as a Responsible Reviewer for the DOE/HQ Office of Declassification for Isotope Separations Processes.

- **Academic Experience**. Dr. Morgan completed his Ph.D. at Oregon State University under the direction of Dr. J. C. Decius, one of the foremost molecular spectroscopists. At Oregon State University, the areas of molecular vibrational spectroscopy and solid-state chemistry were emphasized in his major field of physical chemistry, and he received a minor in inorganic chemistry. He held both teaching and research assistantships while at Oregon State University.

  Dr. Morgan received an appointment in chemistry to the part-time faculty of the Washington State University Tri-Cities Branch Campus (WSU Tri-Cities) (formerly the Tri-Cities University Center), Richland, Washington, in September 1979. He was appointed Chemistry Program Coordinator at the WSU Tri-Cities in January 1981 and continued that assignment until 1992.

Professional Affiliations

- American Association for the Advancement of Science
- American Chemical Society: Richland Section served as Secretary, Chairman-Elect, Chairman, and Treasurer.
- Phi Lambda Upsilon
- Sigma Xi.

Dr. Morgan has authored more than 70 reports and publications.

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