LA-UR-93-2730
TSA-6-93-R111

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TITLE: PROBABILISTIC SAFETY ASSESSMENT FOR HANFORD
HIGH-LEVEL WASTE TANK 241-SY-101

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MAY 1994

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ACKNOWLEDGMENTS

The authors would like to recognize the contributions to this study by the following individuals who provided important information in the form of data, analyses, and suggested technical approaches.

Los Alamos National Laboratory

S. Agnew
J. M. Butner
S. W. Eisenhower
S. R. Fischer
P. H. Kvam
E. A. Rodriguez
K. A. Sasser
J. R. Travis

PLG, Inc.

W. G. He
S. B. Rao
H. F. Perla
E. S. Kim

Square Y Consultants

Y. C. Yuan

EQE Engineering Consultants

D. A. Wesley

PROBABILISTIC SAFETY ASSESSMENT FOR HANFORD HIGH-LEVEL WASTE TANK 241 SY-101

by

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EXECUTIVE SUMMARY

Los Alamos National Laboratory (Los Alamos) is performing a comprehensive probabilistic safety assessment (PSA), which will include consideration of external events for the 18 tank farms at the Hanford Site. This effort is sponsored by the Department of Energy (DOE/EM, EM-36). Even though the methodology described herein will be applied to the entire tank farm, this report focuses only on the risk from the weapons-production wastes stored in tank number 241-SY-101, commonly known as Tank 101-SY, as configured in December 1992. This tank, which periodically releases ("burps") a gaseous mixture of hydrogen, nitrous oxide, ammonia, and nitrogen, was analyzed first because of public safety concerns associated with the potential for release of radioactive tank contents should this gas mixture be ignited during one of the burps. In an effort to mitigate the burping phenomenon, an experiment is being conducted in which a large pump has been inserted into the tank to determine if pump-induced circulation of the tank contents will promote a slow, controlled release of the gases.

At the Hanford Site there are 177 underground tanks in 18 separate tank farms containing accumulated liquid/sludge/salt cake radioactive wastes from 50 yr of weapons materials production activities. The total waste volume is about 60 million gal., which contains approximately 120 million Ci of radioactivity.

The SY Tank Farm was constructed from 1974 to 1976 and consists of three 75-ft-diam by 46-ft-high (liquid level 35 ft) double-shelled waste tanks, each with a capacity of 1,160,000 gal. None of the three tanks has leaked, nor are they interim stabilized or isolated (two are on the watch list). The three tanks, 101, 102, and 103-SY, are essentially identical, with the exception of two additional process pits in

Tank 102-SY. Waste stored in the tanks was initially processed in the 242-S evaporator and pumped into Tank 102-SY beginning in 1977, from which it was subsequently redistributed to Tanks 101 and 103-SY.

The tanks are of the same basic construction, consisting of three concentric structures: (1) an outer, reinforced concrete tank designed to sustain induced loads from soil, seismicity, and thermal gradients between the radioactive wastes and the outside soil; (2) a secondary carbon-steel tank that lines the concrete tank and is designed to serve as a barrier to primary tank leaks; and (3) a free-standing carbon-steel primary tank that rests on an insulating concrete pad within the secondary tank. The primary tank contains the waste material, while the secondary tank, which is 5 ft larger in diameter, encloses the primary tank to create a surrounding annular space. The annulus is ventilated and constantly monitored for evidence of primary tank leakage. If a leak should occur, the secondary tank is designed to contain the liquid waste until it can be removed and stored in a different tank.

The ventilation system for the SY Tank Farm consists of two completely separate subsystems: a primary tank ventilation system and an annulus ventilation system. All three tanks are manifolded to the two subsystems. The ventilation subsystems have no redundancy, and unlike other tank farms, the duct work for the SY Tank Farm is above ground. They have a combined capability of removing 100,000 Btu/h from each tank. The exhaust air flow is filtered to minimize radioactive particulate emissions. Duct work routes the ventilation air from the primary tank and annulus of each tank to the respective filter trains and exhaust fans.

This PSA for Tank 101-SY, which did not consider the pump experiment, future tank-remediation activities, or sabotage, involved three distinct tasks. First, the accident sequence analysis identified and quantified those potential accidents whose consequences result in the release of tank material to the environment. Second, frequencies and release paths for the airborne and liquid radioactive source terms were determined. Finally, the consequences, primarily onsite* and offsite potential health effects resulting from radionuclide release, were estimated, and overall risk curves were constructed. An overview of each of these tasks and a summary of the overall results of the analysis are presented in the following sections.

*i.e., co-located workers as defined by proposed DOE standard No. DOE-DP-STD-3005-93. This PSA does not address the risk to "facility workers" as defined by the aforementioned standard.

Accident Sequence Frequencies

The accident sequence analysis task started with a master logic diagram to identify the potential initiating events, which were then grouped into the 11 categories given in Table ES-1. These initiator groups included external events, such as earthquakes and airplane crashes, as well as internal events, such as gas releases (burps) and liquid leaks.

Next, event trees, whose top events represent physical phenomena, hardware responses, and emergency operator responses, were constructed for initiating-event groups. Accident sequences were defined by the event trees for the various initiators. Accident sequence linking was performed in a manner that allowed for the identification of dependencies between top events as well as initiators. Finally, the frequencies of accident sequences were determined by combining initiating-event frequency estimates with the branch point probabilities, or split fractions, for the occurrence of each event on the event-tree paths. An important aspect of this process was quantification of the branch point probabilities. This quantification was performed using a combination of tank farm historical operating databases and occurrence reports, generic component/system failure data, and specific deterministic analyses for Tank 101-SY. This effort entailed considerable interaction with Westinghouse Hanford Company (WHC) tank farm operations personnel, as well as analysts at Los Alamos and WHC who had performed other related safety analyses. Accident sequence development and quantification are described in Chap. 4.

Release Categories and Source Terms

The source-term characterization task involved identifying factors that influence the magnitude and timing of a radionuclide or toxic gas (ammonia) release, as well as defining release categories for accident-sequence grouping. Deterministic analyses were necessary for modeling material release mechanisms for the various accident sequences, thereby providing estimates for the quantity of material and energy involved in each case. Considerable use was made of safety-related analyses performed by others. Recent core sample analyses for the contents of Tank 101-SY were used to characterize the radionuclide composition of the source terms. To facilitate the comparison of high-frequency/low-consequence accidents with low-frequency/high-consequence accidents and to keep the number of calculations

TABLE ES-1
INITIATING EVENT GROUPS

Initiating Event GROUP		
CODE	DESCRIPTION	EXAMPLE CAUSAL EVENTS
PSB	Primary Tank Shell Breach	Tank Shell Corrosion Drilling Contact with Tank Excavation Contact with Tank
DB	Tank Dome Breach	Vehicle Overloads Dome Water Overloads Dome Heavy Load Dropped over Dome
RVB	Riser or Vent. Line Breach	Vehicle Impact with Above-Ground Equip. Human Error, Tank Left Open
FB1	Tank Exhaust HEPA Filter Breach	Exhaust Filter Breach Exhaust Filter Blockage
LOTV	Loss of Primary Tank Ventilation	Loss of Power to Vent Fan Vent Fan Failure Ventilation Inlet Blockage
LOSP	Loss of Tank Farm Offsite Power	
WI	Water Intrusion Event	Tank Inundated by Transfer Spill Tank Inundated by Raw Water Leak Tank Inundated by Heavy Precipitation
WT	Waste Transfer	New Waste Transfers from Other Facilities Salt Well Transfers to Collector Tank Liquid Transfers to 242-A Evaporator Slurry Transfers from 242-A to DS Tank Storage
SEIS	Seismic Event	
AIRCRSH	Aircraft Crash	
BURP	Bound Gas Release	Waste Turnover Seismic Event Water Intrusion

within a reasonable bound, the sequences were grouped into 12 release categories, based on the release pathway and radionuclide content (Table ES-2). Excluding the possibility of an airplane crash, these analyses generally showed that airborne releases are relatively small because of the lack of an energetic dispersal mechanism.

TABLE ES-2
HTF PSA RELEASE CATEGORY DEFINITION TABLE

RELEASE PATHWAY		RADIONUCLIDE CONTENT	RELEASE CATEGORY CODE
To Atmosphere	Through HEPA	Extremely Small	TG
	HEPA Bypassed	Low	BPL
	HEPA Breached	Low	HEPAL
	HEPA Breached	High	HEPAH
	Dome Collapsed	High	DCH
	Dome Collapsed	Very High (fire)	DCVH
To Ground	Subterranean Leak	Small	SLK
	Subterranean Leak	Large	LLK
To Atmosphere and Ground	Infiltration/Surface Spill	Small	SSP
	Transfer Failure/Surface Spill (NA 101-SY)	Large	LSP
	Dome Collapse + Small Leak	High	DCSLK
	Dome Collapse + Large Leak	High	DCLLK

The potential liquid-pathway source terms were classified as small (<5000 gal.) or large (>5000 gal.), with an upper bound based on both historical tank farm experience and the volume of leakable liquid currently contained in Tank 101-SY. For the purposes of estimating consequences of liquid leaks, the scenario adopted was liquid travel in groundwater to the Columbia River and delayed exposure of down-river populations via drinking water. This obviates the need to develop onsite exposure scenarios based on hypothetical assumptions about future land use. Even though tank leaks may be large in terms of curies released, their health effects are less severe because many radioisotopes remain bound to the soil in nonsoluble form, reaching the Columbia River only after a lengthy delay time, during which most of the radioactivity decays away. The derivations of the source terms for the various release categories are presented in Chap. 5.

Consequences of Releases

The consequence analysis provided estimates of radiological and limited chemical health risks for both co-located workers and offsite residents via the airborne and groundwater pathways. Because of the large onsite population in relatively close proximity to the 200 West Tank Farm Area (location of Tank 101-SY), the airborne dose consequences to this group were also estimated. The calculation of airborne-transport population doses was done with AP-RISK, a computer code recently developed at Los Alamos for the purpose of calculating dose consequences and surface contamination resulting from waste tank accidents. It is based on an integrated Gaussian puff model and includes features for treating large particle settling, as well as modeling discrete population clumps—both refinements needed for the onsite population groups. The code calculates a complete conditional dose distribution function based on a matrix of 576 meteorological combinations of wind speed, direction, and stability class. Plume-rise modeling was included in those cases involving a fire. This result, in combination with the source-term magnitude and distribution, defined the airborne consequences for a particular accident scenario.

The offsite liquid doses were estimated with a modified version of RESRAD, a code developed by Argonne National Laboratory under DOE sponsorship, for planning cleanup and remediation activities. In performing the liquid pathway transport analysis, a variety of water infiltration rates were considered, covering the range from current arid climate conditions to a possible future shift to a much wetter climate. Measured properties for the soil layers underlying the 200 West Area were used in the calculations. The conclusion from the transport analysis was that the river-integrated population doses are independent of the infiltration rate, primarily because the dose is dominated by the isotopes ^{99}Tc and ^{129}I , which both move with the groundwater (i.e., are not adsorbed by soil) and have very long half-lives, so they do not decay appreciably during the transport delay time to reach the river. The shorter half-life ^{90}Sr and ^{137}Cs are retained more readily in the soils, so they have mostly decayed by the time they reach the river. The transuranics, although they have long half-lives, are retained in the soil and are delayed so long that they do not appear at the river for more than 10,000 yr. Doses occurring this far in the future have not been included in the PSA consequence analysis. The airborne and liquid consequence calculations are described in Chap. 6.

In addition to the health risks this PSA includes an estimate of the potential economic impacts due to accidents. This included the following cost elements:

1. surrounding land surface decontamination (from airborne releases),
2. subsurface contaminated soil removal, processing, and disposal (from tank leaks),
3. replacement of damaged tanks, and
4. replacement/repair of damaged tank ventilation system.

Overall Risk Results

The final results of the risk analysis are the unconditional risk curves, which present the relationship between the frequency of occurrence of the radionuclide release categories, given in Table ES-2, and the level of damage (radiological doses to the population) caused by the release. Figures ES.1 and ES.2 present the mean composite risk curves for onsite and offsite airborne exposures, respectively. The contributions of the important release categories to the composite curve are also shown. Even though hundreds of accident sequences were quantified, the burp/burn-initiated sequences emerged as the highest contributors to the risk. These accident sequences begin when the hydrogen released by a burp ignites because of the presence of an ignition source. The resulting burn causes pressure loads that are sufficient to cause confinement failure, such as high-efficiency particulates air filter failure. A portion of the tank contents is then released directly into the environment and dispersed downwind. Other sequences, such as those initiated by an airplane crash, have more serious consequences, but they are much less likely. Natural phenomena, such as earthquakes, high winds, ashfall, etc., did not prove to be significant risk contributors.

The mean risk (summation of the product of frequencies and consequences for all release categories) as determined from the onsite and offsite curves presented in the Figs. ES.1 and ES.2 is 0.15 person-rem/yr [7.3×10^{-5} additional latent cancer fatalities (LCFs)] and 1.1 person-rem/yr (5.5×10^{-4} additional LCFs), respectively. These effects are approximately four orders of magnitude below the health effects resulting from natural background radiation. Clearly the onsite and offsite individual risks are substantially below the DOE safety goals, even using 95th percentile results.

The risk curve for the liquid-pathway doses is presented in Fig. ES.3. For an infiltration rate of 0.2 cm/yr, corresponding to current climatic conditions, the time to reach the Columbia River is about 2000 yr, and the total dose exposure is

Fig. ES.1.
Mean total consequences—onsite.

Fig. ES.2.
Mean total consequences—offsite.

Fig. ES.3.
Mean total consequences—offsite liquid releases.

accumulated over a time of about 300 yr after radionuclides reach the river. The additional LCF corresponding to this exposure is 2.5×10^{-7} .

The results of the economic risk estimates are given in Fig. ES.4. As with the health effects curves, the contribution to the total by release category are shown. The product of the mean cost and mean frequency summed over all release categories gives an annual economic risk of \$1.44 million. Comparing this with the mean health effects, which are at least four orders of magnitude below background radiation affects, indicates that the economic risk is more significant than health effects to the populations at risk.

The conclusions from this PSA for Tank 101-SY may not be valid for other tanks, which may have different chemical or radionuclide source terms, or for the whole waste tank farm complex where common-cause failures, such as earthquakes, may be important. However, the principal consequences of any Tank 101-SY severe accident would be environmental, programmatic, and economic costs. For example, a large leak from Tank 101-SY would be perceived as a significant environmental insult and probably require an expenditure of tens of millions of dollars for containment, clean-up, and disposal operations. Furthermore, alternative storage and other remediation activities, such as construction of a replacement tank for Tank 101-SY, would be viewed suspiciously by the public. Likewise, a Tank 101-SY burp/burn accident, even with limited health effects, would reduce public confidence and jeopardize future remediation efforts.

The following sections of this report describe the methodology, detailed mathematical models, and results for a comprehensive and complete PSA for Tank 101-SY. The results show that the potential health risks from accidents are very low and that the economic risks are low to moderate.

Fig. ES.4.
Total for all release categories.

1.0. INTRODUCTION

This report presents the results of a Level-3* probabilistic safety assessment (PSA), including external events, for Tank 241 SY-101 (Tank 101-SY) at the US Department of Energy (DOE) Hanford Site. This high-level waste (HLW) tank is one of 177 such tanks, located in the 200 West and 200 East Areas of the site, that contain the HLW accumulated over 50 yr of weapons materials production. Since the Hanford Site is no longer in production, the primary focus of the current activities is environmental remediation and restoration directed toward long-term site closure. A centerpiece of the remediation activity is the effort toward developing a permanent method for disposing of the HLW tank's highly radioactive contents. Because these activities are expected to take several decades to complete and because resources are limited, it was deemed advisable to prioritize the HLW tank's activities on a risk basis. One approach to risk-based prioritization is to perform a PSA for the entire HLW Tank Farm complex to identify the highest risk tanks so that remediation planners and managers will have a more rational basis for allocating the limited funding to the more critical areas.

The results presented herein represent the first phase of such an overall HLW Tank Farm PSA. The initial focus was on Tank 101-SY because it has presented some serious problems and accordingly has been the subject of intensive observation and study for the past couple of years. Because of its propensity to periodically release ("burp") mixtures of flammable gases, there are experimental programs underway aimed at reducing the intensity and frequency of the releases.¹ The overall PSA is intended as a baseline risk study for the tanks in their current configuration and as such will not consider the potential risks associated with this or other planned remediation activities. (Appendix H contains a more complete discussion of the scope of this study.)

Consistent with an objective for completeness, all potential health impact pathways were considered. For Tank 101-SY, this includes the possible leaks and spills that find their way to the groundwater over a long time and thus to human receptors via the Columbia River, as well as the short-term pathways from airborne releases. There are obvious problems with interpreting possible health effects hundreds and even thousands of years in the future vs the more immediate (50-yr)

*A Level-3 PSA is the most complete; it estimates frequencies and health effects (consequences) from accidents. Level-1 and Level-2 PSAs stop short of estimating health effects and generally consider only frequencies and/or quantities released for various events.

latent cancer fatalities (LCF) caused by airborne releases. Nevertheless, given the high number of recorded and suspected leaks from the older HLW tanks, and the prognoses for the future as the tanks continue to structurally deteriorate, it is mandatory to include the liquid pathway analysis in the PSA. In addition to the health risks, estimates were made of the potential economic risks from accidents that release radionuclides to the air and to the ground.

The primary focus of this report is the PSA for Tank 101-SY, although there is a certain amount of configuration information, tank farm operational experience, analysis, etc., that applies to other tanks as well. For the most part, generic tank farm information has been placed in the appendices, as has some of the more detailed support analysis for Tank 101-SY. This report organization allows the reader to more easily follow through the assumptions, development, and conclusions of the analysis. It is anticipated that future reports on other tanks will follow this same format and cross reference the appendices of this initial report for generic HLW tank information. The final PSA report will summarize the results for the individual tanks and synthesize a composite tank farm risk profile covering contributions from all 177 tanks and indicate which tanks pose the greatest short-term and long-term risks.

REFERENCE

1. L. H. Sullivan, Compiler, "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-101-SY: Hanford Site, Richland Washington," Los Alamos National Laboratory document LANL-SA-65, Rev. 8, 9, 10 (December 23, 1992).

2.0. OBJECTIVES AND TECHNICAL APPROACH

2.1. Overview

The ultimate objective of the analyses described in this report was to develop a risk profile for the entire Hanford HLW Tank Farm complex. Therefore, the general approach and its application to Tank 101-SY will be the template for applications to the other tanks selected for future analysis. A preliminary list of the other tanks has been developed, based on a qualitative assessment of their perceived risk contributors. The next phase of the work will be to apply the methodology to other tanks. Much of the tank farm descriptive information presented in App. G provides the foundation for this effort. Future reports will address the remaining tanks and form the basis for the composite tank farm risk profile.

2.2. Methodology

The purpose of performing a Level-3 PSA for the Hanford Tank Farm (HTF) is to answer the following questions.

1. What can go wrong during HTF operation, maintenance, or as a result of external events that could result in an accident sequence that could produce a radionuclide or toxic gas releases?
2. How likely are these sequences to occur during a tank's lifetime?
3. What is the potential level of damage to a tank and to the environment (contamination, health impacts, etc.) given that a release occurs?

The first question is answered in the form of a structured set of accident progression scenarios that is systematically developed to account for design and operating features specific to the HTF. This set is organized into an accident sequence model consisting of a set of initiating events, event-sequence diagrams, and event trees supported by other analysis tools that define the progression of accidents and the interdependencies of events.

The second question is answered in terms of the frequency of occurrence of each sequence identified in answering question one. This involves quantifying the frequencies of all events that could initiate an accident sequence and the failure frequencies of the hardware and/or operator action that could mitigate a release. These frequencies are then combined in the accident sequence model to obtain the frequency of each accident scenario. The quantification process is accomplished using data from actual experience (where available) and a wide variety of models

that interpret and combine the data into failure frequencies of the events questioned in the accident sequence model. These quantification models provide the link between the overall risk measure and its underlying causes.

The third question is answered by developing the key characteristics (e.g., pathway, quantity of material releases, etc.) of toxic material releases from tanks that could result from the scenarios identified and the offsite consequences such as public health effects and property damage that could result from these releases.

To answer the above questions, an accident sequence-based approach was developed and applied for the HTF PSA. Each accident-sequence begins with an initiating event. The list of initiating events was obtained by developing a comprehensive master logic diagram (MLD), which is a large logic tree that qualitatively examined all possible failure modes. Sequences that could result from an initiating event were defined in terms of a specific combination of the possible successful and unsuccessful plant responses organized into event-sequence models that model the different ways that tanks can respond to the initiating events. Since the tanks and their supporting systems are relatively simple, it was possible to develop sequence models based on event trees only. Flow charts, called event-sequence diagrams (ESDs), were also developed. They graphically display how the progression of the accident sequence is being modeled and can be used to facilitate communication with operating personnel for purposes of checking the model.

Accident sequences normally involve a combination of hardware failures and human errors. Actual operating experience and more advanced modeling techniques demonstrate that, although the likelihood of a series of failures is quite small, it is numerically higher than would be estimated solely from a postulated chain of independent failures. This is because physical and human interactions result in dependent failures that increase the conditional probability of each successive failure in the chain. In fact, dependent failures tend to dominate the frequency of rare events such as severe accidents. Dependency matrices are used to organize the functional dependencies among the systems to assist in ensuring that all conditional failures are accounted for. The rules for event-tree quantification are expressed in terms of the top event conditional probabilities included in the event trees. The event sequences also consider all accident phenomena that could influence tank integrity and the ultimate severity of release. Sequence frequencies were calculated using the event-tree module in the RISKMAN¹ computer program.

All event-tree sequences (also called accident sequences) are assigned to an end state (*release category*) that characterizes the ultimate response of the tanks and

the nature of any release of radioactive material or toxic gas. For each important release category, the frequency and magnitude of the release are used to estimate the potential for health impacts on the surrounding population. The final results of the HTF PSA are displayed in the form of risk curves that indicate the combined frequency of all sequences exceeding a given level of damage (e.g., person-rem population dose and health effects).

Quantification of risk requires quantifying our confidence in the frequencies of events and source terms, which means displaying frequency uncertainties. This is accomplished using probability distributions for such variables and expressing modeling uncertainties explicitly. Many sources of uncertainty are addressed in the development of the parameters used to quantify the frequency of accident sequences. These include the source of generic data, plant-to-plant variability in the application of generic data, sample size for plant-specific applications, accident progression phenomenological questions, etc. The resulting state of knowledge or confidence in each parameter is expressed by deriving a probability distribution for that parameter. The basic data distributions and selected modeling uncertainties are then propagated through the quantification models and the important accident sequences to obtain uncertainties in the overall results.

The balance of this report describes the details of the PSA development and results for Tank 101-SY. Chapter 3 provides a detailed engineering description of the tank and associated systems. The Level 1 analyses, including details of accident initiator selection, sequence model development, frequency quantification, and release category selection, are given in Chap. 4. Chapter 5 gives the Level 2 analyses leading to the airborne and liquid source-terms development. Consequence analysis methodologies and results for the Level 3 portion of the PSA are presented in Chap. 6. Finally, the combined results are presented in Chap. 7 in the form of frequency of exceedance risk curves. Details of the many deterministic supporting analyses for various aspects of the work are presented in the appendices.

REFERENCE

1. PLG, Inc., *RISKMAN—PRA Workstation Software*, User Manuals I–IV, Version 3.0 (1992).

3.0. SY TANK FARM DESIGN AND OPERATION

3.1. Overview

At the Hanford Site there are 177 underground tanks in 18 separate tank farms containing accumulated liquid/sludge/salt cake radioactive wastes from 50 yr of weapons materials production activities. The total waste volume is about 60 million gal., containing approximately 120 million Ci of radioactivity. The tanks vary in capacity from 55,000 to 1.16 million gal. and contain materials of varying fluidity from relatively thick sludge to easily pumped liquids. Twenty-eight tanks, which entered service after 1969, are double-shell (DS) construction, whereas the remainder of the tanks, some constructed as early as 1944, have only a thin single-shell (SS) steel liner inside the reinforced concrete shell. All tanks have a minimum of 7 ft of earth cover for shielding purposes. To date there are no recorded liquid leaks for the DS tanks, but about half of the SS tanks have leaked. Accordingly, the potential environmental consequence pathways include both airborne releases and releases to the surrounding soils.

Early during site operations, many tanks were equipped with condensers and condensate disposal systems to permit the wastes to self-concentrate due to the boil-off of liquid caused by radionuclide decay heat. These tanks were also equipped with airlift circulators to promote uniform circulation and avoid "bumping"* with resultant tank pressurization. All radionuclides have now decayed sufficiently so that boiling is no longer an issue, although some tanks with carbon steel liners failed because of temperature-induced buckling during early operation.

Today, approximately 50 of the tanks are on a "watch list" because of the perceived risk of possible energetic reactions from the presence of reactive materials such as hydrogen, ferrocyanide, and flammable organics (see App. G). For obvious reasons, such tanks are high on the candidate list for representation in the PSA; Tank 101-SY was selected for this first effort because of its status on the hydrogen watch list and the recent attention it has received.

A plan view of the Hanford Site showing the central location of the 200 E and 200 W Areas is presented in Fig. 3.1. A closer perspective view of the 200 E and 200 W Tank Farm facilities is shown in Fig. 3.2. The ultimate scope of the HTF PSA includes all of the tanks and ancillary equipment (transfer lines, valve and pump pits, and catch basins) in the 18 tank farms (groupings of tanks containing from

* Bumping is a phenomenon wherein there is a sudden, rapid release of vapor bubbles in a superheated liquid. This generally gives rise to significant pressure increases in confined systems.

Fig. 3.2.
Hanford Site 200 Area.

2 to 18 tanks) because the objective of the evaluation is to develop the risk profile for the entire inventory of stored radionuclides and chemicals. The reference model for the various tank farms was their configuration and waste contents as of late 1992. Operations included were the ongoing maintenance activities and limited intertank transfers, but not installation/operation of the mixing pump. Proposed future operations pursuant to waste vitrification were not included in the analyses.

The remainder of this chapter gives the specifics for the SY farm, including tank construction, ancillary systems, and tank contents. This is the basic reference design information for the 101-SY PSA.

3.2. SY Tank Farm Description

The SY Tank Farm was constructed from 1974 to 1976 and consists of three 75-ft-diam by 46-ft-high (liquid level 35 ft) DS waste tanks, each with a capacity of 1,160,000 gal. None of the three tanks has leaked, nor are they interim stabilized or isolated; two are on the watch list. The three tanks, 101, 102, and 103-SY, are essentially identical, with the exception of two additional process pits in Tank 102-SY. Waste stored in the tanks was initially processed in the 242-S evaporator and pumped into Tank 102-SY beginning in 1977, from which it was subsequently redistributed to Tanks 101 and 103-SY.

The tanks are of the same basic construction, consisting of three concentric structures: (1) an outer, reinforced concrete tank designed to sustain induced loads from soil, seismicity, and thermal gradients between the radioactive wastes and the outside soil; (2) a secondary carbon-steel tank that lines the concrete tank and is designed to serve as a barrier to primary tank leaks; and (3) a free-standing carbon-steel primary tank that rests on an insulating concrete pad within the secondary tank (Fig. 3.3). The primary tank contains the waste material, while the secondary tank, which is 5 ft larger in diameter, encloses the primary tank to create a surrounding annular space. The annulus is ventilated and constantly monitored for evidence of primary tank leakage. If a leak should occur, the secondary tank is designed to contain the liquid waste until it can be removed and stored in a different tank.

The primary tank rests on a slotted, insulating concrete pad that is designed both to provide drainage to leak detection equipment and to permit airflow for leak detection and cooling purposes. The thickness of the welded carbon-steel plate used for the primary tank varies from 1 in. on the floor to 0.375 in. on the dome. The primary tank is designed to withstand up to 6 in. of water gauge (w.g.) vacuum and 60 in. w.g. internal pressure. Other design features include a maximum design tank

Fig. 3.3.
Double-shell tank instrumentation configuration.

wall temperature of 250°F, a heat generation rate of 50,000 Btu/h, a pH range from 8 to 14, and a specific gravity of the waste material of 1.7.

The secondary tank is also constructed of welded carbon-steel plates that vary in thickness from 0.375 to 0.5 in. The secondary tank is completely encased by 18 in. of reinforced concrete and rests on a concrete foundation that contains drain slots for the removal of any leaking liquid. The annulus requires a separate ventilation system that serves both to extract heat from the primary tank shell and to provide leak detection for the primary tank. Any significant volume of liquid that reaches the foundation is drained to a leak detection pit (Fig. 3.3).

Each tank contains multiple risers extending vertically from the tank dome either into a process pit or to above grade level. The risers consist of various sizes of pipe, some of which are blind flanged at the top. They are used as tank access points for monitoring devices, observation points, sample ports, and sludge measurements. A general list of the process pits for the SY Tank Farm includes: (1) central pump pits, (2) annulus pump pits, (3) leak detection pits, (4) drain pits, (5) flush pits, (6) service pits, (7) ventilation pits, and (8) sluice pits. These pits contain the processing equipment necessary for operating the tanks, protecting equipment from weather, providing shielding for workers, and functioning as secondary equipment. In addition, Tank 102-SY has two extra process pits: (1) the O2D drain pit that surrounds the riser that receives liquid draining from the 241-S-152 diversion box and SY valve pits, and (2) the O2E feed pump pit that surrounds the riser from which the evaporator feed was pumped.

The SY Tank Farm contains six cleanout boxes associated with waste transfer lines and three direct, buried seal pots. The cleanout boxes consist of a metal structure that contains nozzles and fittings to connect transfer cleanout lines. The cleanout line flush pipes are tied directly into the transfer line. When the transfer pipes are under pressure, the flush pipes are also under pressure. If the transfer line becomes plugged, a water hose is fed into the cleanout box flush lines and then into the waste transfer line. Water is then pumped into the hose to dissolve the plug. The seal pots are small buried tanks that function as large drain traps to collect drainage from several sources; each pot has one overflow drain line extending to the final receiver tank. The seal pots are used to isolate two systems of dissimilar vapor environments, while still allowing liquid to drain.

3.2.1. Ventilation System. The ventilation system for the SY Tank Farm consists of two completely separate subsystems: a primary tank ventilation system and

an annulus ventilation system (Fig. 3.4). As shown in Figs. 3.5 and 3.6, all three tanks are manifolded to the two subsystems. The ventilation subsystems have no redundancy, and unlike other tank farms, the duct work for the SY Tank Farm is above ground. They have a combined capability of removing 100,000 Btu/h from each tank. The exhaust air flow is filtered to minimize radioactive particulate emissions. Ductwork routes the ventilation air from the primary tank and annulus of each to the respective filter trains and exhaust fans. Both subsystems are equipped with ports in the ductwork that allow in-place testing of filter integrity. Differential pressure gauges, which are installed to monitor the pressure drop caused by the buildup of particulates on the filters, and ports for psychometric testing of the primary tank subsystem are also provided.

Primary Tank Ventilation System. The primary tank ventilation system is designed to remove gases and vapors from the primary tank and to maintain a pressure inside the tank that is slightly less than the atmospheric pressure. This constant negative pressure is maintained by exhausting the infiltration air and emitted gas from the tank at flow rates of up to 1000 cfm, although slight positive tank pressures have been measured during gas releases (burps). Operational ventilation rates are monitored and typically range between 400 and 600 cfm. The exhaust unit contains a deentrainment pad to remove moisture, an electric heater to prevent condensation on the filters, a prefilter, two high-efficiency particulate air (HEPA) filters in series, an exhaust fan, and a 5-m exhaust stack with a flow measuring device, air sampler, and radiation monitor. HEPA filters are commonly used for nuclear service because of their high efficiency in removing less than 10-micron-diam particles. For this installation, the HEPA filter package must pass a leak test to remove 99.95% of exhaust particles that have a mean particle size of 10 microns.

The existing instrumentation associated with the ventilation system includes a hydrogen monitor in the segment of the ventilation system ducting that connects to Tank 101-SY, a differential pressure indicator for determining if the exhaust fan is running, a differential indicator across each of the two HEPA filter banks, and a radiation monitor located immediately before the exhaust exits the system. All of the differential pressure indicators are connected to an alarm panel in building 241-SY-271 and to the Computer Automated Surveillance System (CASS). The radiation monitor is connected to alarms in the 241-S and 242-S control rooms. The hydrogen monitor is for indication only and is not alarmed. A backup portable exhaust unit is connected to a riser in Tank 101-SY in case the primary ventilation system fails.

"AP TANK FARM HAS HEATERS ON INTAKE, FOUR INLET STATIONS FOR EIGHT TANKS
 ** AP HAS TWO LEAK DETECTION WELLS, ONE WELL FOR FOUR TANKS

Fig. 3.4
 Tank ventilation schematic.

Fig. 3.5.
SY Tank interconnection via common ventilation system.

Annulus Ventilation System. The purpose of the annulus ventilation system is to remove heat, prevent condensation in the annular space, and to serve as a sensitive method to detect leakage or radioactive materials from the primary tank. Outside air is supplied through carbon-steel pipes located inside the annulus and embedded in the insulating concrete material underneath the primary tank bottom. From the center of the insulating concrete, the air will flow radially outward to the annulus through slots in the insulation under the primary tank. The exhaust filtration system used for the annulus is similar to that of the primary tank and contains a deentrainment pad to remove entrained moisture, an electric heater to prevent condensation on the filters, a pre-filter, two HEPA filters, and an exhaust stack with a flow measuring device, air sampler, and radiation monitor (see Fig. 3-5, Ventilation Pad).

3.2.2. Instrumentation

Exhaust Stack Monitoring System. The exhaust stack monitoring systems each have a continuous air monitor (CAM) and a proportional record sampler. The CAM samples the exhaust stream and is interlocked to shut down the exhaust fan when high radiation is detected. The CAM also has remote alarms for device failure. The record sampler accumulates the particles from a portion of the exhaust stream. If there is an airborne contamination release, the record sampler is used to determine the amount released. These two systems are independent so that failure of one will leave the other in service. Prompt repair of failed air monitoring equipment is administratively controlled.¹

Loss of power to the ventilation system shuts down the exhaust fans and monitoring equipment, but there is a manual backup power supply for the SY Tank Farm. During a loss of power, the tank dome space pressure will essentially equalize with the pressure of the atmosphere. Loss of instrument air to the tank farm causes the loss of dome space pressure transmitters and associated alarms.

Liquid Level Measurement. Each tank is equipped with an automatic, liquid level gauge (FIC) and backup manual tape located on a primary riser (Fig. 3.3). The liquid level gauge consists of a plummet suspended on a tape, reel tape, sight glass, control box, air purge, and water flush sprays. A continuous electrical circuit is maintained between the plummet and the liquid surface. In automatic operation, the plummet is periodically lowered and maneuvered until electrical conductivity between the plummet and the liquid surface is achieved. The plummet position reading is automatically converted to an electrical signal that is transmitted to the CASS.

Sludge Level Measurement. Sludge level probes are used to measure the depth of the sludge layer at the bottom of the tanks. There is a potential for seven sludge weights in each of the SY tanks; however, only one sludge weight currently is used to take readings in Tank 101-SY. Each probe has a 2-in.-diam steel "dough-nut" suspended by calibrated tape from a reel. The reels are housed in Plexiglas enclosures that are permanently mounted to the tank riser flange. The difference between the sludge reading and the reading obtained when the tank was empty represents the sludge depth.

Temperature Measurement. Each tank is equipped with approximately 100 chromel-constant thermocouples for monitoring temperatures throughout the tank. The thermocouples are distributed, both vertically and radially, to achieve a representative sample of actual temperatures. A single probe containing 18 thermocouples is used to monitor waste temperatures at various levels in the primary tank. The concrete walls and dome contain 24 thermocouples located at the outer surfaces. Twenty-four additional thermocouples are located in the interior next to the steel in the primary tank dome and the steel liner. Nine thermocouples are located in the concrete slab base. Twenty-four thermocouples are located in the insulating concrete layer next to the bottom of the primary tank. All thermocouples read out in the instrument buildings and at the CASS.

Other Instrumentation. Three pole-mounted area radiation monitors (ARMs) are used to provide overall surveillance of radiation levels in the SY Tank Farm. In addition to the leak detection provided by the CAMs, conductivity probes are installed in the annulus, process pits, and encasements. These areas are normally dry; the presence of any liquid would activate the probe to indicate a leak and sound an alarm in the instrument building. Leak detection wells collect leakage from secondary tanks. The liquid level in each leak detection well is monitored using specific gravity and weight-factor detectors and associated instrumentation. A radiation detection element is installed adjacent to each leak detection well to monitor radiation levels in the wells, and a thermocouple is installed near the bottom of each well to monitor the temperature of the liquid in the well.

Tank farm sensors are continuously monitored by the CASS system; a few are monitored on an hourly basis. Continuous monitors are maintained for the following:

- CASS equipment (substation failures)
- Leak detection pits (high radiation, high liquid level)

- Tank pressure indicators (high and low pressure)
- Annulus leak detectors
- Exhaust systems
- Radiation detection units (annulus exhaust, exhaust stacks, raw water line in service pit, area radiation monitors, and instrument building interior)
- Process line encasement leak detectors, process pit leak detectors, clean out box leak detectors (if applicable)
- Process line heat trace temperature

3.2.3. Transfer Facilities. Currently there are no liquid transfers in or out of Tank 101-SY because it is full and has been isolated. Therefore, the PSA accident sequence initiators caused by waste transfers are not an issue.

3.2.4. Utilities and Services. Electrical power, steam, water, and compressed air are supplied to tank farm facilities as needed for specific equipment or operations. A schematic for the Hanford Electrical Transmission System is shown in Fig. 3.1. Site electrical power is stepped-down and supplied via existing lines to the SY Tank Farm facilities. Compressed air is provided to specific facilities by either a local compressor or by piping instrument air from the nearest existing source in the tank farms. Steam and water are obtained from existing supply lines in the tank farms.

Descriptions of utility systems for specific facilities are contained in manuals and supporting documents issued for the facility. Operating procedures may contain information related to utility systems. A description of emergency actions related to a loss of utility systems is contained in RHO-MA-111.5, Emergency Plan—Tank Farms. In the event of the loss of power and/or heating, ventilating, and air conditioning (HVAC), there is no detrimental effect from waste overheating because the current heat generation rates in Tank 101-SY are extremely low (see App. E).

The utility systems that are essential to maintaining safety are designed to include alternative supplies with capacity to perform their safety functions. Reliable emergency power is provided to controls, instruments, confinement systems, service systems, and process systems necessary to allow operations to be shut down safely and to be maintained safely in a shutdown condition. Emergency utility systems are designed to maintain their functions during a single failure. Emergency utility services are designed to permit the testing of their functional operability and capacity, including both the full operational sequence of each system for transfer

between normal and emergency sources and the operation of associated safety systems.²

3.3. Chemical and Radionuclide Contents of Tank 101-SY

Characterization of the contents of Tank 101-SY is very important because this tank has received top priority in terms of unresolved safety issues. The periodic releases (approximately every 100 days) of flammable (hydrogen and ammonia) and oxidizer gases (nitrous oxide) approaching flammability limits places this tank on the top of the current watch list. Extensive research and testing efforts have been directed at managing and controlling the potential risk from this tank. For a more complete description of all Hanford Tank Farm wastes, see App. G.

3.3.1. Chronology of Tank Fill. The first waste transferred to Tank 101-SY was from the first DS slurry campaign using the 242-S evaporator in 1977. DS slurry is the most concentrated material that the evaporators can produce. The degree of concentration was only limited by the ability to pump the evaporator bottom's slurry. In April 1977, 274,000 gal. (equivalent to 100 in. of tank level change) of this material was pumped into the tank. As shown in Table 3-1, from 1977 to 1980, the tank received three different batches of complexed concentrate waste. A total of 203 in. of complexed concentrate waste was placed on top of the heavier DS slurry.

TABLE 3-1
TANK 241-SY-101 CONTENTS

Tank Fill Chronology	Gal.	Substance	In.
April 1977	274,000	Double-Shell Slurry ^a	100
November 1977	365,000	Complexed Concentrate ^b	133
June 1978	131,000	241-SX-106 Complexed Concentrate	48
August 1978	60,000	111-U Complexed Concentrate	22
November 1980	230,000	Double-Shell Slurry	84
September 1984 to May 1988	8000	Water	3
Total	1,068,000		390

^aDouble-shell slurry is a concentration waste produced by the evaporator. It is high in hydroxide, nitrate, and aluminate concentration.

^bComplexed concentrate is an evaporator product similar to double-shell slurry (though not as concentrated). It also contains significant organic complexant concentrations.

Source: Ref. 3.

Complexed concentrate is a waste from the cesium/ strontium recovery process and is rich in complexants such as ethylenediaminetetraacetic acid (EDTA), N-(hydroxyethyl)-ethylenediaminetetraacetic acid (HEDTA), citric acid and hydroxyacetic acid. The last material added was from another campaign of DS slurry in the fall of 1980. About 84 in. was transferred to the tank, which brought the final level to 387 in. Lancing water totaling 8000 gal. was added to the tank between September 1984 and May 1988.

3.3.2. Chemical and Physical Composition of Tank 101-SY. As a result of increased sampling and analyzing, Tank 101-SY is perhaps the best characterized tank in the HTF.⁴ Based on a variety of analyses and measurements, tank contents are believed to be in the configuration shown in Fig. 3.7.

Several samples were taken from different locations in the tank. These locations included top crust, convective liquid layer, nonconvective slurry layer, and nonconvective bottom sludge. The samples were subjected to a variety of chemical, thermal, and radiological analysis. A complete detailed analysis report is presented in Ref. 5. Comparison of the chemical content in the convecting and nonconvecting layers in the tank is presented in Table 3-2. Measured selected physical properties for various segments within the tank is presented in Table 3-3.

Fig. 3.7.
Waste tank layers.

TABLE 3-2
LAYER AVERAGE CONCENTRATION OF VARIOUS CHEMICAL SPECIES
(ALL VALUES IN WEIGHT PERCENT)

	Convective Liquid	Nonconvective Slurry
NO ₃	10.3	10.2
NO ₂	11.7	9.1
TOC	1.25	1.9
Na	20.1	21.2
Al	3.4	3.5
Ca	0.012	0.036
Cr	0.088	0.70

Source: Ref. 5, Table 2-3, p. 2-6.

REFERENCES

1. T. B. Powers and S. D. Morales, "SY Tank Farm Ventilation; Situation Option Risk Assessment Report," Westinghouse Hanford Company unnumbered draft report (June 1992).
2. W. V. Baumgartner et al., "Aging-Waste Facility Safety Analysis Report," Rockwell International, Rockwell Hanford Operations, report SD-HS-SAR-010, Rev. 1, prepared for the US Department of Energy under Contract DE-AC06-77RL01030 (December 1983).
3. H. Babad et al., "Evaluation of Generation and Release of Flammable Gases in Tank 241-SY-101," Westinghouse Hanford Company report WHC-EP-0517, p. 3 (November 1991).
4. Pacific Northwest Laboratory, Tank Waste Science Panel, "Chemical and Physical Processes in Tank 241-SY-101: A Preliminary Report," PNL-7595-AD-940, prepared for the US Department of Energy (February 1991).
5. D. L. Herting, "Laboratory Characterization of Samples Taken in May 1991 from Hanford Waste Tank 241-SY-101," Westinghouse Hanford Company report WHC-SD-WM-DTR-024, Rev. 0 (February 18, 1992).

TABLE 3-3
PHYSICAL PROPERTIES OF SAMPLES FROM TANK 101-SY

Property	32°C	50°C	65°C	80°C
Nonconvective Slurry				
Density (g/ml)—bulk	1.68	1.66	1.66	1.74
Density—centrifuged supernate	1.50	1.46	1.44	1.44
Density—centrifuged solids	1.75	1.75	1.73	2.03
Vol% settled solids	100%	100%	100%	100%
Vol% centrifuged solids	78%	72%	65%	62%
Wt% centrifuged solids	79%	76%	67%	72%
Shear strength (dyn/cm ²)	15,000	6400	3000	5100
Wt% water, gravimetric	31.4%			
Convective Liquid				
Density (g/ml)—bulk	1.53	1.54	1.54	1.48
Density—centrifuged supernate	1.46	1.45	1.47	1.43
Density—centrifuged solids	1.93	1.85	1.82	2.16
Vol% settled solids	44%	48%	54%	56%
Vol% centrifuged solids	22%	23%	20%	8%
Wt% centrifuged solids	28%	27%	24%	10%
Shear strength (dyn/cm ²)	<530			
Wt% water, gravimetric	38.9%			
Sludge				
Density (g/ml)—bulk	1.71	1.71	1.71	1.70
Density—centrifuged supernate	1.46	1.51	1.52	1.53
Density—centrifuged solids	1.78	1.82	1.79	1.79
Vol% settled solids	100%	100%	100%	99%
Vol% centrifuged solids	79%	73%	68%	64%
Wt% centrifuged solids	83%	78%	72%	68%
Shear strength (dyn/cm ²)	116,000	26,400	4000	14,000
Wt% water, gravimetric	28.5%			

Source: Ref. 5, Table 9-3, p. 9-5.

4.0. ACCIDENT SEQUENCE MODEL

4.1. Overview

The accident sequence model serves two primary purposes. The first is to document the PSA team's understanding of how radionuclide and/or toxic gas releases potentially could occur from the tanks. The second purpose is to create a logic model describing the potential accident sequences that can be used to quantify the likelihood of releases.

Development of the accident sequence model follows the steps discussed in Chap. 2. The logic model is developed to a level of detail sufficient to provide the following:

- a reasonable degree of completeness in the coverage of accident sequences due to both internal and external causes;
- explicit treatment of key dependencies among systems, initiating events, and human actions;
- proper characterization of accident sequences to facilitate the evaluation of waste chemical reactions, tank response phenomena, and operator actions; and
- adequate definition of accident sequences to support the unambiguous assignment of release categories.

The balance of this section describes the development of the Tank 101-SY accident sequence model in detail.

4.2. Assumptions

The following assumptions were used in the development of the Tank 101-SY accident sequence model:

1. Tank 101-SY is modeled as configured in December 1992,
2. the potential safety implications of experimental mixing pump installation and operation are not addressed in this analysis, and
3. the operations that are being planned for ultimate retrieval and disposal of the tank contents are not considered.

4.3. Identification of Initiating Events

The first step in developing the accident sequence model is to define a set of initiating events. For an accident sequence to occur, an event must first perturb the normal conditions of a waste tank or its contents. Subsequent events may (or may not) result in a release of radionuclides or toxic gas. The main objectives of this section are as follows:

- to provide adequate assurance that all possible events are accounted for;
- to account for unique tank design and operational features;
- to provide a way to categorize events in all unique ways that the event may impact the entire tank population; and
- to group together events that present similar threats to safety functions for quantification.

Candidate initiating events were identified through the use of several different analytic approaches, including:

- Master Logic Diagram (MLD) Development
- Hazard and Operability (HAZOP) Study Analysis
- External Events Analysis

Applications of the MLD and HAZOP techniques are described later in this section. External events analyses are presented in App. C. In addition to the approaches identified above, new insights are often obtained from other PSA tasks that lead to identification of new initiating events or that alter the judgments made in finalizing the list. This is a highly iterative process and is difficult to predict. For example, the results of accident sequence quantification for one initiating event may be used to eliminate some others from the list. Also, a review of operating experience often reveals new initiating events.

4.3.1. Master Logic Diagram. The MLD is similar to a fault tree and provides a deductive approach for answering the question How can a significant release of radioactivity (or toxic gas) into the environment occur? The waste tank MLD is shown in Fig. 4.1. The key objective of the MLD is to identify all possible sources of hazardous materials and the pathways by which a release can occur down to a level of detail at which all important safety functions and barriers have been accounted for. Once this is accomplished, then specific causal events that can threaten a safety

Fig. 4.1.
Hanford Tank Farm hazardous material release master logic diagram.

Fig. 4.1a.
Primary ventilation and annulus ventilation drain systems.

Fig. 4.1b.
Primary tank waste.

Fig. 4.1c.
Primary ventilation and annulus ventilation system HEPA filter release.

Fig. 4.1d.
Primary tank dome and secondary tank annulus space.

Fig. 4.1e.
Primary tank dome space—toxic gas.

1. Radioactive particulates are assumed to be present in the tank vapor space at all times. Negative pressure from active ventilation retains particulates in non-isolated tanks. Isolated tanks are sealed and allowed to breath through filtered passive vents.
2. Retention of aerosols by the soil is assumed for releases occurring below grade level.
3. Primary tank ventilation filters and drains are assumed to be contaminated and a release will result from their failure. Secondary tank ventilation filters and drains are assumed to be clean, unless a primary tank leak occurs.
4. Overflow paths to grade level are assumed to exist through the tank central pump pit or other riser.
5. Toxic gases are assumed to be generated at low levels in the tanks at all times. Tank vapor space concentrations are controlled by normal ventilation systems. If not removed through ventilation, toxic gas concentrations are assumed to build to levels of concern. Tank exhaust filters are ineffective in retaining toxic gases.
6. For single shell tanks (SST's), there are no secondary shells and primary shell failure leads directly to a release.
7. No active control actions are normally required except for certain specific tanks. In general, some other initiator must occur that changes the current (stable) condition of the tank to challenge safety function control.

Fig. 4.1f.
Master Logic Diagram notes.

barrier or function can be listed. The question of completeness is then reduced to an assessment of the total frequency of all causal events that could produce any of the conditions shown on the MLD. It should be noted that it is not the objective of the MLD to delineate all possible accident scenarios that could result from the initiating event. For example, safety function failures could result in the failure of one or more fission product barriers. Such scenarios are not illustrated by the MLD but are addressed in the accident sequence model.

Many of the events shown at the bottom of the MLD may be subdivided to reveal more specific causal events. A listing of such events that could threaten the safety barriers or functions shown at the bottom of the MLD is shown in Table 4-1. The events listed are also matrixed against the MLD basic events to help identify common cause initiators that can simultaneously threaten multiple safety barriers or functions.

4.3.2. Identification of Initiating Event Groups. The process of grouping initiating events by similarity of response is common to all PSA models and helps to limit the number of event-tree sequence models. It is necessary and practical to analyze only those initiating events that make appreciable contributions to risk. Given knowledge of the approximate frequency of the initiating events and the relative impact of these events on the tanks, it is possible and desirable to group and screen initiating events to simplify the quantification of risk.

Grouping of the events listed in Table 4-1 is shown in Table 4-2. Different causal events that impact the tanks in a similar way are grouped together. Care has been taken, however, to separate common cause initiators and initiators with special dependencies. MLD basic event groups "Secondary Tank Shell Breach" and "Annulus Vent Line Breach" are not included as initiating events in Table 4-2. Secondary shell breach is questioned in the event-sequence model following a breach of the primary tank. The initiating event groups listed in Table 4-2 are generally applicable to all storage tanks. However, because of differences in tank design, tank status, and waste characteristics, these general initiating event groups may need to be subdivided to account for these differences between tanks in constructing the integrated model of the entire HTF. Evaluations of the susceptibility of individual tanks to each initiating event group are presented in Sec. 4.4. Event trees were constructed for 10 of the 12 initiating event groups to characterize tank response to these initiators. One of the event groups, i.e., Waste Transfer, was not applicable to Tank 101-SY.

**TABLE 4-1
MLD BASIC EVENTS AND CAUSES**

EXAMPLE CAUSAL EVENTS	MLD BASIC EVENTS																
	Primary Tank Shell Breach	Secondary Tank Shell Breach	Tank Dome Breach	Annulus Vent Line Breach	Riser Breach	Primary Exhaust Vent Line Breach	Exhaust HEPA Filter Breach	Vent. Drain Line Leak	Vent. Seal Pot Leak	Waste Transfer System Leak	Inadequate Primary Ventilation Flow	Inadequate Corrosion Control	Inadequate Level Control	Inadequate Criticality Control	Inadequate Chemistry Control	Inadequate Pressure Control	Inadequate Temperature Control
Drilling Contact with Tank	X	X															
Excavation Contact with Tank	X	X	X		X												
Vehicle Overloads Dome			X														
Load Dropped Over Tank			X	X	X	X											
Vehicle Impact w Above Ground Equip.				X	X	X	X	X	X								
Human Error, Tank Left Open				X	X	X	X	X	X	X	X						
Excessive Moisture in Vent System							X					X					
Ventilation Exhaust Filter Blockage											X						
Ventilation Inlet Blockage											X						
Vent Fan Failure											X						
Loss of Power to Vent Fan											X						
Loss of Waste Mixing Equipment														X	X		X
Tank Inundated by Transfer Spill			X										X				
Tank Inundated by Raw Water Leak			X										X				
Tank Inundated by Heavy Precipitation			X										X				
New Waste Transfers From Other Facilities										X		X	X	X	X	X	
Salt Well Transfers to Collector Tank										X		X		X	X		X
Liquid Transfers to 242-A Evaporator										X		X	X	X	X	X	
Slurry Transfers from 242-A to DST Storage										X		X	X	X	X	X	
Bound Gas Release	X	X	X	X	X	X	X	X	X		X				X	X	
Lightening Strike on Tank											X						
Seismic Event	X	X	X	X	X	X	X	X	X	X	X						
Aircraft Crash	X	X	X	X	X	X	X	X	X	X	X						
Range Fire*											X						
High Wind & Dust Storm*				X		X					X						
Volcanism*											X						
Dam Break*			X										X				

* Screened from model based on analyses in App. C.

TABLE 4-2
INITIATING EVENT GROUPS

Initiating Event GROUP		
CODE	DESCRIPTION	EXAMPLE CAUSAL EVENTS
PSB	Primary Tank Shell Breach	Tank Shell Corrosion Drilling Contact with Tank Excavation Contact with Tank
DB	Tank Dome Breach	Vehicle Overloads Dome Water Overloads Dome Heavy Load Dropped over Dome
RVB	Riser or Vent. Line Breach	Vehicle Impact with Above-Ground Equipment Human Error, Tank Left Open
FB1	Tank Exhaust HEPA Filter Breach	Exhaust Filter Breach Exhaust Filter Blockage
LOTV	Loss of Primary Tank Ventilation	Loss of Power to Vent Fan Vent Fan Failure Ventilation Inlet Blockage
LOSP	Loss of Tank Farm Offsite Power	
WI	Water Intrusion Event	Tank Inundated by Transfer Spill Tank Inundated by Raw Water Leak Tank Inundated by Heavy Precipitation
WT	Waste Transfer	New Waste Transfers from Other Facilities Salt Well Transfers to Collector Tank Liquid Transfers to 242-A Evaporator Slurry Transfers from 242-A to DS Tank Storage
SEIS	Seismic Event	
AIRCRSH	Aircraft Crash	
BURP	Bound Gas Release	Waste Turnover Seismic Event Water Intrusion

4.3.3. Review of Previous Studies. In addition to the development of the initiating event list described above, initiating events identified for Hanford waste storage tanks in a Westinghouse Hanford Company (WHC) study were examined to compare initiators. This study was the "Tank Farm Risk Assessment—Plant Familiarization and Hazard Identification Report" performed by WHC.¹ Comparisons of the initiators identified in this study with the initiating event groups from Table 4-2 is presented in Table 4-3.

4.4. Accident Sequence Logic Model Development

The purpose of performing a PSA is to answer the following questions that are fundamental to a quantitative risk assessment:

1. What can go wrong during operation or maintenance that could result in an accident sequence that could produce a gaseous or liquid radionuclide or toxic gas release?
2. How likely are these sequences to occur during the tanks' lifetime?
3. What is the level of damage to the tanks and to the environment (health effects) that could result if a release occurs?

To answer these three fundamental risk assessment questions, an accident-sequence-based approach has been developed and applied. As shown in Fig. 4.2, each sequence begins with a well-defined initiating event from the initiating event groups presented in Table 4-1. Each possible sequence that could result from an initiating event is defined in terms of the specific responses of the tank waste materials, structures, and systems to challenges presented by the initiator and subsequent events. The event-tree sequence models organize the successful and unsuccessful responses that characterize the different ways that tanks can respond to the initiating events. Flow charts called event-sequence diagrams graphically display how the progression of the accident sequence is being modeled to facilitate communication with non-PSA analysts. The event sequences also consider all accident phenomena that could influence tank integrity and the ultimate severity of release.

The frequency of each accident sequence is assigned to an appropriate release category that characterizes the ultimate response of the tank and the nature of the release of radioactive material or toxic gas to the environment. For each important release category, the frequency and magnitude of the release are used to estimate the potential for health impacts on the surrounding population, as described in Chaps. 5 and 6.

TABLE 4-3
COMPARISON OF INITIATING EVENT GROUPS WITH WHC PRELIMINARY
HAZARDS ANALYSIS (PHA) INITIATORS

No.	PHA Initiating Event Description	Corresponding HTF PSA Initiating Event Group^a
1.	Lightning strike causes loss of facility electrical power to powered ventilation systems	LOSP
2.	Accumulation of fissile material and criticality	Consequence of WT
3.	Air compressors [for DS tank air lift circulators (ALCs) in aging waste tanks] fail and cause waste to heat up	Not Applicable
4.	Plugged air line causes ALCs to fail and waste to heat up	Not Applicable
5.	Aircraft crash causes structural failure of tank or ignition source from fire	AIRCRSH
6.	Earthquake or large vibration induces shock-sensitive chemical reactions	SEIS
7.	Seismic event causes structural failure of tank	SEIS
8.	Tornado causes excessive vacuum in tank	HW/Tornado
9.	Corrosive materials in pipes cause pipe integrity failure	Consequence of WT
10.	Line plugs, and during attempts to free the blockage, the pipe ruptures	Consequence of WT
11.	Thermal stresses on piping causes pipe failures	Consequence of WT
12.	Freezing weather causes pipes to burst, possibly flooding a tank farm area with liquids that may get into tanks	Consequence of WT
13.	Earthquake fails ventilation instrumentation, causing a spark source and release of a flammable mixture of gases	SEIS
14.	Noise from equipment either harms personnel's hearing or causes personnel errors due to miscommunication	Not Applicable

^aSee Table 4-2 for acronym definitions.
Source: Ref. 1, Table 8-1

TABLE 4-3 (CONT)

No.	PHA Initiating Event Description	Corresponding HTF PSA Initiating Event Group
15.	Cranes lifting heavy objects over tank farm areas with potential for dropping	DB
16.	Radiation field in the tank waste that initiates chemical reactions	BURP
17.	Degradation of chemicals to a more reactive form	BURP
18.	Suitable catalysts put into tank wastes that promote chemical reactions	WT
19.	Corrosion causes leaks in tank wall	PSB
20.	Radionuclide content sufficient to cause high enough temperature for chemical reactions	LOTV
21.	Low humidity in outside air increases probability of static charges in or near flammable gas tanks	Phenomena within Burp Sequences
22.	Lightning strike provides a possible ignition source in or near a flammable gas tank	Phenomena within Burp Sequences
23.	In-tank instrumentation failure causes an electrical spark source in a flammable gas tank	Phenomena within Burp Sequences
24.	Electrical spark created upon reenergizing ventilation system following shutdown of fans in flammable gas tanks	Phenomena within Burp Sequences
25.	Water runoff drains to stabilized tanks and may result in more hydrogen production than when waste was drier	WI
26.	Range fires may provide ignition sources near flammable gas tanks	RF
27.	Blowing sand plugs filters or loop seals	HW
28.	Corrosion of deentrainers on DS tank ventilation systems causes filters to fail from moisture plugging	FB1

TABLE 4-3 (CONT)

No.	PHA Initiating Event Description	Corresponding HTF PSA Initiating Event Group
29.	Corrosion of ventilation ductwork causes releases to either the atmosphere or the ground	RVB
30.	Personnel discharge static charge buildup near flammable gas tanks	Phenomena within BURP Sequences
31.	Steam supply loss to SY exhaust heater fails filters due to moisture plugging	FB1
32.	Higher-than-expected moisture in tank atmosphere causes plugging of filters and resultant filter failure	FB1
33.	Release of gases that pressurize the tank	BURP
34.	Heavy equipment placed over top of tanks causes structural failure of tank	DB
35.	Loss of electrical heaters on ventilation systems causes filters to fail from moisture plugging	FB1
36.	Steam heater coil leak on SY tank farm ventilation system results in condensing steam to drain to SY tank that is leaking	WI
37.	Water runoff from heavy rains or snow melt drains into tanks that are already leakers	WI
38.	Corrosion failure of condensers on DS tank ventilation condensers causes contamination to be drained to condensate storage ponds	RVB
39.	Release of toxic gases	BURP
40.	Overexposure of personnel to radiation from tank wastes when opening risers, transferring wastes, etc.	Not Applicable

Fig. 4.2.
Risk model structure.

4.4.1. Event Sequence Diagram Development. ESDs are graphical depictions of the system response to an initiating event in flow chart format. They are used to display the possible course of events that occur in response to an initiating event. The event sequences include possible chemical and nuclear reactions, tank hardware responses, and the expected steps taken by the operators to implement emergency operating procedures (EOPs).

The thought process that is followed in the development of the ESD, as illustrated in Fig. 4.3, is to first develop the expected (most likely) sequence of events across the top of the diagram. The events along the sequence include so-called stochastic events that have two or more possible outcomes and deterministic physical events that are a direct result of the previous events along the sequence. Then a systematic process is followed by postulating the alternative outcomes of the stochastic events one by one and then, by defining the most likely event sequence that would result, including the introduction of new physical events as appropriate. This process is continued until all possible outcomes of all stochastic events are exposed. The responses of hardware systems and proceduralized operator actions are emphasized in the ESD development. Sufficient events are used to determine whether a release has occurred, and if so, to which release category to assign the sequence. When developed to this level of detail, the ESDs provide the following key inputs to the PSA process:

- list assumptions regarding accident progression for use in event-tree development,
- define top events and boundary conditions for quantification, and
- define sequence boundary conditions and dependencies for human actions analysis.

Fig. 4.3.
Thought process for event-sequence diagram development.

The final steps in the ESD development process are to document modeling assumptions by deciding on the top events to be modeled in the event trees and to define the success criteria to be associated with each of these top events. The plant conditions shown in the ovals assist in defining the boundary conditions. All event trees incorporate some modeling assumptions in deciding which events to include, which events to combine, etc. The ESD helps to document some of these modeling assumptions, as well as to define the boundaries of the analysis that needs to be performed to quantify the frequency of each event-tree top event.

The symbols used in constructing ESDs are shown in Fig. 4.4. The initiating event is drawn in the upper-left-hand corner of the diagram; subsequent operator actions and system responses to the initiator are then presented throughout the remainder of the figure. The normal, or expected, sequence of events is drawn to the right across the figure, as with the convention for event trees. These events are arranged, for the most part, in chronological order. This is not always strictly adhered to because sometimes it is easier to follow events if related actions that are dependent on each other are grouped together, even though they may not be closely related in time.

Fig. 4.4.
Event-sequence diagram symbology.

Events where the occurrence or nonoccurrence influences the course of a scenario are represented in the ESD by rectangles. Successful occurrence of the event described within the rectangle is represented by the arrow exiting the right side of the rectangle; failure or nonoccurrence of the described event is represented by the arrow exiting from the bottom of the rectangle.

These event blocks are the only symbols in the ESDs having two or more exit paths; labels are affixed to each exit path for those blocks with multiple outcomes. The sequences leading into the stochastic events are shown by arrows entering from the left or from the top of the rectangle. Although a given event block may appear several places in the ESD, the event block will appear no more than one time on any particular sequence.

The oval symbol is used for describing the status of key parameters or the phenomena that would likely occur as a result of an accident sequence described by the events up to that point in the ESD. These physical event ovals are used to define the subsequent sequence of events. Several entry paths that may enter from any direction are permitted. However, because the symbol is a descriptive block only, only one exit path is allowed. The exit path may be drawn from the bottom or the right side of the oval. The position of this exit path does not signify anything special but merely facilitates the linking of events. Event sequences result in either successful mitigation of the initiating event or an unfavorable end state, such as a liquid release or toxic gas release. Successful end states are symbolized by elongated hexagons.

Two additional symbols are used to represent transfers to other places in the ESD logic that cannot be conveniently connected by continuous solid lines. The triangle transfer symbols connect two locations in the same ESD. These transfers are numbered to permit ease of identification. The large arrowhead symbol transfers the reader to a completely different ESD, which is identified within the symbol. Some paths through the ESD are judged to have a likelihood of occurrence so small that no further modeling is performed. These paths may terminate in parallelogram-shaped figures that explicitly say "not developed further." The preceding event is then assumed always to result in the alternative outcome, which is developed further.

4.4.2. Event-Tree Development. Although ESDs are easily understood and are useful tools for documenting required facility system and operator actions after an initiating event has occurred, they do not lend themselves directly to accident sequence quantification. A necessary next step therefore is to convert the ESD into an event tree for the purpose of quantifying the accident sequences. The event tree represents the transformation of the qualitative details contained in the ESD into a functional logic framework for quantification.

Once the ESDs have been developed for all of the initiating event groups, the tree is used to provide the basic structure for the quantification process. Top events for the event tree correspond with the event blocks in the ESD except that, in some cases, ESD event blocks are combined to simplify the event tree. In other cases, ESD events are expanded so that functional dependencies between top events can be properly modeled. In developing the event trees, it is important to arrange the top events in an event tree so that the sources of dependency precede the events which

are impacted by their dependencies. When organized in this way, the conditions under which the dependent event is challenged are established by prior top events.

The following terms are used in describing the structure and quantification of event trees.

- **Initiating Event.** The entry state to the event tree at the upper left.
- **Top Events.** The questions listed across the top of the event tree. Top events are represented with a code of up to five characters for use in the RISKMAN computer code.
- **Success Branch.** The branch running straight across from left to right.
- **Failure Branch.** Downward branch beneath the failed top event. If there is no downward branch, the event-tree top does not require branching at that point and is labeled N/I, for not important.
- **Sequence.** A unique path of successes and failures leading from the initiating event through the event tree to an end state.
- **End State.** The conditions resulting from a specific sequence. The end states for the HTF PSA are the release categories that are described in Sec. 5.2.
- **Split Fraction.** The numerical value used for the failure probability of a top event under specific boundary conditions. Multiple (conditional) split fractions are often needed for different branches under one top event because the failure probability of that top event is changed (i.e., there are dependencies among events) by the events that have occurred previously in the event tree. Rules for assigning conditional split fractures are provided in terms of previous top event successes and failures and initiating events. Split fractions are represented in RISKMAN with a code of up to six characters (usually composed of the top event code plus a unique suffix). In this PSA the suffix letters "S" and "F" were reserved for designation of guaranteed success (probability of 0.0) or guaranteed failure (probability of 1.0) of the top event.

Once event trees are constructed for each initiator and loaded into the RISKMAN software, all of the event trees are quantified to provide a fully integrated set of scenarios for the PSA. The use of these event trees in the event-sequence quantification process is described in Sec. 4.6.

4.4.3. End State Assignment. Sequences are grouped into release categories according to similarities in the quantity of materials released and the mode and timing of the release. The most important distinction among the types of releases is whether they are initially released into the atmosphere or to the ground. In general, atmospheric releases require substantially less time to reach the populace, whereas underground releases require greater time and could appear in liquid pathways.

Each sequence through the accident sequence model is assigned to one of the release categories listed in Table 4-4. A complete description of these release categories and the development of radionuclide and toxic gas source terms is presented in Chap. 5. The actual assignment of the event-tree sequences to release categories is performed automatically during event tree quantification through the use of binning logic rules. Section 4.6 provides a complete description of the event-tree quantification process.

TABLE 4-4
HTF PSA RELEASE CATEGORY DEFINITION TABLE

RELEASE PATHWAY		RADIONUCLIDE CONTENT	RELEASE CATEGORY CODE
To Atmosphere	Through HEPA	None	TG
	HEPA Bypassed	Low	BPL
	HEPA Breached	Low	HEPAL
	HEPA Breached	High	HEPAH
	Dome Collapsed	High	DCH
	Dome Collapsed	Very High (fire)	DCVH
To Ground	Subterranean Leak	Small	SLK
	Subterranean Leak	Large	LLK
To Atmosphere and Ground	Infiltration/Surface Spill	Small	SSP
	Transfer Failure/Surface Spill (NA Tank 101-SY)	Large	LSP
	Dome Collapse + Small Leak	High	DCSLK
	Dome Collapse + Large Leak	High	DCLLK

4.5. Accident Sequence Analysis and Modeling for Tank 101-SY

This section presents the detailed logic model development for the initiating events identified in Sec. 4.3 and App. C.

4.5.1. Bound Gas Release (BURP). Approximately every 100 days Tank 101-SY experiences spontaneous releases of bound gas. The gas released to the tank dome space is a mixture of hydrogen, nitrous oxide, nitrogen, and ammonia. Should the release gas contain sufficient quantities of hydrogen to result in a flammable mixture and be ignited, serious damage could result to the tank and/or the ventilation system. Analyses of historical data for 28 burp events and projections of future burp size and frequency are presented in App. E.1.3.

The ESD for burps from Tank 101-SY is presented as Fig. 4.5. Because the released gas typically contains about 4% ammonia (500 ppm is generally considered the threshold for potentially life threatening toxicity), there are no success paths through the ESD following a burp event (i.e., for all burps there will be a release of toxic gas). Next, the hydrogen concentration in the dome space following the burp is questioned. If the hydrogen concentration remains below 4%, then no burning is possible. But if the concentration is above 4%, additional questions are asked to determine if a burn occurs in either the tank or the ventilation system. Both the likelihood of a hydrogen ignition and the next question of burn propagation from the ventilation system to the tank are dependent on the status of the ventilation system. If ventilation is operating, propagation of a burn in the ventilation system back into the tank is made more difficult by the ventilation gas flow away from Tank 101-SY. Analyses of the probability of hydrogen ignition and flame propagation are presented in App. E.1.2.

If a hydrogen burn takes place in the tank or the ventilation system, then the effect of the peak pressure and temperature on the tank and ventilation system integrity are questioned. Analysis of the probability of tank failure following a hydrogen burn event is presented in App. E.1.

The question of waste crust flammability following a hydrogen burn is addressed in App. E.7. Due to the moisture content of the crust in Tank 101-SY, a sustained burn is not expected. Therefore, the possibility of a waste fire is not modeled in the burp event tree.

The event tree corresponding to the burp ESD is shown in Fig. 4.6. The following paragraphs describe each top event, the split fractions required, and the approach used in quantification of the split fractions. Split fraction definitions and

Fig. 4.5.
BURP event-sequence diagram.

Fig. 4.5. (Cont.)
BURP event-sequence diagram.

BURP Initiating Event	Hydrogen Concentration < 4% (H2HI)	Ventilation Continues to Run (VOP)	No Hydrogen Burn in Tank (TBURN)	No Hydrogen Burn in Vent System (VBRN)	No Propagation from Vent Line to Tank (PROP)	Dome Integrity OK (DOME)	Primary Shell Integrity OK (PSI)	Secondary Shell Integrity OK (SSI)	Seq. #	Frequency per Year	Release Category
3.51	8.9E-1	N/I	N/A	N/A	N/A	N/A	N/A	N/A	1	4.0E-01	TG
									2	3.1E+00	TG
									3	1.9E-02	HEPAL
									4	1.5E-03	HEPAH
									5	1.4E-06	HEPAH
									6	5.1E-08	LLK
									7	2.1E-04	DCH
									8	2.0E-07	DCH
									9	7.0E-09	DCLLK
									10	3.5E-03	HEPAH
									11	3.4E-06	HEPAH
									12	1.2E-07	LLK
									13	4.8E-04	DCH
									14	4.6E-07	DCH
									15	1.6E-08	DCLLK
									16	1.4E-02	TG
									17	8.1E-05	HEPAH
									18	7.8E-08	HEPAH
									19	2.7E-09	LLK
									20	1.1E-05	DCH
									21	1.1E-08	DCH
									22	3.8E-10	DCLLK
									23	1.6E-05	HEPAH
									24	1.5E-08	HEPAH
									25	5.3E-10	LLK
									26	2.2E-06	DCH
									27	2.1E-09	DCH
									28	7.4E-11	DCLLK

LEGEND:

N/I Not Important
 N/A Not Applicable
 G/F Guaranteed Failure

Fig. 4.6.
BURP event Tree.

values are summarized in Table 4-5. Results of the event-tree quantification are presented in Sec. 4.6.

Top Event H2HI—Hydrogen Concentration is Less than 4%?

- **Success Criteria.** If the hydrogen concentrations in the tank dome space and ventilation system remain below 4% following a burp, then hydrogen burns cannot occur.
- **Split Fraction Definition.** Only one split fraction (H2HI1) is needed for all burp events.
- **Split Fraction Quantification.** An analysis of hydrogen concentrations in the tank dome space and ventilation lines following a burp event is presented in App. E.1.2. It should be noted that this split fraction is based on a combination of actuarial data and projections for the volume of gas released from the waste as well as computer code (HMS) calculations of the hydrogen concentration in the vent line given a release. Projections were based on the observation that there has been an upward trend in the volume of gas released. This trending was extrapolated for a period of 3 yr. Thus, the probability distribution used in this study would be appropriate (assuming no perturbations in the existing trend) for a time 3 yr in the future and somewhat conservative for any time in the interim.

Top Event VOP—Active Tank Ventilation Continues to Operate?

- **Success Criteria.** For actively ventilated tanks, continuous air flow must be maintained into the tank and out through HEPA filters. For passively ventilated tanks, the vent pipe and HEPA filter must remain unplugged, maintaining tank dome space pressure within plus or minus 6 in. w.g. of atmospheric pressure.
- **Split Fraction Definition.** Only one split fraction (VOP1) is needed for all burp events. The electric power system components required for operation of the ventilation system are included in the fault tree model for the ventilation system.
- **Quantification Modeling.** The availability of the SY Tank Farm ventilation system was developed using the fault tree in App. D.
- **Modeling Assumptions.** None.

TABLE 4-5
HTF PRA TOP EVENT SPLIT FRACTION VALUES

TOP EVENT AND SPLIT FRACTION DESCRIPTIONS		SPLIT FRACTION VALUES				SECTION REFERENCE
		MEAN	5% Tile	50% Tile	95% Tile	
Top Event: AVI						
Description: ANNULUS VENT INTEGRITY OK						
AVI1	ANNULUS VENT PIPE FAILED	5.90E-2	2.25E-2	5.13E-2	1.01E-1	4.5.2
Top Event: DOME						
Description: DOME INTEGRITY						
BRCHD1	DOME BREACHED GIVEN DOME BREACH INITIATOR	1.00E+0				
BRCHD2	DOME BREACHED BY H ₂ BURN	0.00E+0				E.1
COLAP1	DOME COLLAPSED GIVEN DOME BREACH INITIATOR	0.00E+0				
COLAP2	DOME COLLAPSED BY H ₂ BURN	1.21E-1	Note 1			E.1
DOMES1	DOME OK GIVEN DOME BREACH INITIATOR	0.00E+0				
DOMES2	DOME OK FOLLOWING BURP AND H ₂ BURN	8.79E-1	(Complement of COLAP2)			E.1
Top Event: H2HI						
Description: HYDROGEN CONCENTRATION IS < 4%						
H2HI1	H ₂ IS > 4% FOLLOWING A BOUND GAS RELEASE (BURP)	8.85E-1	Note 1, 5			E.1 - 4.1
H2HIF	H ₂ IS > 4% FOLLOWING A SEISMIC EVENT	1.00E+0				
Top Event: HEPA						
Description: HEPA EXHAUST FILTER OK						
HEPAF	GUARANTEED FAILURE GIVEN HEPA FAILURE INITIATOR	1.00E+0				
Top Event: LEVEL						
Description: LEVEL REMAINS WITHIN LIMITS						
LEVEL3	LEVEL OVERFLOW GIVEN WATER INTRUSION INITIATOR	1.00E-1	Note 2			4.5.9
Top Event: LI						
Description: LEVEL INDICATION						
LI1	LEVEL INDICATION FAILURE WITH ELECTRIC POWER AVAILABLE	1.00E-2	1.20E-3	6.20E-3	3.10E-2	D.2

Note: Exponential notation is indicated in abbreviated form; 5.90E-2 = 5.90 × 10⁻².

TABLE 4-5 (CONT)

TOP EVENT AND SPLIT FRACTION DESCRIPTIONS		SPLIT FRACTION VALUES				SECTION REFERENCE
		MEAN	5% Tile	50% Tile	95% Tile	
Top Event: LKD Description: LEAK DETECTORS OPERABLE						
LKD1	LEAK DETECTION FAILURE WITH ELECTRIC POWER AVAILABLE	1.00E-1	1.20E-2	6.20E-2	3.10E-1	D.2
LKDF	GUARANTEED FAILURE OF LEAK DETECTION	1.00E+0				
Top Event: OP Description: OPERATOR PREVENTS RELEASE						
OP1	OPERATOR PREVENTS OVERFLOW (LI=S)	1.30E-2	1.45E-3	7.15E-3	3.34E-2	F.3
OPF	GUARANTEED FAILURE OF PREVENTION ACTIONS	1.00E+0				
Top Event: PROP Description: NO BURN PROPAGATION FROM VENT LINE TO TANK						
PROP1	H ₂ BURN PROPAGATES WITH VENTILATION ON	8.33E-2	Note 1			E.1
PROP2	H ₂ BURN PROPAGATES WITH VENTILATION OFF	1.00E+0				E.1
Top Event: PSI Description: PRIMARY SHELL INTEGRITY						
LARGE1	LARGE TANK LEAK GIVEN A SMALL PRIMARY TANK LEAK INITIATING EVENT	0.00E+0				
LARGE2	LARGE TANK LEAK GIVEN A LARGE TANK LEAK INITIATING EVENT	1.00E+0				
LARGE3	LARGE TANK LEAK FOLLOWING A HYDROGEN BURN	1.00E-3	Note 2			4.5.1
SMALL1	SMALL TANK LEAK GIVEN A SMALL PRIMARY TANK LEAK INITIATING EVENT	1.00E+0				
SMALL 2	SMALL TANK LEAK GIVEN A LARGE PRIMARY TANK LEAK INITIATING EVENT	0.00E+0				
SMALL3	SMALL TANK LEAK AFTER H ₂ BURN	0.00E+0				
SOUND1	PRIMARY TANK SHELL INTACT GIVEN A SMALL PRIMARY TANK LEAK INITIATING EVENT	0.00E+0				
SOUND2	PRIMARY TANK SHELL INTACT GIVEN A LARGE PRIMARY TANK LEAK INITIATING EVENT	0.00E+0				
SOUND3	PRIMARY TANK SHELL INTACT AFTER H ₂ BURN	9.99E-1	(Complement of LARGE3)			4.5.1

TABLE 4-5 (CONT)

TOP EVENT AND SPLIT FRACTION DESCRIPTIONS		SPLIT FRACTION VALUES				SECTION
		MEAN	5% Tile	50% Tile	95% Tile	REFERENCE
Top Event: RVINT						
Description: RISER AND VENT INTEGRITY OK						
RVINT1	VENT LINE FAILED BY H ₂ BURN	1.00E+0				4.5.1
RVINTF	VENT INTEGRITY FAILED BY INITIATING EVENT	1.00E+0				
Top Event: SEP						
Description: SEISMIC FAILURE OF ELECTRIC PANELS						
SEP1	SEISMIC FAILURE OF ELECTRIC PANELS AT 0.15 g	0.00E+0	Note 3			4.5.11
SEP2	SEISMIC FAILURE OF ELECTRIC PANELS AT 0.25 g	5.03E-2	Note 3			4.5.11
SEP3	SEISMIC FAILURE OF ELECTRIC PANELS AT 0.4 g	2.98E-1	Note 3			4.5.11
SEP4	SEISMIC FAILURE OF ELECTRIC PANELS AT 0.6 g	6.67E-1	Note 3			4.5.11
SEP5	SEISMIC FAILURE OF ELECTRIC PANELS AT 0.85 g	8.96E-1	Note 3			4.5.11
SEPY	GUARANTEED SUCCESS (NONSEISMIC EVENT)	0.00E+0				4.5.11
Top Event: SIP						
Description: SEISMIC FAILURE OF I&C PANELS						
SIP1	SEISMIC FAILURE OF I&C PANELS AT 0.15 g	0.00E+0	Note 3			4.5.11
SIP2	SEISMIC FAILURE OF I&C PANELS AT 0.25 g	0.00E+0	Note 3			4.5.11
SIP3	SEISMIC FAILURE OF I&C PANELS AT 0.4 g	0.00E+0	Note 3			4.5.11
SIP4	SEISMIC FAILURE OF I&C PANELS AT 0.6 g	1.71E-1	Note 3			4.5.11
SIP5	SEISMIC FAILURE OF I&C PANELS AT 0.85 g	5.79E-1	Note 3			4.5.11
SIPY	GUARANTEED SUCCESS (NONSEISMIC EVENT)	0.00E+0				4.5.11
Top Event: SOP						
Description: SEISMIC FAILURE OF OFFSITE POWER						
SOP1	SEISMIC FAILURE OF OFFSITE POWER AT 0.15 g	1.08E-1	Note 3			4.5.11
SOP2	SEISMIC FAILURE OF OFFSITE POWER AT 0.25 g	3.72E-1	Note 3			4.5.11
SOP3	SEISMIC FAILURE OF OFFSITE POWER AT 0.4 g	6.97E-1	Note 3			4.5.11
SOP4	SEISMIC FAILURE OF OFFSITE POWER AT 0.6 g	8.92E-1	Note 3			4.5.11
SOP5	SEISMIC FAILURE OF OFFSITE POWER AT 0.85 g	9.69E-1	Note 3			4.5.11
SOPY	GUARANTEED SUCCESS (NONSEISMIC EVENT)	0.00E+0				4.5.11
Top Event: SPT						
Description: SEISMIC FAILURE OF PRIMARY TANK						
SPT1	SEISMIC FAILURE OF PRIMARY TANK AT 0.15 g	0.00E+0	Note 3			4.5.11

Note: I&C = Instrument and Control.

TABLE 4-5 (CONT)

TOP EVENT AND SPLIT FRACTION DESCRIPTIONS		SPLIT FRACTION VALUES				SECTION REFERENCE
		MEAN	5% Tile	50% Tile	95% Tile	
SPT2	SEISMIC FAILURE OF PRIMARY TANK AT 0.25 g	0.00E+0	Note 3			4.5.11
SPT3	SEISMIC FAILURE OF PRIMARY TANK AT 0.4 g	2.88E-2	Note 3			4.5.11
SPT4	SEISMIC FAILURE OF PRIMARY TANK AT 0.6 g	1.59E-1	Note 3			4.5.11
SPT5	SEISMIC FAILURE OF PRIMARY TANK AT 0.85 g	4.12E-1	Note 3			4.5.11
SPTY	GUARANTEED SUCCESS (NONSEISMIC EVENT)	0.00E+0				4.5.11
Top Event: SSI						
Description: SECONDARY SHELL INTEGRITY						
SSI1	SECONDARY TANK SHELL FAILS AFTER PRIMARY TANK FAILURE, NO ENERGETIC EVENT	3.43E-2	1.77E-2	3.09E-2	5.38E-2	D.3.1
SSI2	SECONDARY TANK FAILS AFTER PRIMARY TANK FAILURE, ENERGETIC EVENT	3.43E-2	1.77E-2	3.09E-2	5.38E-2	D.3.1
Top Event: TBRN						
Description: NO H₂ BURN IN TANK						
TBRN1	H ₂ BURN IN TANK AFTER BURP	1.28E-3	Note 1			E.1
Top Event: VBRN						
Description: NO H₂ BURN IN VENT SYSTEM						
VBRN1	H ₂ IGNITION IN VENT DUCT AFTER BURP	6.6E-3	Note 1			Ref. 8
Top Event: VOP						
Description: VENTILATION CONTINUES TO RUN						
VOP1	VENTILATION FAILURE WITH ELECTRIC POWER AVAILABLE	4.48E-3	Note 4			D.2
VOPF	GUARANTEED FAILURE OF VENTILATION	1.00E+0				

- Notes:
1. This is the mean value of a double delta function. The possible values of the function are 0.0 and 1.0. The probability associated with the 1.0 value is equal to the mean value displayed. See Ref. 8 for deviation of this value.
 2. The mean values of these split fractions were based on engineering judgment. These split fractions were not important with respect to risk, and therefore, no uncertainty distributions were developed.
 3. Point estimate mean values were calculated for component failure fractions. These failure fractions were not important with respect to risk, and therefore, no uncertainty analysis was performed.
 4. The mean value for the unavailability of the primary ventilation system was calculated based on the fault-tree analysis presented in App. D. The independent failure of the ventilation system was not a significant contributor to risk; therefore, no distribution for Split Fraction VOP1 was required.
 5. Figure E-9 shows a gas release of 4600 ft³ (best estimate) to reach 4% H₂ in the ventilation system. From Fig. E-15 the probability of exceeding a 4600 ft³ release is 0.89 (i.e., 1.0–0.11).

Top Event TBRN—No Hydrogen Burn Occurs in Tank?

- **Success Criteria.** No hydrogen burn reaction capable of overpressurizing the tank or ventilation equipment occurs in the tank.
- **Split Fraction Definition.** Only one split fraction (TBRN1) is needed for all burp initiating events.
- **Quantification Modeling.** The likelihood of hydrogen ignition following a BURP event was taken from Ref. 2.
- **Modeling Assumptions.** A hydrogen burn in the tank or the ventilation system is assumed to have the following impacts:
 1. The SY Tank Farm ventilation system is assumed to be intact before a burp event. If no hydrogen burn occurs, the ventilation system is assumed to remain intact. If a burn does occur in either the tank or vent system, the ventilation system is assumed to fail.
 2. The SY Tank Farm primary tank ventilation system HEPA filters are assumed to be intact before a burp event. If no hydrogen burn occurs, they are assumed to remain intact. If a burn occurs in either the tank or vent system, the HEPA filter is assumed to fail. Failure of the exhaust HEPA filters will result in a direct ground level release path to the environment for tank aerosols and the release of any radionuclides trapped by the filter material.
 3. The SY Tank Farm annulus vent system is assumed to be intact before a burp event. If no hydrogen burn occurs or a burn occurs and the primary tank remains intact, the annulus vent system is assumed to remain intact. If a burn occurs and the primary tank fails, then the annulus vent system is also assumed to fail.

Top Event VBRN—No Hydrogen Burn in Ventilation System?

- **Success Criteria.** No ignition of hydrogen in vent line (all burns assumed to be capable of damaging piping or equipment in the ventilation system).
- **Split Fraction Definition.** Only one split fraction (VBRN1) is needed for all burp initiating events.
- **Quantification Modeling.** The likelihood of hydrogen ignition following a burp event was taken from Ref. 8.
- **Modeling Assumptions.** None.

Top Event PROP—No Propagation of a Hydrogen Burn from the Vent Line to the Tank?

- **Success Criteria.** No propagation of a hydrogen burn from the ventilation line to Tank 101-SY.
- **Split Fraction Definition.** Given ignition in the ventilation system, the likelihood of propagation back to the tank is dependent on ventilation system operation and flame speed. Thus, unique split fractions are needed for scenarios with ventilation operating (PROP1) and ventilation failed (PROP2).
- **Split Fraction Quantification.** An analysis of hydrogen burn propagation is presented in App. E.1.2.
- **Modeling Assumptions.** If a burn propagates back into the tank from the ventilation system, the effects of the burn are assumed to be the same as if the burn had occurred in the tank initially.

Top Event DOME—Dome Integrity Maintained?

This top event questions the integrity of the tank dome above the waste material. Three potential outcomes are allowed for Top Event DOME: dome integrity maintained, dome breached, and dome collapsed. If the dome is breached but does not collapse, only airborne aerosol releases are possible. However, if the dome should collapse, a significant pathway would be open to the environment, and soil or other material falling into the tank could cause dispersal of waste material above grade.

- **Success Criteria.** No direct pathways, except through risers, can be allowed for tank vapors or aerosols in the tank dome space to escape into the atmosphere.
- **Split Fraction Definition.** In the burp event tree, the dome integrity is only questioned following a hydrogen burn in the primary tank (including those originating in the ventilation system). The likelihood of dome integrity maintained, dome breach, or dome collapse are represented by split fractions DOMES2, BRCHD2, and COLAP2, respectively. The analysis included an App. E indicates that the failure mode for a hydrogen burn is a dome collapse and not a tank breach.
- **Quantification Modeling.** The susceptibility of the tank dome to failure following a hydrogen burn event is assessed in App. E.

- **Modeling Assumptions.** See App. E.

Top Event PSI—Primary Shell Integrity Maintained?

Loss of primary tank shell integrity will allow free liquids in the tank to leak. For SS tanks, failure of this block leads directly to a subterranean release. For DS tanks such as 101-SY, primary tank leaks pass into the secondary tank. The term "shell" is used here to denote the bottom and sides of a tank, i.e., the portion containing any liquids.

- **Success Criteria.** No significant quantities of liquids leak from the tank.
- **Split Fraction Definition.** Two possible failure states are allowed for this top event: large primary tank leaks and small primary tank leaks. Following a hydrogen burn event, the likelihood of no leak, small leak, and large leak are represented by split fractions SOUND3, SMALL3, and LARGE3, respectively.
- **Quantification Modeling.** The conditional probability of tank shell failure following hydrogen burns or other energetic events is evaluated as part of the phenomenological analyses in App. E.1. This analysis concludes that dome collapse is the expected tank failure mode following a hydrogen burn. Although considered unlikely, failure of the tank shell producing a large leak was assigned a conditional frequency of 1E-3, based on engineering judgment, given the occurrence of a hydrogen burn event.
- **Modeling Assumptions.** None.

Top Event SSI—Secondary Shell Integrity Maintained?

This block is questioned following failure of the primary shell for DS tanks. Failure of this block leads directly to a subterranean release. The frequency of an atmospheric release from this scenario is insignificant compared to the HEPAH sequences.

- **Success Criteria.** No detectable quantities of liquids can leak from a tank.
- **Split Fraction Definition.** Only one split fraction (SSI1) is needed for all burp initiating events.
- **Quantification Modeling.** An analysis of secondary tank shell integrity is presented in App. D.
- **Modeling Assumptions.** See App. D.

4.5.2. Primary Tank Shell Breach. Analysis performed to estimate the frequency of future leaks from both SS and DS tanks is presented in App. D. Frequencies were developed for both small (less than 5000 gal.) and large leaks. Given that a primary tank leak has occurred, the accident frequency analysis is completed by assessing the likelihood that the primary leak is not contained by the secondary tank. The same aging analysis approach used to calculate the frequency of primary tank failure was employed for the secondary tank. This analysis is also described in App. D.

Additional questions could be included in the accident sequence model to examine the probability of leak detection and subsequent operator intervention to minimize the consequences of the leak. Because no formal plans are known to exist for the possible mitigation of a leak from Tank 101-SY, no recovery actions were included in the model.

The event-sequence diagram and corresponding event tree for primary leaks from Tank 101-SY are presented as Figs. 4.7 and 4.8. These models are used to quantify the frequency of radionuclide releases from Tank 101-SY for both large and small primary tank leaks. The following paragraphs describe each top event, the split fractions required, and the approach used in quantification of the split fractions. Split fraction definitions and values are summarized in Table 4-5. Results of the event-tree quantification are detailed in Sec. 4.6.

Top Event PSI—Primary Shell Integrity Maintained?

Loss of primary tank shell integrity will allow free liquids in the tank to leak. In the primary shell breach event-sequence diagram and event-tree models, the event serves as a switch, such that for the large primary leak initiating event (LPSB), the state of this event is guaranteed to be "LARGE," and for small primary leak initiating event (SPSB), the state of this event is guaranteed to be "SMALL." For DS tanks such as 101-SY, primary tank leaks pass into the secondary tank. The term "shell" is used here to denote the bottom and sides of a tank, i.e., the portion containing any liquids.

Top Event SSI—Secondary Shell Integrity Maintained?

This top event is questioned following failure of the primary shell for DS tanks. Failure is assumed to lead directly to a subterranean ground release (no credit is given for retention by the concrete shell).

Fig. 4.7.
PSB event-sequence diagram.

Primary Shell Breach Initiating Event SPSB/LPSB*	Primary Shell Integrity (PSI)	Secondary Shell Integrity OK (SSI)	Annulus Vent Integrity OK (AVI)	Seq. #	Frequency per Year SPSB	Frequency per Year LPSB	Release Category
5.8E-3/1.3E-2	N/I	N/I		1	0.0E+00	0.0E+00	SUCCESS
	1.0/0.0			2	5.8E-03	0.0E+00	SUCCESS
			5.90E-02	3	3.3E-04	0.0E+00	BPL
		3.43E-02	N/I	4	2.0E-04	0.0E+00	SLK
	0.0/1.0			5	0.0E+00	1.3E-02	SUCCESS
			5.90E-02	6	0.0E+00	7.4E-04	BPL
		3.43E-02	N/I	7	0.0E+00	4.5E-04	LLK

*NOTE: This event tree is used for both the small leak (SPSB) and large leak (LPSB) events. Where the frequencies are divided by a slash (/), the small leak frequency is given first.

Legend:

N/I = Not Important

Fig. 4.8.
PSB event tree.

- **Success Criteria.** No significant quantities of liquids have leaked from a tank.
- **Split Fraction Definition.** Only one split fraction (SSI1) is needed for both large and small primary shell breach initiating events.
- **Quantification Modeling.** An analysis of secondary tank shell integrity is presented in App. D.
- **Modeling Assumptions.** See App. D.

Top Event AVI—Annulus System Integrity Maintained?

- **Success Criteria.** The annulus ventilation piping must be intact to direct annulus ventilation flow (including aerosols resulting from primary tank failure) to the annulus exhaust HEPA filters and stack.
- **Split Fraction Definition.** Only one split fraction (AVI1) is required for the quantification of the large and small primary tank leak events.

- **Split Fraction Quantification.** The likelihood of breaching the annulus ventilation system is assumed to be the same as the likelihood of breaching the primary tank ventilation system. (See App. D.1.)
- **Modeling Assumptions.** The SY Tank Farm ventilation systems are assumed to be intact and operational at the time of the primary tank leak initiating event. It is assumed that the material leaked into the annulus will remain there for one year. Failure of the annulus vent system integrity within that time would cause a radionuclide release.

4.5.3. Tank Dome Breach. Tank dome breach is defined as an event that allows the dome space aerosols to escape the tank, without passing through the filtered ventilation system and HEPA filters. No subsequent events are required to produce a release. Therefore, the frequency of dome breach initiating events is mapped directly into release category BPL.

4.5.4. Riser or Ventilation Line Breach. Riser or ventilation line breach is defined as an event that allows the dome space aerosols to escape the tank, bypassing the ventilation system and HEPA filter. Ventilation system failures that allow small amounts of liquids to escape from drain lines or seal pots, as well as aerosols, are also included in this initiating event group. No subsequent events are required to produce a release. Therefore, the frequency of riser or vent line breach initiating events is mapped directly to release category BPL.

4.5.5. Exhaust HEPA Filter Failure. Failure of the exhaust HEPA filters will result in a direct release path to the environment for tank aerosols and the release of any radionuclides trapped by the filter material. No subsequent events are required to produce a release. Therefore, the frequency of HEPA breach initiating events is mapped directly to release category HEPAL. HEPA filter failure could also result from other initiators such as burp and is included in the models for those initiators.

4.5.6. Loss of Primary Tank Ventilation. The effects of a loss of ventilation flow through Tank 101-SY would be a reduction of heat removal from the wastes. Loss of the normal negative tank pressure due to ventilation flow could allow dome space aerosols to escape to the atmosphere through the normal inlet leakage paths. However, with no breach of either the tank dome, risers, or ventilation lines, such releases are not expected to be significant.

Loss of waste heat removal could result in an unsatisfactory rise in waste temperature. The peak temperature in Tank 101-SY is normally about 130°F. If the temperature were to increase significantly, increased hydrogen production and

enhanced aerosolization of wastes could result. A scoping level analysis of tank heatup for Tank 101-SY is presented in App. E. This analysis shows that several years without evaporative heat removal would be required for waste temperatures to reach levels of concern. Based on this finding and the knowledge that tank temperatures are regularly monitored, loss of ventilation flow is not developed further as an initiating event for Tank 101-SY.

One additional scenario included under loss of ventilation events is the possibility of higher-than-normal tank vacuum pressures. High vacuum scenarios could result from blockage of the normal tank in leakage paths with continued ventilation fan operation. This scenario is not considered credible for Tank 101-SY for the following reasons:

1. The SY ventilation system includes instrumentation to automatically shut down the ventilation fan if tank vacuum pressure exceeds preset limits.
2. The SY ventilation fan is capable of producing a maximum vacuum pressure of -10-in. w.g. at the fan inlet while the tank design pressure is -6-in. w.g. However, the weakest section of the tank is the bottom, and because Tank 101-SY is filled, the bottom is not subject to dome vacuum pressures. Thus, in a full tank, -10 in. w.g. is not believed to be a threat to tank integrity.
3. Even if a blockage scenario developed, it is unlikely that the -10-in. w.g. shut-off value could be maintained throughout the system from the fan all the way to Tank 101-SY. Ventilation system components are not designed for high vacuum, and any in-leakage in the vent system or Tank 102-SY or 103-SY would cause the vacuum pressure to drop significantly below the -10-in. shut-off value.

4.5.7. Loss of Tank Farm Offsite Power. The primary impact of a loss of offsite power on Tank 101-SY is the resulting loss of ventilation flow. The potential unavailability of ventilation owing to loss of offsite power is included in the analysis of top event VOP following a burp initiator. However, as an initiating event, the impact of loss of offsite power is essentially the same as that for the loss of ventilation flow discussed previously. Therefore, loss of offsite power is not developed further as an initiating event for Tank 101-SY.

4.5.8. Water Intrusion. Water intrusion to Tank 101-SY could result from precipitation run-off, raw water from a broken line, or another source leaking into

the tank through the unsealed hatch covers. Even though Tank 101-SY is filled to near its working limit, an intrusion of about 200,000 gal. would be needed to overflow the tank. An intrusion of this volume would take many hours or even days to reach overflow, thus providing an opportunity for operator intervention to stop the intrusion before overflow. In addition, many intrusion sources will not be large enough to produce overflow even if unchecked.

Another possible side effect of a water intrusion for Tank 101-SY could be a premature burp event caused by sludge dilution. Even if all water intrusion events are assumed to cause a burp, the frequency of water intrusion burp events would be about 0.5% of the frequency of spontaneous burps. Thus, risks from water intrusion burps are judged to be enveloped by the BURP initiator.

The event-sequence diagram and corresponding event tree for water intrusion and overflow of Tank 101-SY are presented as Figs. 4.9 and 4.10. The following paragraphs describe each top event, the split fractions required, and the approach used in quantification of the split fractions. Split fraction definitions and values are summarized in Table 4-5. Results of the event-tree quantification are detailed in Sec. 4.6.

Fig. 4.9.
Water intrusion event-sequence diagram.

Water Intrusion Initiating Event	Level Remains Within Limits (LEVEL)	Level Indication (LI)	Operator Prevents Release (OP)	Seq. #	Frequency per Year	Release Category
1.93E-02		N/I	N/I	1	1.7E-02	SUCCESS
	1.00E-01			2	1.9E-03	SUCCESS
			1.30E-02	3	2.5E-05	SSP
		1.00E-02	G/F	4	1.9E-05	SSP

LEGEND:

N/I Not Important

G/F Guaranteed Failure

Fig. 4.10.
Water intrusion event tree.

Top Event LEVEL—Tank Level Remains within Limits?

- **Success Criteria.** Tank level must remain below the operating limit at all times.
- **Split Fraction Definition.** Only one split fraction (LEVEL1) is needed for the water intrusion initiating event. This failure fraction represents the fraction of water intrusion initiating events that would cause an overflow of Tank 101-SY with no operator intervention.
- **Quantification Modeling.** Because none of the water intrusion events that have occurred at the site have caused a tank to overflow, a conservatively high value of 0.1 was used for this split fraction.
- **Modeling Assumptions.** If overfilled, waste liquids will exit the tank through the pump pit risers, enter the pump pit, and overflow onto the ground from the pump pit hatch covers.

Top Event LI—Tank Level Indication Operates?

This event is questioned on scenarios that could lead to a tank overflow to determine if tank level indication is available to the operators. If level indication is operable, operator intervention to prevent the overflow is questioned.

- **Success Criteria.** Continuous, accurate level indication must be provided to the CASS in Building 2750-E.

- **Split Fraction Definition.** Only one split fraction (LI1) is needed for the water intrusion event-sequence model.
- **Quantification Modeling.** Level indication availability is approximated from the WHC short-term equipment condition report, as described in App. D.
- **Modeling Assumptions.** None.

Top Event OP—Operator Responds to Increasing Tank Level and Prevents a Release?

Given that level indication is available, this event assesses the success of operator intervention to prevent tank overflow.

- **Success Criteria.** The operator must diagnose potential tank trouble and initiate the actions required to prevent the tank overflow and release of radionuclides. The potential accident scenario must be proceeding slowly enough to allow operator intervention.
- **Split Fraction Definition.** Split fraction OP1 represents failure of the operator to intervene given a water intrusion event with level indication available.
- **Quantification Modeling.** The analysis of operator actions is presented in App. F.3.
- **Modeling Assumptions.** None.

4.5.9. Waste Transfer. All transfer lines to and from Tank 101-SY have been isolated and there are no current plans to transfer waste into or out of the tank. Therefore, waste transfer is not developed as an initiating event for Tank 101-SY.

4.5.10. Seismic Analysis. A seismic response assessment was performed on a double-walled waste storage tank, associated equipment pits, tank gas exhaust duct-work system, and support facilities. The assessment consisted of the following:

1. **Seismic Hazard Analysis.** Determination of the frequency of various potential peak ground accelerations at the site.
2. **Fragility Analysis.** Determination of the seismic-initiated peak ground acceleration at which plant structures and components are predicted to fail.

3. **Logic Analysis.** Development of a logic model that depicts the potential component failure scenarios, considering possible combinations of associated equipment or structure failures.
4. **Preliminary Quantification and Results.** Assembly of seismic hazard, fragilities, and models, and the quantification of the frequency of causing sufficient damage to release hazardous materials, as well as identification of dominant contributors.
5. **Final Quantification.** Calculation of uncertainty in the damage and release frequency. The seismic uncertainty analysis was not performed in this study because the contribution to total risk owing to seismic events was negligible compared to nonseismic-initiated events.

The approach taken in each of these steps and the findings are discussed in App. C. A summary of the quantification process and the results are presented in the following sections.

4.5.10.1. Seismic Hazards. A seismic hazard analysis was performed by Woodward-Clyde Consultants (WCC) in April 1989 for a number of nonreactor locations at the Hanford Reservation.³ In addition, a seismic hazard evaluation was performed by Sandia National Laboratories (SNL) in November 1990 as part of an analysis of external events effects at the N Reactor Site.⁴ Rather than initiate new seismic hazard studies for this tank assessment project, we chose to use both of the earlier studies, being satisfied that considering the uncertainty of seismic hazard predictions, the use of these studies should be quite acceptable.

The SY Tank Farm is located in Site 1 at Hanford. The WCC study predicted peak ground acceleration frequencies at six Hanford Sites, including Site 1 and Site N, the location of the N Reactor, which is the subject of Ref. 4. As in other contemporary probabilistic seismic hazard studies, the WCC results were based on: (1) the location and nature of earthquake sources relative to the site, (2) the recurrence frequency of earthquakes of various magnitudes for these sources up to the maximum magnitudes for each source, and (3) the attenuation of ground motions from the sources to Site 1. The source models and attenuation relationships that were developed earlier by WCC for the WNP-2 nuclear power plant, which is located in the region, and for the N Reactor studies performed earlier in 1987, were used in the WCC 1989 study. The uncertainty in the source models and attenuation relationships in these studies was embedded in the 1989 study.

Figure 4.11 presents the overall site plan and indicates the proximity of Sites 1 and N to each other. Table 4-6 presents the annual mean number of events exceeding the peak accelerations at Site 1 and Site N. Figure 4.12 presents the mean hazard curve for Site 1 in graphical form. These three exhibits were taken directly from Ref. 3. Although the curve for Site 1 is represented as the mean curve, the uncertainty about the curve is not represented, nor was it included in Ref. 3 or available elsewhere.⁵ However, the 1990 SNL study calculated an uncertainty distribution about the mean for the N Reactor Site. By comparing the results for Site 1 and Site N in Table 4-6, it can be seen that there is a similarity in the annual probability of exceedance between the two sites. Therefore, it was judged reasonable to apply a normalized version of the uncertainty distribution about the Site N mean curve to the Site 1 mean curve. This is seen in Fig. 4.13, which also shows the extrapolation of the hazard curves to an annual exceedance frequency of 1×10^{-7} . The extrapolated curves were used in this analysis.

TABLE 4-6
ANNUAL MEAN NUMBER OF EVENTS EXCEEDING PEAK ACCELERATIONS

Peak Acceleration (g)	Site 1	Site N
0.05	1.51×10^{-3}	1.45×10^{-3}
0.10	5.76×10^{-4}	5.68×10^{-4}
0.15	2.94×10^{-4}	2.77×10^{-4}
0.20	1.71×10^{-4}	1.49×10^{-4}
0.25	1.07×10^{-4}	8.47×10^{-5}
0.30	7.02×10^{-5}	4.96×10^{-5}
0.35	4.74×10^{-5}	2.98×10^{-5}
0.40	3.27×10^{-5}	1.81×10^{-5}
0.50	1.62×10^{-5}	6.92×10^{-6}
0.60	8.29×10^{-6}	2.71×10^{-6}
0.70	4.37×10^{-6}	1.08×10^{-6}
1.00	6.91×10^{-7}	4.95×10^{-8}

Source: Ref. 3.

Fig. 4.12.
Mean seismic hazard curve, Site 1.

Fig. 4.13.
Seismic hazard curves, Site 1, used in analysis.

To develop point estimates of scenario frequencies, it is necessary to divide the mean frequency curve into a number of incremental ranges of acceleration. Five ranges were judged to be ample to reflect the curve shape. Table 4-7 presents the mean frequency for the increments of acceleration ranges. These ranges are each given a designated acceleration for ease of reference, which was used in the analysis along with the mean frequency within the range. The lower-bound acceleration is discussed in Sec. 4.5.10.2. The upper bound is limited by the mean frequency of $1 \times 10^{-7}/\text{yr}$ because values lower than this are of little interest in the tank farm risk assessment.

4.5.10.2. Fragility Analysis. A fragility analysis of Tank 101-SY and of associated facilities is included as App. B to this report. A summary of that analysis and the results are presented here.

Fragility Curve Formulation

Seismic-induced failure data are generally unavailable for specific plant components or structures. Thus, the peak ground acceleration at which the component is expected to fail must be determined primarily from analysis and engineering judgment supported by limited test data. See App. C for a detailed description of the fragility curve formulation.

Structure and Equipment Fragilities

The approach used to analyze fragilities relied on existing reports, drawings, photographs taken by others in the field, and seismic capacity calculations performed by others. The following components were evaluated:

TABLE 4-7
MEAN ANNUAL FREQUENCIES OF ACCELERATION RANGES

Acceleration Range (g)				
0.10–0.20	0.20–0.30	0.30–0.50	0.50–0.70	0.70–1.0
Designated Acceleration				
0.15	0.25	0.40	0.60	0.85
4.05×10^{-4}	1.01×10^{-4}	5.40×10^{-5}	1.18×10^{-5}	3.68×10^{-6}

- primary tank,
- secondary tank,
- exhaust ductwork,
- exhaust fan,
- electrical panels,
- instrument and control panels,
- offsite power, and
- piping.

Possible failure modes were evaluated for each of the components, recognizing that for a single component, alternative failure modes are not independent; that is, one failure mode will likely influence other failure modes of that component. Therefore, the capacity of a component was determined to be that of the most likely failure mode that would result in the same type of release as other modes.

A review of the mean seismic hazard curve in Fig. 4.13 indicates that the annual frequency of a 1.0-g peak ground acceleration is less than 1×10^{-6} . This is too low of a frequency to be of interest in this risk assessment because of the much higher release frequency from nonseismic events. Therefore, where it could be shown that the median capacity of a component is greater than 1.0 g, no further analysis was conducted.

The results of the fragility analysis is presented in Table 4-8. Besides the values of $\hat{\alpha}$, β_R , and β_U that define the fragility family for each component (as defined in App. C), the high-confidence, low-probability-of-failure (HCLPF) value is also shown. The HCLPF is the value at which there is a 95% probability that there is no greater than a 5% chance of failure, or essentially less than a 1% chance of failure. By scanning the components for the lowest HCLPF value, we determine that there is no need to include failure contributions below 0.10 g because none of the components would fail below that value. Thus, 0.10 g was established in Table 4-7 as the lower-bound acceleration of interest.

4.5.10.3. Logic Analysis. It can be seen from the fragility analysis that only offsite power, electrical panels, instrument racks, and the primary tank can fail within the possible acceleration levels. On this basis, we can construct a simple event tree (Fig. 4.14) to reflect these potential seismic failures. Components can be unavailable owing to seismic failures, as well as from nonseismic failures and other nonseismic unavailabilities. The seismic tree is linked to the nonseismic event tree to simultaneously evaluate the combination of seismic and nonseismic events.

TABLE 4-8
COMPONENT FRAGILITIES

Component	$\hat{a}$ (g)	β_R	β_U	HCLPF (g)	Failure Mode
1. Offsite Power	0.30	0.25	0.50	0.10	Substation Transformer Insulators
2. Electrical Panel	0.50	0.25	0.34	0.19	Component Function
3. Instrument/Control Panels	0.80	0.25	0.17	0.40	Instrument Function
4. Primary Tank	0.94	0.27	0.36	0.33	Shear Buckling and Cracking at Knuckle (dome collapse > 1.0 g)
5. Exhaust Ducts	> 1.0				
6. Exhaust Fan	> 1.0				
7. Above-Ground Piping	> 1.0				
8. Secondary Tank	> 1.0				

Source: EQE Analysis; App. B.

Earthquake Frequency	Primary Tank Failure	Loss Offsite Power	Electric Panel Failure	Instrument/Control Panel Failure	Seq. #	Frequency Per Year	Release Category
IE(g)					1	Depends	Feeds to
(Table 4-7)				SIP(n)	2	upon	BURP
			SEP(n)	(Table 4-5)	3	earthquake	event
			(Table 4-5)	SIP(n)	4	severity	tree
		SOP(n)	G/F	G/F	5		(Fig. 4.6)
	SPT(n)	(Table 4-5)			6		
	(Table 4-5)			SIP(n)	7		
			SEP(n)		8		
				SIP(n)	9		
		SOP(n)	G/F	G/F	10		

LEGEND:

G/F = Guaranteed Failure

Fig. 4.14.
Seismic event tree.

After linking the trees, a point estimate of the frequency is performed for each designated acceleration. The mean fragility of each component at the designated acceleration represents the top event probability in the seismic tree. The frequencies of like scenarios from each designated acceleration run are added to determine the total seismic frequency over all accelerations. In contrast, the probability of failure for each top event in the nonseismic tree is the same as was used in the nonseismic analysis. This value is constant for all initiating event frequencies; i.e., designated acceleration level frequencies.

This analysis assumes that a bound flammable gas release (burp) will occur in the tank following a seismic event. Therefore, the internal event tree used to evaluate the effects from a burp initiating event is linked to the seismic event tree for the quantification of seismic events. The burp event tree, presented in Fig. 4.6, reflects all the events that could follow the potential seismic failures. Some seismic failures will directly cause events in the nonseismic event tree to be unavailable. Therefore, it was necessary to prepare a dependency table (Table 4-9) that correlates these failures as rules for inclusion in the quantification process.

4.5.10.4. Preliminary Quantification and Results. The five designated accelerations and their mean frequencies are given in Table 4-7. The failure fractions, or conditional failure probabilities, for the seismic failures at each of these designated

TABLE 4-9
DEPENDENCY MATRIX

Seismic Failure	Nonseismic Top Event (Burp Event Tree)							
	H2HI ^a	VOP	TBRN	VBRN	PROP	DOME	PSI SSI	LI
Primary Tank							X	
Offsite Power		X						X
Electrical Panel		X						X
Instrument/Control Panels		X						X

^aHydrogen concentration in the dome space is assumed to be greater than 4% following seismic-initiated bound gas release events.

accelerations were calculated from Eq. (C.2.6) (App. C) and are summarized in Table 4-10. Using RISKMAN,⁶ the linked event trees were quantified to determine scenario frequencies. Release category frequencies are given in Table 4-11. The total frequency for all seismic-initiated releases is 5.7×10^{-4} , which is substantially lower than for the nonseismic-initiating events. Even comparing individual release category frequencies with those from nonseismic-initiating events, it is apparent that seismic-initiated events are not significant.

TABLE 4-10
CONDITIONAL SEISMIC FAILURE PROBABILITIES

Component	Designated Acceleration (g)				
	0.15	0.25	0.40	0.60	0.85
SOP—Offsite Power	1.08×10^{-1}	3.72×10^{-1}	6.97×10^{-1}	8.92×10^{-1}	9.69×10^{-1}
SEP—Electrical Panel	0.00	5.03×10^{-2}	2.98×10^{-1}	6.67×10^{-1}	8.96×10^{-1}
SIP—Instrument/ Control Panels	0.00	0.00	0.00	1.71×10^{-1}	5.79×10^{-1}
SPT—Primary Tank	0.00	0.00	2.88×10^{-2}	1.59×10^{-1}	4.12×10^{-1}

TABLE 4-11
RELEASE FREQUENCIES

	Seismic-Initiated Events		Internal Events
Release Category	Dominant Scenarios	Annual Mean Frequency ^a	Annual Mean Frequency
TG	(no failures)	5.7×10^{-4}	3.5
HEPAL	VBRN1	2.6×10^{-6}	1.2×10^{-1}
HEPAH	SOP I VBRN1 I PROP2	1.7×10^{-6}	5.1×10^{-3}
DCH	SOP I VBRN1 I PROP2 I COLAP2	2.3×10^{-7}	7.0×10^{-4}
LLK	—	1.2×10^{-9}	4.5×10^{-4}
DCLLK	—	1.5×10^{-10}	2.4×10^{-8}

^aFrequency is the total for the release category.

As shown in Table 4-11, the dominant seismic-initiated release category is TG, a toxic release. This category accounts for essentially all of the seismic-initiated release and is dominated by the scenario in which an earthquake occurs and causes a toxic gas burp in the tank that is released through the stack. Thus, the dominant seismic contributions to release involve only the earthquake and no seismic-caused failures.

The dominant scenario contributing to an aerosol release, release category HEPAL, is a seismic event causing a toxic gas burp in the tank, release of the gas to the ventilation duct, and explosion in the duct, resulting in a release containing a nominal amount of radioactivity.

At about two-thirds the frequency of release category HEPAL, an enhanced aerosol release, HEPAH, is caused by an earthquake-induced failure of offsite power causing stoppage of the ventilation system blower. This results in a flammable gas buildup and explosion in the ventilation system, which propagates back to the tank, thereby causing failure of the HEPA filter from the pressure pulse and release of toxic gas that contains some radioactivity through the stack or through the failed exhaust duct.

At a significantly lower frequency than the foregoing releases, but with more severe consequences, a catastrophic release, category DCH, is caused by an earthquake and burp of toxic gases in the tank, seismic failure of offsite power followed by an explosion in the ventilation system propagating to the primary tank, collapse of the secondary tank dome, and a major release of the tank contents into the atmosphere and onto the ground.

4.5.11. Aircraft Crash. The analysis of the frequency of an aircraft crash causing the dome of Tank 101-SY to collapse and a discussion of the consequences of such an event are presented in App. C, Sec. 6.1.2. The results and conclusions of the analysis presented in App. C are summarized in this section.

The issue of whether the dome of a Hanford waste tank would collapse given the impact of a large aircraft crash is addressed in Ref. 7. The characteristics of the aircraft used in this study (i.e., a Boeing 707-320 weighing 200,000 lb) were similar to the characteristics of the commercial aircraft operated in the vicinity of the tank farm site; therefore, the results were assumed to be applicable to the analysis of Tank 101-SY. The study found that for brittle response of the tank, both the engine and the fuselage of the postulated aircraft would perforate the tank structure. For ductile response, it was concluded that the aircraft impact would cause the tank structure to collapse completely. The referenced study gave no information on the

potential damage owing to the impact of a smaller aircraft on the tank. Therefore, a gross aircraft weight of 75,000 lb was assumed as the threshold for dome collapse given an aircraft crash.

The frequency of a large aircraft (75,000 lb or greater) crashing into Tank 101-SY is quantified in App. C, Sec. 6.1.2. A mean value of 3.08×10^{-9} crashes per tank-year was calculated. The parameters of the distribution for crash frequency per tank-year are presented in Table 4-12 along with those for the other initiating events.

In addition to failing the tank, a subsequent fire involving jet fuel and waste material is considered likely. Such a fire could cause waste material to be dispersed over a wide area, producing a release more severe than any release category defined for internal accident sequences. Therefore, the frequency of the aircraft crash initiating event is mapped directly to a unique release category designated as DCVH.

4.6. Accident Sequence Quantification

The quantification of accident sequence frequencies involves the combination of the conditional probabilities of equipment operation or failure operator actions in response to initiating events, and phenomenological events with the frequency of those initiating events. The sequences of failures that are of the most interest here are those that result in radionuclide or toxic gas release, although the quantification process treats all sequences, including those resulting in successful event mitigation. This process requires the assembly of many distinct parts of the PSA model and can be divided into two major tasks: sequence assembly and sequence quantification.

Sequence assembly requires the linking of initiating events that have been identified for analysis with the appropriate event trees that model the subsequent hardware, human, and phenomenological questions that are needed to respond to the initiating event. An important aspect of sequence quantification is the calculation and assignment of split fraction value to each branch in each event tree. The value of a split fraction is the conditional probability of failure of a given event-tree top event. It can be dependent on the status of top events in previous trees, the specific initiating event, and on the success or failure of the previous top events of the same tree. In other words, each specific split fraction value represents the frequency of failure of the event-tree top event based on preceding scenario conditions. The annual frequency of each sequence through the tree is quantified by multiplying the initiating event frequency, expressed in units of expected events per year, by the product of all of the branch probabilities along that sequence path. Both success and

TABLE 4-12
INITIATING EVENTS USED IN THE HTF PSA

INITIATING EVENT		ANNUAL FREQUENCY				SECTION REFERENCE
CODE	DESCRIPTION	MEAN	5%	50%	95%	
SPSB	Small Primary Tank Shell Breach	5.84E-3	1.04E-3	4.28E-3	1.29E-2	D.3.1
LPSB	Large Primary Tank Shell Breach	1.30E-2	6.71E-3	1.17E-2	2.04E-2	D.3.1
DB	Tank Dome Breach	5.00E-4	1.36E-4	3.67E-4	1.03E-3	D.3.2
RVB1	Ventilation Riser or Line Breach	5.90E-2	2.25E-2	5.13E-2	1.01E-1	D.3.3
FB1	Exhaust HEPA Filter Breach	9.75E-2	4.30E-2	8.85E-2	1.55E-1	D.3.4
BURP	Bound Gas Release	3.51E+0	2.64E+0	3.44E+0	4.74E+0	D.3.5
LOTV	Loss of Tank Ventilation	5.66E-1	4.32E-1	5.62E-1	7.16E-1	D.3.6
LOSP	Loss of Tank Farm Electric Power Supply	4.18E-1	2.65E-1	4.06E-1	6.14E-1	D.3.7
WI3	Water Intrusion Event	1.93E-2	1.13E-2	1.81E-2	2.71E-2	D.3.8
WT	Waste Transfer Event	N/A				D.3.9
SEIS1	0.15-g Seismic Event	4.05E-4	Note 1			4.5.10
SEIS2	0.25-g Seismic Event	1.01E-4	Note 1			4.5.10
SEIS3	0.40-g Seismic Event	5.40E-5	Note 1			4.5.10
SEIS4	0.60-g Seismic Event	1.18E-5	Note 1			4.5.10
SEIS5	0.85-g Seismic Event	3.68E-6	Note 1			4.5.10
AC	Aircraft Crash	3.08E-9	3.39E-10	1.83E-9	1.04E-8	4.5.11

N/A: Not applicable to Tank 101-SY.

Note 1: Point estimate mean values were used for the discrete seismic initiating event frequencies.

Note 2: Exponential notation is indicated in abbreviated form; 5.90E-2 = 5.90 × 10⁻².

failure branches are considered. To account for dependencies, the branching probabilities are quantified, dependent on the status of preceding top events in the tree. Therefore, the branching probability for the same top event but along different sequences in the tree may differ. Thus, top events may have more than one split fraction value for the same event tree.

The result of sequence assembly and quantification is a set of scenarios, each one leading to either success or one of various release categories. The frequency of each sequence is known. Together, the sequences include all of the possible combinations of success and failure of the event-tree top events. The individual sequence frequencies are summed by release categories to determine the annual frequency of each release category (and of successful mitigation). The sum total of all the sequence frequencies is equal to the sum total of all the release category frequencies (including success), which is also equal to the sum total of all of the initiating event frequencies. This is true because the event-tree sequences represent a set of exhaustive and mutually exclusive outcomes of the initiating events.

The event-tree computations outlined above must account for a variety of sources of uncertainty that prevent the development of accurate estimates of accident sequence frequencies. These sources of uncertainty include the lack or sparsity of data from which to quantify risk model input parameters (i.e., component failure rates, initiating event frequencies, etc.), variability in the performance of similar equipment, modeling uncertainty, equipment behavior in harsh environments, uncertainty in classification of common-cause event data, and many other sources.

The basic approach to quantifying the effects of uncertainties on the PSA results is to develop probability distributions for each uncertain parameter in the analysis. When the event trees are first quantified and linked together, point estimates (usually the mean values) of the split fractions are used. Because of the large number of sequences that are included in the event-sequence model, the point estimates of sequence frequencies approximate the mean values of the sequence frequencies because mean values of the split fraction, initiating event, and human error rate distributions are used from the preceding steps of the uncertainty propagation.

The uncertainty of the overall risk is expressed in the important sequence model. The important sequence model accepts a prioritized set of the most important sequences from the results of the event-tree analysis for predefined groups of accident sequences. These groups include, for example:

- all release sequences,
- each release category or release category group,
- each initiating event, and
- any other groups of interest.

For each group, the equations for the frequency of each sequence within that group are used in the Monte Carlo sampling step to propagate the split fraction uncertainties and to obtain the uncertainties in the overall results. An uncertainty propagation accomplished in this manner encompasses the major contributor to risk while permitting efficiency in calculation. The PC code RISKMAN⁶ was used to perform the event-tree quantification and uncertainty propagation.

4.6.1. Summary of Quantification Inputs. Table 4-12 lists the initiating events used in the accident sequence model for Tank 101-SY. Also shown are the key parameters of their frequency distributions and references to the report sections that describe their development. Table 4-5 lists the event-tree top event split fraction values used in the accident sequence model for Tank 101-SY. Also shown are the key parameters of their frequency distributions and references to the report sections that describe their development. Descriptions of the source terms for the release categories into which the event-tree sequences are binned are given in Sec. 5.2. The calculation of conditional health effect consequences for each of the important release categories is presented in Chap. 6.

4.6.2. Accident Sequence Results. This section presents the results of the accident sequence quantification process described above. The top level quantification results are the frequencies of each release category. The release category results are then decomposed to reveal the important contributing initiators and top events.

Table 4-13 presents the mean annual frequency for each release category defined for the HTF PSA. The release categories are listed in descending order by frequency. Some release categories contained no sequences for the Tank 101-SY model and thus exhibit a frequency of zero.

The contributions of each initiating event to each non-zero release category are presented in matrix form in Table 4-14. The dominance of bound flammable gas releases (burps) across all release categories is evident, but this is not surprising since it involves more than 3 initiating events per year.

The contribution of selected important sequences to each release category is also displayed in Table 4-15. This table clearly shows the dominance of the "burp and burn" sequence to the results for Tank 101-SY.

TABLE 4-13
HTF RELEASE CATEGORY FREQUENCIES

RELEASE CATEGORY	PRINCIPAL SEQUENCES	FREQUENCY PER YEAR			
		Mean	5th Percentile	50th Percentile	95th Percentile
TG	Burp, no burn	3.49E+0	2.18E+0	3.29E+0	4.88E+0
HEPAL	Burp, burn in vent line, and no propagation to tank or HEPA filter breach	1.16E-01	5.89E-02	1.09E-01	1.79E-01
BPL	Vent line breach	6.06E-02	2.44E-02	5.27E-02	1.04E-01
HEPAH	Burp, burn in tank, or burn in vent line and propagation to tank, with no tank failure, but HEPA break	5.07E-03	0.00E+0	3.94E-03	1.01E-02
DCH	Burp, burn in tank, or burn in vent line and propagation to tank, with dome collapse	6.98E-04	0.00E+0	0.0	4.36E-03
LLK	Large primary tank leak with secondary tank failure	4.46E-04	1.22E-04	3.78E-04	1.10E-03
SLK	Small primary tank leak with secondary tank failure	2.00E-04	3.02E-05	1.33E-04	4.70E-04
SSP	Water intrusion and tank overflow	4.35E-05	1.70E-05	3.28E-05	8.62E-05
DCLLK	Seismic event or burp-burn with dome collapse and large primary leak and secondary tank failure	2.41E-08	0.00E+0	0.0	1.65E-07
DCVH	Aircraft crash with tank collapse and fire	3.08E-09	3.39E-10	1.83E-09	1.04E-08
LSP	Transfer spill (N/A for Tank 101-SY)	0.00E+0			
DCSLK	(None)	0.00E+0			

TABLE 4-14
HTF RELEASE CATEGORY FREQUENCIES BY INITIATING EVENT

Release Category Code	INITIATING EVENTS AND FREQUENCIES													
	H ₂ Gas Release Event	HEPA Filter Failure	Vent Line Breach	Tank Dome Breach	0.15-g Seismic Event	Water Intrusion Event	0.25-g Seismic Event	Large Primary Tank Shell Breach	0.4-g Seismic Event	Small Primary Tank Shell Breach	0.6-g Seismic Event	0.85-g Seismic Event	Aircraft Crash	Release Category Totals
	BURP 3.51E+0	FB1 9.75E-2	RVB1 5.90E-2	DB 5.00E-4	SEIS1 4.05E-4	WI3 1.93E-2	SEIS2 1.01E-4	LPSB 1.30E-2	SEIS3 5.40E-5	SPSB 5.84E-3	SEIS4 1.18E-5	SEIS5 3.68E-6	AC 3.08E-9	
TG	3.49E+0				4.02E-4		1.00E-4		5.36E-5		1.17E-5	3.65E-6		3.49E+0
HEPAL	1.87E-2	9.75E-2			2.17E-6		3.62E-7		6.91E-8		2.12E-9	3.00E-11		1.16E-1
BPL			5.90E-2	5.00E-4				7.41E-4		3.33E-4				6.06E-2
DCH	6.98E-4				1.23E-7		5.24E-8		4.30E-8		1.09E-8	3.45E-9		6.98E-4
HEPAH	5.07E-3				8.92E-7		3.80E-7		3.13E-7		7.93E-8	2.51E-8		5.07E-3
LLK	1.74E-7				3.00E-11		1.12E-11	4.46E-4	3.17E-10		4.35E-10	3.59E-10		4.46E-4
SSP						4.35E-5					.			4.35E-5
SLK										2.00E-4				2.00E-4
DCVH													3.08E-9	3.08E-9
DCLLK	2.39E-8				3.09E-12		1.03E-12		4.20E-11		5.84E-11	4.91E-11		2.41E-8
IE Totals	3.51E+0	9.75E-2	5.90E-2	5.00E-4	4.05E-4	4.35E-5	1.01E-4	1.19E-3	5.40E-5	5.33E-4	1.18E-5	3.68E-6	3.08E-9	3.66E+0
Success						1.93E-2		1.18E-2		5.31E-3				
Percentage	95.7	2.66	1.60	—	—	—	—	—	—	—	—	—	—	100

Note: Exponential notation abbreviated; 5.90E-2 = 5.90 × 10⁻².

TABLE 4-15
ACCIDENT SEQUENCE CONTRIBUTORS TO RELEASE CATEGORY RESULTS

PERCENT CONTRIBUTION TO RELEASE CATEGORY TOTAL										
Accident Sequence Description	TG	HEPAL	BPL	DCH	HEPAH	LLK	SSP	SLK	DCVH	DCLLK
Burp, no failures	100									
Burp, H ₂ ignition in vent line		16		31	31					31
Burp, H ₂ ignition in tank				69	69					69
HEPA filter breach		84								
Ventilation line breach			100							
Large primary tank leak, secondary tank fails						100				
Small primary tank leak, secondary tank fails								100		
Overflow from water intrusion, operator fails to prevent overflow							56			
Level indication failed, overflow from water intrusion, operator fails to prevent overflow							44			
Aircraft crash, dome collapses									100	

The release category frequency results were also examined to identify the important event-tree top event contributors. To do this, the importance of each top event to the release category frequency was calculated. Top event importance is defined as the ratio of the release category frequency involving failure of the top event to the total initial release category frequency. The resulting fraction is then multiplied by 100 so that the importance can be reported in percent. Table 4-16 displays the importances of key top events for each release category. Please note that importances are not additive; therefore, they may total to more than 100%.

REFERENCES

1. T. B. Powers et al., "Tank Farm Risk Assessment Plant Familiarization and Hazard Identification Report," Westinghouse Hanford Company report EDT 115133 (May 31, 1991).
2. T. B. Powers and S. D. Morales, "SY Tank Farm Ventilation Option Risk Assessment Report," Westinghouse Hanford Company draft report (June 1992).
3. Woodward-Clyde Consultants, "Evaluation of Seismic Hazard for Non-Reactor Facilities, Hanford Reservation," Richland, Washington (July 1989).
4. Sandia National Laboratories, "Analysis of Core Damage Frequency due to External Events at the DOE N-Reactor," SAND89-1147, UC-610 (November 1990).
5. Telephone Communication, A. M. Tallman, Westinghouse Hanford Company, and H. F. Perla, PLG, Inc. (May 29, 1992).
6. PLG, Inc., *RISKMAN-PRA Workstation Software*, User Manuals I-IV, Version 3.0 (1992).
7. D. A. Smith, "Aircraft Impact on the Hanford Waste Vitrification Plant," Westinghouse Hanford Company report WHC-SD-HWV-RA-001 (April 1990).
8. Bott, T. A., "Ignition Probability of Hydrogen in Tank 101-SY Vent Header," Los Alamos National Laboratory document LA-UR-94-1313 (April 1994).

TABLE 4-16
TOP EVENT IMPORTANCE BY RELEASE CATEGORY GROUP

	TOP EVENT IMPORTANCE (%)									
Top Event Description	TG	HEPAL	BPL	DCH	HEPAH	LLK	SSP	SLK	DCVH	DCLLK
Dome Collapse				100						100
H ₂ Concentration > 4%	87	16		100	100					100
H ₂ Ignition in Vent System		16		31	31					31
Burn Propagation from Vent to Tank				31	31					31
H ₂ Ignition in Tank				69	69					69
Ventilation Running				2	2					2
Secondary Tank Integrity						100		100		100
Annulus Ventilation Integrity			2							
Operator Prevents Overflow							56			
Level Indication Operable							44			

5.0. SOURCE-TERM ANALYSES

5.1. Overview

The principal determinants of consequences are source terms and dispersion characteristics for airborne aerosol releases and liquid releases to the soil column. There is a basic difficulty in trying to combine the risks of population health consequences via these two pathways. Airborne releases typically involve transport times to receptors and exposure times of minutes to hours. The population at risk and the exposure doses for various accident scenarios can be determined reasonably accurately, based on dispersion modeling and current census data. In contrast, the releases of liquids to the soil column may involve transport delay times to receptors and exposure times of hundreds or thousands of years. This introduces an enormous uncertainty in quantifying possible future health effects based on current population distributions and lifestyles. Furthermore, there is considerably more difficulty with the accuracy of the vadose zone and groundwater transport modeling that is an essential element in such population dose predictions. Also, philosophical questions arise about the significance of health effects thousands of years in the future vs the priorities and concerns of today.

For all of these reasons, the approach used in this work is to report the long-term doses and risks from the ground transport pathways separate from the immediate doses and risks from the airborne transport pathway. Thus, in those scenarios that involve both an airborne aerosol release and a liquid release to the soil column, two source-term numbers are reported.

5.2. Release Category Definitions

The release categories are derived from the accident sequence modeling presented in Chap. 4. Detailed descriptions of the representative scenarios for the release categories are presented in Sec. 4.5 and summarized in Table 4-4. A given release category may include either or both airborne and liquid pathway source terms. Descriptions of the tank configuration, the tank ventilation system, and support systems are presented in Chap. 3.

Each of the potential accident sequences defined by the models presented earlier in this report could result in a unique release of radioactive and/or toxic materials to the environment. The amount of radioactive or toxic material released is referred to as the "source term" and is used as an input for assessing the potential human health consequences of the release. Because source-term analyses and

consequence calculations are costly to perform, it is desirable to group sequences with similar release characteristics together for source-term and consequence analysis. The purpose of this section is to identify those factors that can potentially influence the magnitude and timing of radionuclide or toxic gas releases and to define appropriate release categories for accident sequence grouping.

5.2.1. Release Pathways. Figure 5.1 graphically portrays the primary pathways for the release of radionuclides or toxic gases from the storage tanks. Radioactive releases can exit the waste tanks directly to the atmosphere in the form of aerosols, seep to the ground as liquids, or both. Toxic gases would disperse directly into the atmosphere. The distinction of an airborne or liquid pathway is especially important because airborne releases could reach onsite or offsite populations in a matter of minutes vs many years for subterranean liquid releases.

Atmospheric releases are indicated in the HTF PSA accident sequence model by any failure of the tank dome, risers, ventilation lines, or the HEPA filter in the ventilation line. Liquid releases can result from failures of the tank primary and secondary shells or overflows. The factors below have been identified as potentially important in determining the magnitude and timing of radionuclide and/or toxic gas releases from the HTF tanks.

It is obvious that the use of all possible combinations of the factors discussed above would produce an unmanageably large number of release categories. By identifying likely correlations between the factors and grouping less severe categories with more severe ones, the combinations of factors can be reduced to a manageable level for use as release categories. All significant release categories are identified by the release pathway and magnitude of the radionuclide release. Table 4-7 presents the frequencies of release categories defined using these key factors.

5.2.2. HEPA Filter Integrity. The ventilation system deentrainer and HEPA exhaust filters are assumed to contain an inventory of radioactive material, which would be released if the filter media failed. The integrity of the HEPA filters is monitored directly by a top event in the accident sequence model.

5.2.3. Radionuclide Content of Aerosol Released. Under normal conditions, the radionuclide content of the atmosphere in the tank dome space is very low. If disturbed by an energetic event, however, the concentration of radionuclides in the gases available for release could be greatly increased. Enhancement of the radionuclide content of the dome space atmosphere would be expected following a hydrogen burn event, a criticality, or a sustained fire in the waste material. Sequences

Fig. 5.1
Hanford Tank Farm source term and consequence model structure.

involving sustained fires in the waste material could also provide significant energy for release plume rise and increased dispersion of releases in the atmosphere.

5.2.4. Toxic Gas Content of Released Gases. Because HEPA filters are not effective in trapping gases such as ammonia, the presence of toxic gases in concentrations above levels of concern is assumed to result in a toxic gas release. For Tank 101-SY, the normal ventilation exhaust is not toxic. However, toxic gas concentrations could be increased from normal levels in a manner similar to that described for radionuclides.

5.2.5. Elevation of Release. The dispersion of atmospheric releases of radionuclides and toxic gases would be influenced by the elevation at which the release occurs into the atmosphere. The intake and exhaust stacks (5 m) are the release elevation for sequences where the ventilation system is intact. All other sequences are assumed to be ground level releases. Dispersion calculations show that, because of the short stack height, the elevation of release is potentially important within a range of only about 0.5 km of the release point. However, for fire scenarios where there is a significant plume rise, there is a major affect on the down wind dispersion.

5.2.6. Radionuclide Content of Liquids Released. The significance of liquid releases will be proportional to the volume of waste released and the radionuclide concentration of the liquid released. Estimates of the drainable liquid and radionuclide content of each tank are available. Small leaks are defined as less than 5000 gal. and can occur from any tank. Large leaks (greater than 5000 gal.) can only occur from nonstabilized tanks.

5.3. Waste Characterization

The radiological source-term composition, derived from the WHC analysis of the Tank 101-SY composition is summarized in Table 5-1. The airborne source terms consist primarily of materials picked up and entrained in the gas flow across the crust surface.

Because one of the impacts to be quantified in this PSA was the cost for clean-up of decontamination after an accident, it was necessary to have some data on the particle size distribution in the airborne source term. When estimating inhalation doses it is conservative to consider all the material released to be in the respirable size range. However, when estimating surface contamination from particle settling (fallout), this approach will give a gross under estimate of the cleanup required since

TABLE 5-1
RADIONUCLIDE SOURCE TERMS^{1,2}

Radionuclide	Ci/kg Convecting (Liquid)	Ci/kg Crust (Airborne)
C 14	7.0E-5	—
Sr 90	3.0E-3	3.4E-2
Tc 99	1.3E-4	3.0E-4
I 129	6.0E-7	2.9E-4
Cs 137	4.5E-1	4.5E-1
Np 237	7.0E-8	5.1E-4
Pu 239	1.1E-7	1.6E-5
Pu 240	—	1.0E-9
Am 241	5.0E-7	1.5E-4

Note: 3.0E-3 = 3.0×10^{-3} .

it is primarily the larger particles (above respirable sizes) that contribute to surface contamination. The data presented in Fig. 5.1a, were from the Window C¹ and Window E² sample analyses. For the dispersion calculations presented in Chap. 6, the particles were binned as follows:

Physical Dia. (μm)	AMAD (μm)	Mass Fraction
3	5	0.52
10	16	0.15
30	47	0.07
60	95	0.15
133	210	0.11

5.4. Airborne Source Terms

This section presents a discussion of the source terms developed for each of the airborne release categories. They are presented as mean, low (10th percentile), and high (90th percentile) values to reflect the uncertainties involved in the deterministic estimates. The results of the source-term estimates for the various release categories are summarized in Table 5-2. The release terms for the individual isotopes are obtained by multiplying the appropriate concentrations in Table 5-1 by the estimated releases in Table 5-2.

Average Distribution (Samples 5C+3E)

Fig. 5.1a.
Particle size distribution for dispersion source term.

TABLE 5-2
RADIOLOGICAL SOURCE-TERM SUMMARY

Release Category	Low Release (kg) (10th Percentile)	Mean Release (kg)	High Release (kg) (90th Percentile)
BPL	3.4E-4	7.0E-4	2.1E-3
HEPAL	0.8	1.8	2.8
HEPAH	4.1	6.9	10.2
DCH	14.7	32.8	55.2
DCVH	57 (Cs Enhanced)	113 (Cs Enhanced)	283(Cs Enhanced)
SLK	5680	17,100	28,400
LLK	28,400	681,600	1,363,200
SSP ^a	570/5.7E-3	1700/1.7E-2	2840/2.8E-2
DCLLK	—	DCH + SLK	—
DCLLK	—	DCVH + LLK	—

^aFor this category there is an airborne contribution due to entrainment of aerosol resulting from the surface spill. It is the second number listed in each column.

5.4.1. Nonburn Sequences—Filter Bypassed (BPL). The BPL release category represents scenarios where the ventilation system operates, but the HEPA filters and deentrainer are bypassed because of a failure in the ventilation system containment envelope. As described in Chap. 3, the primary ventilation system removes vapors from the tank head space and maintains a slightly negative internal tank pressure so that all air leaks under normal operations are into the tank. The primary exhaust system in the SY Tank Farm consists of a moisture separator (deentrainer), a heater to prevent condensation on the filters, a bank of two HEPA filters, and an induced draft fan. The source-term evaluation for this release category is summarized in Fig. 5.2. The key issues for this release category are: (1) the time to detect and fix the HEPA filter/deentrainer leak, and (2) the amount of radionuclides released during this period. The rate of radionuclide release is estimated conservatively assuming nominal ventilation flow, even though ventilation may fail for certain BPL sequences.

According to published data for 1990, the measured annual radioactivity release from the 241-SY Tank Farm is $3.6\text{E-}7$ Ci of gross beta activity.³ Assuming this release is primarily ^{90}Sr (0.034 Ci/kg of crust material), and assuming the other dose-contributing isotopes are present in the same ratios as the tank wastes, this translates to an annual release through the HEPA filters (and deentrainer) of $1.06\text{E-}5$ kg of the crust material containing isotopic concentrations listed in the third column of Table 5-1.

The Tank 101-SY nominal ventilation flow rate is $14.2\text{ m}^3/\text{min}$ (500 cfm) through the deentrainer and the HEPA filter. Both of these devices remove radionuclides from the stream, depending on their operating efficiencies. The HEPA filters are assumed to have a combined mean efficiency of 99.99% (with a range from 99.95 to 99.995%; see Fig. 5.2). Reference 4 lists an individual HEPA filter efficiency of 99.99% for 0.3-micron particles. The as-installed efficiency of the combined HEPA filter package is expected to be no less than 99.95% for 0.5-micron particles. The deentrainer is assumed to have a mean efficiency of 90% (with a range from 85 to 95%). It is assumed that the mean time to detect the leak is 8 h (corresponding to one 8-h shift). However, it is possible that the leak could be detected earlier (within a few hours) or later (after 1/2 day). Thus, the distribution shown in Fig. 5.2 was selected to represent the release duration (or time to detect and fix a leak).

Based on the annual release rates, HEPA filter and deentrainer efficiencies, and the release duration, the amount of radionuclides (aerosols) released can be

Fig. 5-2.
Source term summary for release category BPL.

evaluated by a Monte Carlo simulation. The results of the simulation are shown in Fig. 5.2. The salient point values of the resulting distribution are:

10%	3.4E-4 kg
mean	7.0E-4 kg
90%	2.1E-3 kg

5.4.2. Nonburn Sequences—Filter Breached (HEPAL). The HEPAL release category represents those scenarios where the HEPA filters and deentrainer are breached as a result of a system malfunction, such as excessive moisture loading, external events, etc. The radiological source term arising from this scenario is due to the release of the material entrapped in the deentrainer and HEPA filters. The source-term evaluation for this release category is summarized in Fig. 5.3. The key issues in this source-term evaluation relate to estimation of the material entrapped in the deentrainer and HEPA filters and the fraction of this amount released during the scenario. It is estimated that the amount of material entrapped here could be as high as 11 kg (a very conservative estimate, Ref. 5, p. 4-14, and Ref. 6). Depending on when the HEPA filters and the deentrainers have been cleaned or replaced, the amount entrapped could be as low as a few kilograms. Therefore, a distribution depicted in Fig. 5.3 was assumed for the amount entrapped in the deentrainer and the HEPA filters. This distribution has a mean of 6 kg. It is further assumed that under this scenario (nonburn event) about 30% (mean) of this material would be released to the environment. Acknowledging that this could range from 0 to 60%, a distribution shown in Fig. 5.3 was selected.

Based on the amount of material entrapped and the fraction released, the source term can be evaluated. Figure 5.3 depicts the resultant distribution for the amount released for HEPAL scenario with a mean release of 1.8 kg. The salient point values for this distribution are:

10%	0.8 kg
mean	1.8 kg
90%	2.9 kg

5.4.3. Burp/Burn Sequences—Filter Breached (HEPAH). The HEPAH release category represents those scenarios where the HEPA filter and deentrainer are breached because of the overpressure resulting from a burp/burn sequence.

Fig. 5-3.
Source term summary for release category HEPAL.

The details of the deentrainer and HEPA filter are the same as those described in Sec. 5.3.2. The source-term evaluation for this release category is summarized in Fig. 5.4.

The key issues in this source-term evaluation are: (1) estimation of the material entrapped in the deentrainer and HEPA filters; (2) the fraction of this entrapped amount released during the scenario; (3) the amount of crusted material that is seared due to the burp/burn; and (4) the fraction of this seared amount that is released. As noted in Sec. 5.4.2, it is estimated that the amount of material entrapped could be as high as 11 kg (a very conservative estimate, Ref. 5, p. 4-14, and Ref. 6). Depending on when the HEPA filters and deentrainers have been cleaned or replaced, the amount entrapped could be much lower. Therefore, a distribution depicted in Fig. 5.4 was assumed for estimating the amount entrapped in the deentrainer and HEPA filters. This distribution is the same as the one used in Sec. 5.3.2 and has a mean of 6 kg. For this scenario (burp/burn event) it is assumed that about 70% (mean) of the entrapped material would be released to the environment. This is higher than the HEPAL scenario because the HEPAH scenario with a burp/burp event is likely to be more energetic. Assuming that the release could range from 40 to 100%, the distribution shown in Fig. 5.4 was selected.

The amount of material seared/crusted was obtained from App. E. The distribution shown in Fig. 5.4 has a mean of about 13.4 kg and depicts the amount seared during a realistic burp/burn (short burn with temperature decay). Due to convection currents generated by fire, some fraction of this seared material could be released to the atmosphere. It is estimated that about 20% of this seared material may be released (mean 20%, with a range from 5 to 50%) in such a fashion. Based on the amount of material entrapped in the HEPA filter/deentrainer and the amount of material seared along with the individual release fractions, the source term can be evaluated for the HEPAH scenario. Figure 5.4 depicts the resultant distribution for the amount released for the HEPAH scenario with a mean release of 6.9 kg. The salient point values for this distribution are:

10%	4.1 kg
mean	6.9 kg
90%	10.2 kg

5.4.4. Burp/Burn Sequences—Catastrophic Dome Collapse (DCH). The DCH release category represents those scenarios where a catastrophic tank failure,

Release category HEPAH represents those scenarios where HEPA filters and deentrainer are breached because of overpressure resulting from a burp burn sequence.

The key issues are :- 1) Amount of material entrained in the HEPA filters/ Dentrainer (and fraction of this amount released) 2) Amount of material seared due to burp burn (and fraction of this amount released).

Parameter	Units	Value	Comment
Amount stored in Deentrainer and HEPA filters	Kg of crust material	6.03	Reference 3
Stored Fraction released to atmosphere	None	0.70	Assumption
Amount Released during BURP burn	Kg of crust material	13.35	From Appendix E for a realistic burn with temperature decay
Burnt Fraction released to atmosphere	None	0.20	Assumption
Amount released for HEPAH scenario	Kg of crust material	6.90	Result / Calculation

Fig. 5-4.
Source term summary for release category HEPAH.

resulting in collapse of the dome, leaves the tank open to the environment. Tank failure could occur if the burp/burn pressure loads are significant. Dome collapse leaves the tank vulnerable to winds and gusts, which may entrain some material and provide a direct release path. The source-term evaluation for this release category is summarized in Fig. 5.5.

The key issues in this source-term evaluation are: (1) estimation of the material entrapped in the deentrainer and HEPA filters and the fraction of this amount released during the scenario, (2) amount of seared crusted material owing to the burp/burn and the fraction of this amount released, and (3) amount of material entrained and removed by winds or gusts. The distribution depicted in Fig. 5.4 was assumed for representing the amount entrapped in the deentrainer and the HEPA filters. This distribution is the same as that used in Secs. 5.3.2 and 5.3.3 and has a mean of 6 kg. It is further assumed that under this scenario (burp/burn event), about 90% (mean) of this entrapped material would be released to the environment. This release fraction is higher than that for the HEPAH scenario because the DCH scenario with a burp/burp event leading to a dome collapse is likely to be much more energetic. It was assumed that the release fraction could range from 80 to 100%; thus, the distribution shown in Fig. 5.5 was selected.

The amount of material seared was estimated, as shown in App. E. The distribution shown in Fig. 5.5 has a mean of about 13.4 kg and depicts the amount seared during a realistic burp/burn (a short burn with temperature decay). This distribution is same as the one selected for the HEPAH scenario in Sec. 5.3.3. Some fraction of this crusted material is prone to be carried upward owing to convection currents and thus will be released to the atmosphere. Because the burp/burn event is much more energetic, it is estimated that about 80% (as opposed to only 20% for the HEPAH scenario) of the seared material will be released (mean 80%, with a range from 60 to 100%).

After a dome collapse, the tank contents can be directly exposed to the atmosphere and subjected to wind entrainment. The exposure period for entrainment is the time from dome collapse to the time when the tank is completely covered as a result of postaccident recovery operations. This exposure time could vary from 1/2 a day to a week. The distribution shown in Fig. 5.5 reflects this range and has a mean exposure time corresponding to 1 day. It has been shown by separate HMS calculations that only winds greater than 20 mph are capable of entraining tank waste materials (App. E). The highest peak wind gusts recorded in the Hanford 200 Area at a height of 15 m (50 ft) in any given year range from 65 to 80 mph,⁷ while

Fig. 5-5.
Source term summary for release category DCH.

the annual frequency of winds in excess of 19 mph at 61 m (200 ft) is 0.26% (23 h). Recorded frequency of sustained winds in excess of 19 mph at the 10-m (30-ft) elevation is zero, with an annual average velocity of only 7.6 mph. Based on this information, a time window for entrainment was evaluated (per exposure day). The distribution reflecting this time window is shown in Fig. 5.5 and has a mean of 8 s/day with a distribution ranging from 1 to 28 s/day. HMS analysis also predicts entrainment rates ranging from 10 to 300 g/s for winds from 20 to 70 mph. The entrainment rate distribution assumed for this analysis is shown in Fig. 5.5. This distribution has a mean of 20 g/s with a range from 10 to 50 g/s and was judged appropriate for the HTF meteorological conditions.

Based on the amount of material entrapped in the HEPA filters/deentrainer, the amount of material crusted, the release fractions, the wind exposure period, the entrainment time window (fraction), and the wind entrainment rate, the source term can be evaluated for the DCH scenario. Figure 5.5 depicts the resultant distribution for the amount released for the DCH scenario with a mean release of 32.8 kg. The salient point values for this distribution are:

10%	14.7	kg
mean	32.8	kg
90%	55.2	kg

5.4.5. Large Jet Aircraft Crash and Fuel Fire (DCVH). Release category

DCVH is a scenario where a large jet aircraft directly impacts the waste tank, spilling 5000 gal. of jet fuel onto the top of the waste. The resulting 1.8-in. layer of fuel ignites and burns at a rate* of 0.2×0.287 in./min,⁸ yielding a total heat release of $5.53\text{E}+08$ Btu over a burn time of about 30 min (7.75×10^7 cal/s). Assuming that 10% of this heat is conducted downward to the waste, $2.26\text{E}+04$ kg of water would be vaporized. For a convecting liquid waste density of 1.5 g/cm^3 , this amount of water is associated with $1.13\text{E}+04$ kg of waste-dissolved salts and suspended particulates. Based on a fire release factor of 1% for nonvolatile chemical species,⁹ this yields a release of 113 kg of dried solids. For the volatile ^{137}Cs fraction, the release factor is assumed to be 10 times greater, or 10%. Therefore, the curies of ^{137}Cs released are obtained by multiplying the product of the release values in Table 5-2 and the concentration in Table 5-1 by 10. The high value for the release is based on a 25% frac-

*The factor 0.2 reduction in burn rate is to allow for the nonideal geometry in a damaged tank wherein the burning fuel will likely have a smaller area exposed to air.

tion of the fire heat going to vaporize water, thereby yielding a release of 283 kg. The low value is based on 5% of the heat going to the liquid waste, or a release of 57 kg.

5.5. Liquid Pathway Source Terms

Because Tank 101-SY is currently in an inactive status as far as transferring liquid in or out of it, there are no liquid leaks owing to spills during transfers. However, the occurrences that can lead to liquid spills are (1) a primary tank leak with secondary tank failure, and (2) a water intrusion leading to tank overflow. The corresponding liquid release source terms, summarized in Table 5-2 are described below. As indicated in Table 5-1, the dissolved radioisotope concentrations in the tank liquids is different from those found in the surface crust material. While the ^{137}Cs is about the same, the ^{90}Sr and transuranics are found to be factors of about 10 and 100, respectively, lower owing to their lower solubilities.

5.5.1. Small Leak. This represents release category SLK, those scenarios where there is a primary tank leak concurrent with a secondary tank failure leading to a maximum liquid release of 5000 gal. (28,400 kg). The corresponding mean value is assumed to be 3000 gal. (17,100 kg), and the low value is 1000 gal. (5680 kg).

5.5.2. Large Leak. This represents release category LLK, those scenarios where there is a primary tank leak concurrent with a secondary tank failure leading to a liquid release of 240,000 gal. (1,363,200 kg). This corresponds approximately to the stated amount of drainable liquid available in Tank 101-SY. The corresponding mean value is assumed to be 120,000 gal. (681,600 kg), and the low value is 5000 gal. (28,400 kg).

5.5.3. Water Intrusion and Overflow. This represents release category SSP, those scenarios where there is an undetected intrusion of water leading to a tank overflow. The assumed high value is 500 gal. (2840 kg), the mean value is 300 gal. (1700 kg), and the low value is 100 gal. (570 kg).

The fraction of a liquid spill converted to airborne aerosol for various conditions is given in Ref. 8 (p. 4.74). Because a waste tank overflow due to water intrusion is nonenergetic, in the sense that there would be no splashing as the liquid impacts a surface, the models in Ref. 8 probably overpredict the aerosol fraction. Using the Ref. 9 models, the initial fraction aerosolized would be about 1×10^{-6} . However, there also would be a contribution due to high wind over the contaminated pool/ground should the spill be coincident with such a condition. To allow for this, the mean value fraction of the spill converted to aerosol has been assumed to be 1×10^{-5} for this analysis. This gives the source terms, listed in Table 5-2 as

5.7×10^{-3} , 1.7×10^{-2} , and 2.8×10^{-2} for the 10th percentile; mean; and 90th percentile; respectively.

5.6. Summary of Radiological Source Terms

Table 5-2 presents a summary of the source terms for each of the release categories. The airborne release and liquid release estimates are kilograms of the appropriate isotopic mixture listed in Table 5-1.

The radiological doses from these releases are presented in Chap. 6.

REFERENCES

1. D. L. Herting, "Laboratory Characterization of Samples taken in May 1991 from Hanford Waste Tank 241-SY-101," Westinghouse Hanford Company report WHC-SD-WM-DTR-024 (February 10, 1992).
2. D. L. Herting, "Laboratory Characterization of Samples taken in Window E from Hanford Waste Tank 241-SY-101," Westinghouse Hanford Company report WHC-SD-WM-DTR-026 (August 1992).
3. Westinghouse Hanford Company, "Environmental Releases for Calendar Year 1990," WHC-EP-0527 (1992).
4. Westinghouse Hanford Company, "Waste Tank Operations Plant Specifics Manual," draft of undated, unnumbered report.
5. US Department of Energy, "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-101-SY: Hanford Site, Richland Washington," Los Alamos National Laboratory document LA-UR-92-3196, Rev. 8 (March 8, 1993).
6. J. R. White, "Filter System Release Accident Analysis," Los Alamos National Laboratory calc note N-6-CN-WT-SA-RAD-1, Rev. 0 (January 4, 1993).
7. D. I. Herborn, et al., "Hanford Waste Vitrification Plant Preliminary Safety Analysis Report," Westinghouse Hanford Company report WHC-EP-0250, Rev. 1, Chapter 3.0 (January 1992).
8. F. P. Lees, *Loss Prevention in the Chemical Process Industries*, Butterworths, London, Vol. I, p. 518 (1986).
9. J. E. Ayer, et al., "Nuclear Fuel Cycle Facility Accident Analysis Handbook," US Nuclear Regulatory Commission report NUREG-1320, Table 4.10, p. 4.35 (May 1988).

6.0. CONSEQUENCE ASSESSMENT

6.1. Overview

This chapter presents the results of dose calculations for the source terms given in the previous chapter. For the airborne releases, estimates are made for both the onsite and offsite population doses. These numbers are reported separately. In a usual PSA consequence analysis, only the offsite persons are considered, but because of the large number of workers in the 200 East and 200 West Areas close to the tank farms, it was decided that the workers in the adjacent facilities should be considered, as well.

In contrast, the much longer term liquid pathway doses apply only to offsite persons along the Columbia River, downstream from the Hanford Site. As will be shown, these exposures are delayed in time for hundreds of years for some isotopes and thousands of years for others, so clearly, using the present population distributions is questionable. Nevertheless, there was no rational basis upon which to predict that far into the future; therefore, we did not attempt to do so. A further assumption was made that no water for human consumption would ever be drawn from onsite wells in close proximity to the tank farm locations. This is indefensible, but it does give a consistent basis for performing the liquid pathway consequence assessment.

For convenience in deriving the doses for the individual release categories, these doses are calculated as unit release factors, i.e., the dose corresponding to a release of 1 kg of the appropriate liquid or airborne radionuclide mix given in Table 5-1. Although the primary interest here is in the man-rem population doses and concomitant LCF health effects calculated by AP-RISK, we also have reported maximum individual doses (AI-RISK) at various distances for reference purposes.

6.2. Atmospheric Dispersion and Dose Assessment Models

Two related computer codes, AI-RISK and AP-RISK, have been developed by Los Alamos to perform radiation risk calculations for individuals and for the collective populations, respectively. The details of the AI-RISK code, used for performing the dose calculations, are given in Ref. 1 and AP-RISK is presented in Ref. 3. The program originally was developed to facilitate comprehensive analyses of health consequences, ground contamination, and cleanup associated with possible energetic chemical reactions in HLW tanks. Because this type of accident can release aerosols containing significant fractions of large particles, AI-RISK and AP-RISK

have provisions for environmental transport and dosimetry models for all dispersible particle sizes. Both employ a tilted Gaussian plume model that tracks the dispersion of particles in five separate size groups, or bins. Deposition and settling velocities are specified for each size group. Gravitational settling of large particles, in addition to momentum and thermal buoyancy of a release, is taken into account in estimating the effective release height. To estimate the range of potential doses to an individual, a cumulative probability distribution of dose values is constructed by using the windrose data for the site. This probabilistic dose distribution then is used to determine the "median" (50th percentile) and reasonable "maximum" (95th percentile) dose values at the plume center line. The inhalation dose factors (DFs) are calculated based on values of committed dose equivalent factor per unit intake given in the ICRP-30 report.² Particle size-dependent and solubility class-dependent dose factors for various radionuclides (based on ICRP-30) are used to calculate the resulting effective dose equivalent (EDE). In addition to the acute accident dose, the code calculates appropriate long-term offsite doses (50 yr) resulting from continuous ingestion of contaminated food and water. The code also calculates the long-term occupational dose (50 yr) owing to postaccident occupancy of a partially contaminated work place, the dose contributors being ground shine and the inhalation of resuspended particulate contamination. This dose contribution is based upon user-specified site occupancy factors and postaccident cleanup criteria. Both codes also estimate the potential health effects from calculated doses based on ICRP-recommended models and methodology. They are presented as lifetime probabilities of (1) latent cancer mortality, (2) genetic effects, or (3) acute mortality, depending on the dose level.

To perform the population risk calculations, the AI-RISK code was expanded into the AP-RISK code. In AP-RISK, atmospheric transport, pathway, dose, and prompt and latent effects to a population are analyzed for potential accidental releases. In contrast to the maximum plume center line doses given by AI-RISK, the AP-RISK methodology estimates the doses based on the actual plume "footprints" for discrete exposure concentration levels. This is an improvement over the sector-averaged or maximum center line doses given by many population dose codes. The atmospheric transport model, which is used to calculate the time-integrated air concentration from an instantaneous release, is based on the integrated Gaussian puff model:

$$\langle C_a(x,y,0) \rangle = \frac{Q(x)}{\pi\sigma_y\sigma_z u} \exp \left\{ - \left[\frac{y^2}{2\sigma_y^2} + \frac{H^2}{2\sigma_z^2} \right] \right\} , \quad (6.1)$$

where

$C_a(x,y,0)$ = (time-integrated) ground-level air concentration at x,y from a release at $0, 0, H$;

$Q(x)$ = effective release source term;

σ_y, σ_z = standard deviations of the plume distribution; and

u = wind speed (m/s).

For a given air concentration, $\langle C_a \rangle$, the isopleth contour $y(x)$ can be derived from Eq. (6.1) as

$$y(x) = \pm \sigma_y \left[2 \ln \left(\frac{Q(x)}{\pi\sigma_y\sigma_z u \langle C_a \rangle} \right) - \left(\frac{H}{\sigma_z} \right)^2 \right]^{1/2} . \quad (6.2)$$

The area A , which contains an air concentration equal to or greater than a given air concentration level, $\langle C_a \rangle$, is calculated by

$$A = 2 \int_{x_1}^{x_2} y(x) dx , \quad (6.3)$$

where x_1 and x_2 are the downwind distances (e.g., x_1 = site boundary, x_2 = 80 km for offsite LCF calculations). A series of nested areas within x_1 and x_2 are calculated by Eq. (6.3), with each area corresponding to a successively descending air concentration value (Fig. 6.1). Each nested area represents the size of population exposed to a specific concentration level in a radioactive cloud. The total population dose (or fatality) is the sum of doses (or fatalities) calculated for each nested area.

As stated, the pathway model in AI-RISK and AP-RISK includes external exposure from cloud and ground contamination, as well as internal exposure from inhalation of radionuclides in the air and ingestion of contaminated foods and water. Radiation consequences to individuals in the exposed population are estimated in terms of chances of prompt fatality from short-term exposure to the plume and chances of LCF from both short-term and long-term exposures to deposited

Fig. 6.1.
Contour calculation scheme.

radioactive materials. The prompt effects model, which is based on a recent US Nuclear Regulatory Commission (USNRC) study,⁴ considers fatalities associated with injury to the bone marrow, gastrointestinal tract, and lungs. The consequence model also contains provisions for the consequence-reduction benefits of indoor shielding, medical treatment, evacuation, interdiction of contaminated foods, and long-term protective actions such as clean-up of contaminated areas to protective action guide (PAG) levels.

The 200 Area Hanford site meteorology data (10 m) is input as a joint frequency wind speed/stability class matrix. A dose is calculated for each joint frequency combination in the matrix, and a cumulative dose vs frequency curve is constructed for that receptor location. AI-RISK and AP-RISK output this curve as well as the numerical dose values for 50 and 95 percentiles—the doses that will be exceeded 50% and 5% of the time, respectively, based on the site meteorological data. All dose calculations were performed for a ground level release point at tank 101-SY. The parameters for the ground level release are:

- release height 1m (3.27ft)
- velocity 0.5 m/s (1.6 ft/s)
- temperature 800 K (527°C)

6.2.1. Maximum Individual Doses. Although not directly used in the population dose consequence assessment, for reference purposes calculated doses to individual onsite receptors at the 242-S Evaporator, U-Plant, and Highway 240 are presented in Table 6-1. They are the acute doses, received *during cloud passage* at the plume centerline, corresponding to the mean release quantity for each release category (Table 5-2). The 242-S Evaporator, 120 m due west of the SY Tank Farm, is the nearest location that is continuously occupied by onsite workers, while Highway 240 is a public road that has transient occupancy as vehicles pass. The nearest offsite person is located on the site boundary to the west. The distances from Tank 101-SY are given in the second column. Note that the doses for the releases involving a fire (category DCVH) are lower than for other categories even though the quantity released is considerably higher. This is because the effective release height is much greater due to the large plume rise from the heat input, causing the plume to pass above the closed receptors.

TABLE 6-1
MEAN ACUTE INDIVIDUAL RADIOLOGICAL DOSES FOR
RELEASE CATEGORIES (95% METEOROLOGY)

Receptor Location	Distance (km)	Release Category BPL (rem EDE)	Release Category HEPAL (rem EDE)	Release Category HEPAH (rem EDE)	Release Category DCH (rem EDE)	Release Category DCVH (rem EDE)
242-S Evap	0.12 W	8.0E-4	2.05	7.86	37.4	1.23
U-Plant	0.78 NE	3.9E-5	0.101	0.386	1.83	0.432
Hwy 240	3.9 SE	2.9E-6	0.0074	0.0280	0.134	0.085
Max. Offsite	13.8 WNW	4.3E-7	0.0011	0.0043	0.020	0.020

6.2.2. Toxic Gas Exposure Levels. At tank 101-SY there is a possibility of release of gaseous NH_3 during a BURP event (release category TG), and this could result in workers at the tank being exposed to high concentrations of the gas. However since the PSA is limited to health effects for co-located on-site workers and the off-site public, these potential exposures to the 101-SY tank workers is not included in this evaluation. For a detailed discussion of potential tank worker NH_3 exposures see Ref. 5, Chap. 5.0.

6.2.3. Population Doses. Population dose estimates were made with AP-RISK using the parameters for a ground level release listed above. Because of the significant onsite worker population at Hanford doses were estimated for the onsite as well as the offsite populations. Results for the mean release quantity for each release category (Table 5-2) are summarized in Table 6-2. The assumptions for the onsite calculations were:

- occupancy factor for long term exposures due to ground shine and dust resuspension 0.3,
- fraction of time outdoors 0.15,
- no food pathway exposure, and
- PAG cleanup level after accident to 5 rem/50 yr exposure.

TABLE 6-2
POPULATION MEAN DOSES FOR 95TH PERCENTILE
METEOROLOGY (PERS-REM EDE)

Release Category	Onsite Acute	Onsite Total	Offsite Acute	Offsite Total
BPL	3.2E-4	2.4E-3	3.6E-4	7.7E-3
HEPAL	0.81	6.21	0.933	19.9
HEPAH	3.1	22.7	3.58	76.4
DCH	14.8	95.6	17.0	363
DCVH	103	1620	30.1	4630

The onsite areas found to contribute to the onsite dose by virtue of proximity to the 241SY tank farm and number of workers were the 200 W, 200 E, and 400/WPPSS areas, with contributions of 85, 13, and 2%, respectively. The geometry used in modeling these onsite area exposures is shown in Fig. 6.2. The population data was derived from the Hanford telephone directory, i.e., 1873, 2772, and 1808 workers in the 200 W, 200 E, and 400/WPPSS areas, respectively.⁵ The offsite population is based on the 1990 census data; it includes a total of 375,860 people in all compass sectors from 16 to 80 km.⁶

The offsite dose area covered was 360° for a distance of 16 km to 80 km. The assumptions for the offsite calculations were:

- occupancy factors; frame house 0.3; brick house 0.3; office building 0.3; cars on road 0.1,
- fraction of time outdoors 0.25,
- food pathway exposure included; initially contaminated crops not interdicted, and
- PAG cleanup level after accident 5 rem/50 yr exposure.

Onsite and offsite conditional population dose curves (CDF) for release category DCH are presented in Figs. 6.3 and 6.4. Similar curves were generated for all the nonfire release categories.

Fig. 6.2.
Geometry for onsite population dose calculations.

Fig. 6.3.
Onsite dose CDF curve for release category DCH.

Fig. 6.4.
Offsite dose CDF curve for release category DCH.

Fig. 6.5.
Onsite dose CDF curve for release category DCVH.

Fig. 6.6.
Offsite dose CDF curve for release category DCVH.

As discussed in Sec. 5.4.5, release category DCVH involves an aircraft crash followed by a fire. Therefore, because of its volatility, the ^{137}Cs release was increased by a factor of 10 over the other isotopes, that is its concentration in Table 5-1 was increased to 4.5 Ci/kg for the source term for this release category. The onsite and offsite conditional population dose curves (CDF) for this release category are presented in Figs. 6.5 and 6.6.

6.2.4. Surface Contamination Estimates. One of the objectives for this PSA was to quantify the economic impacts of any required repair and clean up following an accident. Accordingly, AP-RISK was used to calculate the resulting ground contamination as a function of required decontamination factor (DF) for each of the release categories. The code calculates an area/DF vector for each meteorological condition and then computes a frequency weighted average for the release category. Results of these calculations are presented in Fig. 6.7 for the mean release quantities for the four categories that result in ground contamination. In the figure the solid lines are the cumulative areas for all DFs less than a given value and the dotted show the area for a given DF. The exposure scenario assumptions for the clean up area calculations were:

- site access is restricted to remediation employees at current employment levels for the next 50 yr,
- occupancy factor for long term exposures due to ground shine and dust resuspension 0.3,
- fraction of time outdoors 0.15,
- no food pathway exposure, and
- PAG cleanup level after accident 5 rem/50 yr exposure.

Complete details on cleanup costs are given in App. J; summary results are in Chap. 7.

6.3. Liquid Pathway Dose Assessment Model

The liquid exposure path considered is due to the use of Columbia River water by the downriver populations. The dose estimates were made using the RESRAD code⁷ and the parameters given in Tables 6-3 and 6-4.

6.3.1. Geology Affecting Radionuclide Transport below the 200 West Area.

Rainfall and Drainage. The yearly average rainfall for the Hanford Area from 1912 through 1980 was 16.02 ± 4.41 cm, and the yearly average rainfall for the years

Fig. 6.7.
Decontamination areas for release categories.

TABLE 6-3
REGIONS IN THE VADOSE ZONE UNDERLYING THE 200 WEST AREA
OF THE HANFORD SITE

Depth below Surface, m (approx.)	Elevation above Sea Level, m (approx.)	Composition of Region	Conductivity, K_{sat} , m/day	Porosity, h_{sat}
0-12	193-205	Backfill—silty, sandy gravel	1.07	0.26
12-20	185-193	Pebbly sand	0.52	0.52
20-24	181-185	Medium sand	1.62	0.41
24-27	177-179	Silt	0.04	0.43
27-29	175-177	Caliche		
29-31	173-175	Fine sand		
31-34	171-173	Cemented caliche		
34-38	167-171	Fine sand		
38-57	146-167	Sandy gravel	1.07	0.26
57-61	141-144	Conglomerate		
61	144	Top of aquifer		

Source: Ref. 8.

TABLE 6-4
DISTRIBUTION COEFFICIENTS FOR TANK 101-SY RADIONUCLIDES IN
HANFORD SEDIMENTS

Radionuclide	Coefficient, ml/g
^{90}Sr	0.64
^{99}Tc	0.0
^{129}I	0.0
^{137}Cs	26.0
^{237}Np	16.0
^{239}Pu	71.0
^{241}Am	76.0

Source: Ref. 9, pp. 23, 26, and 41.

1947 to 1988 was 16.72 ± 4.87 cm.⁸ The authors of Ref. 8 modeled the evaporation from and percolation through the 2-m-thick backfill on top of a tank. The model predicted an average evaporation of 3.4 ± 0.78 cm/yr and drainage at the 2-m depth of 13.1 ± 3.03 cm/yr.

The Vadose Zone

1. Different layers in the vadose zone. The vadose or unsaturated zone underlying the 200 West Area extends from the land surface (approximately 205 m above sea level), down about 61 m to the top of the underlying unconfined aquifer (approximately 144 m above sea level). Table 6-3 lists the different regions and their thicknesses, approximated from the diagrams in Ref. 8.

The hydraulic conductivities and porosities are also included. The data shows a layer of extremely low conductivity underlying the 200 West Area. This low-conductivity layer is not present underneath the 200 East Area, where other tanks are situated.

2. Soil moisture content in the vadose zone. The moisture content of soil below about 7 m on the 200 Area plateau, although slightly variable, tends to average about 6%.¹⁰

3. Recharge rates in the vadose zone. The recharge rate is the annual infiltrating precipitation moving downward through the vadose zone. It is an important factor for contaminant movement within this zone. The layered strata underlying the 200 Area plateau should inhibit percolation rates through the vadose zone, allowing added time for evapotranspiration to further limit net recharge.¹⁰ Thus, the recharge rate might be much less than the drainage rate mentioned above.

In 1990, Routson and Johnson¹⁰ reported results from two tests in the 200 East Area. Moisture changes in a lysimeter sealed at the bottom and contaminant movement from a trench were measured. From these experiments, the authors calculated a recharge rate of 0.0 ± 0.2 cm/yr. Because of the low-conductivity layer in the 200 West Area vadose zone, the recharge rate should be even lower underneath the 200 West Area than the 0 ± 0.2 cm/yr value underneath the 200 East Area. The above numbers imply the possibility of a negative recharge rate, i.e., moisture moving upward through the vadose zone from the aquifer to the surface. This is possible and indeed was indicated by the contaminant movement from a trench reported in the Routson and Johnson¹⁰ work. The Environmental Impact Statement (EIS)⁹ used recharge rates of 0.5 and 5 cm/yr over the entire site "to represent current and wetter conditions which may vary with time."

The Underlying Aquifer. The unconfined aquifer underlying the 200 West Area is described in the EIS (Ref. 9, Vol. 1, pp. 4.18–4.22). The water table "ranges from 56 to 100 m beneath the ground surface in the 200 Areas. The unconfined aquifer is over 70 m thick in some areas and thins to zero thickness along the flanks of the bordering rock formations."

Natural recharge to the aquifer is estimated to be about 5×10^6 l/day from the surrounding highlands. Artificial recharge to the aquifer results from the disposal of waste water to the ground. The artificial recharge was estimated to be about 5×10^7 l/day at its peak. Because of the artificial recharge, groundwater mounds were detected underneath U pond (within the 200 West Area) and B pond (east of the 200 East Area). The water table underneath U pond has risen about 26 m since the start of operations in 1944; the water underneath B pond has risen about 9 m.

The flow in the aquifer is in a general west-to-east direction. It travels from the recharge areas along the Yakima Ridge and Rattlesnake Hills downgradient to the discharge areas along the Columbia River. In the southern part of the site, the aquifer is recharged by the Yakima River. In the EIS (Ref. 9, Vol. 3), the aquifer is modeled by a number of nonconnecting stream tubes traversing the distance between the highlands and the Columbia River.

Distribution Coefficients and Retardation Factors. A critical factor in the transport of radionuclides by moisture through both the vadose zone and the aquifer is the holdup of the radionuclide by the solid medium. The holdup is caused principally by sorption of the radionuclide by the solid phase; liquid holdup in micropores also may contribute. This holdup ranges from almost negligible for ^{129}I to very large for ^{241}Am . Because movement through the geologic media is slow compared with transport on the microscopic scale, equilibrium between the solid and liquid phases is usually assumed in models of radionuclide transport.

The holdup is characterized by either a distribution coefficient or a retardation factor. Distribution coefficients are used to account for the sorption characteristics of the soil. The term "sorption" is used to describe, in a nonmechanistic way, reactions whereby a species is removed from a liquid phase and held in some manner by a solid. The distribution coefficient, K_d , is a lumped parameter, which can be defined for a substance, C, as:

$$K_d = \text{weight fraction of C in solid} / \text{concentration of C in liquid} \quad . \quad (6.4)$$

Thus, the distribution coefficient gives the amount at equilibrium of radionuclide per gram of solid phase divided by the amount per unit volume liquid phase; the units of the distribution coefficient are typically ml/g or cm³/g. The higher the coefficient, the greater the holdup. Table 6-4 gives conservative values of distribution coefficients in Hanford sediments for the radionuclides contained in the Tank 101-SY slurry. They are presented and discussed in the EIS (Ref. 9, pp. 23–26 and 41). These are the distribution coefficients used for modeling transport of these radionuclides through the geologic media underlying the tank.

Using a simple distribution coefficient implies that the sorption is fast, reversible, independent of contaminant concentration, and not influenced by other variable species in the solution. While these conditions are seldom completely true, the distribution coefficient is often used because of its simplicity or because contaminant concentrations are sufficiently low that the sorption lies in the linear region of the isotherm. Another reason for its use is insufficiency of data to justify a more sophisticated approach. Many discussions appear in the literature on the ramifications of using K_d .¹¹

Sometimes the holdup of a substance by the soil is characterized by a retardation factor. The retardation factor is related to the distribution coefficient through the expression

$$R = 1 + \frac{\rho_B K_d}{\theta} , \quad (6.5)$$

where

ρ_B = bulk density of soil, and

θ = fraction occupied by liquid.

The retardation factor appears in the basic mass balance for contaminant transport.

The Columbia River. The Columbia River flows through the northern part of the site and along the eastern boundary. The average annual flow of the river in the Hanford Reach over a 65-yr period was 3400 m³/s, and additions to this flow from tributaries increased it to 7300 m³/s at the river mouth (Ref. 10, Vol. 1, pp. 4.10 and 4.19).

6.3.2. Estimation of Doses from Leaks/Spills. The RESRAD code⁷ was modified to calculate doses at offsite locations from HLW spill scenarios. RESRAD is simple to use and provides a conservative means to assess the long-term radiolog-

ical impacts from a radioactively contaminated area such as one resulting from a HLW tank spill. It includes major features necessary to model the process of water infiltration through the contaminated zone owing to a spill and the transport of radionuclides through the unsaturated (vadose) zone and saturated zone (aquifer) to a well or point of seepage into surface water. The code also considers radionuclide decay and ingrowth from the time of release to the time of water consumption. This section describes the modifications made in the code for calculating doses to offsite well and surface water from water-dependent pathways.

For radionuclide i , RESRAD calculates the breakthrough time Δt_i (the time following the radiological release at which radionuclides first appear in the water at the point of use) and the rise time δt_i (the time following the breakthrough time for the radionuclide concentration in the water to attain a maximum value). The dilution factor f_i (the ratio between the concentration at the point of use to the concentration in the infiltrating water as it leaves the contaminated zone) is an important parameter. There are two models in RESRAD for calculating these parameters: (1) the mass-balance (MB) model and (2) the nondispersion (ND) model. Only the ND model is appropriate for offsite wells.

Breakthrough Time. The point of seepage of the aquifer into the surface water or the well from which water is withdrawn for domestic use or irrigation is assumed to be located at $D^{(sz)}$ meters from the downgradient edge of the contaminated zone. The transport time through the aquifer from the contaminated zone to the seepage point or offsite well is included in the calculation. The breakthrough time is equal to the transport time through the unsaturated zone, which is the sum of the times for a radionuclide to be transported through those strata of the unsaturated zone that lie below the contaminated zone and the transport time in the aquifer from the contaminated zone to the offsite well.

$$\Delta t_i = \sum_{m=1}^n \Delta t_{im}^{(uz)} + \Delta t_i^{(sz)} , \text{ and}$$

$$\Delta t_i^{(sz)} = D^{(sz)} p_e^{(sz)} R_d^{(sz)} / V_{wfr} ,$$

where

n = number of distinct horizontal strata in the unsaturated zone below the contaminated zone at time 0,

$\Delta t_{im}^{(uz)}$ = transport time for the i^{th} principal radionuclide through the m^{th} stratum (yr),
 $\Delta t_i^{(sz)}$ = transport time for the i^{th} principal radionuclide through the aquifer,
 $D^{(sz)}$ = distance from the edge of the contaminated zone to the point of seepage or offsite well,
 $P_e^{(sz)}$ = effective porosity of aquifer (dimensionless),
 $R_{di}^{(sz)}$ = retardation factor of the i^{th} principal radionuclide in the saturated zone, and
 V_{wfr} = water flow velocity in the aquifer.

Rise Time of Concentrations. When the well is located at $D^{(sz)}$ meters from the downgradient edge of the contaminated zone, the rise time given by the formula in the RESRAD manual is assumed to be appropriate as

$$\begin{aligned}
 \delta t_i &= \tau_{li} & \zeta \leq d_w, D_{wt}(t) \geq C_d(t) + T(t) \\
 &= \tau_{li} / (\zeta / d_w) & \zeta > d_w, D_{wt}(t) \geq C_d(t) + T(t) \\
 &= 0 & D_{wt}(t) < C_d(t) + T(t)
 \end{aligned} ,$$

where

$\zeta = (I/V_{wfr}) l^{(cz)}$,
 = distance from water table to lower boundary of contamination in aquifer at the downgradient edge of the contaminated zone (m); if the calculated value of ζ is greater than Z , ζ is made equal to the value of Z ;
 Z = thickness of the aquifer;
 I = infiltration rate (m/yr);
 $l^{(cz)}$ = length of the contaminated zone parallel to the hydraulic gradient;
 d_w = distance of well intake below the water table (m);
 $\tau_{li} = P_e^{(sz)} R_{di}^{(sz)} l^{(cz)} / V_{wfr}$ = time for the i^{th} principal radionuclide to be transported from the upgradient edge to the downgradient edge of the contaminated zone (yr);
 $R_{di}^{(sz)}$ = retardation factor for the i^{th} principal radionuclide in the saturated zone (dimensionless); and

$P_e^{(sz)}$ = effective porosity of aquifer (dimensionless).

Dilution Factor. It is assumed that the water flow is vertically downward from the bottom of the contaminated zone to the water table; thus, no dilution will occur in the unsaturated zone. The dilution in the saturated zone for the offsite well is estimated as follows. For an offsite well located $D^{(sz)}$ meters from the down-gradient edge of the contaminated zone, the dilution factor, f , for the ND model is given by the formula

$$f = \frac{IA}{Z_d P_e^{(sz)} V_{wfr} \left[A / l^{(cz)} + 2D^{(sz)} \tan(\alpha / 2) \right]} ,$$

where

$$Z_d = (I/V_{wfr})/D^{(sz)}$$

= distance from water table to lower boundary of contamination in the aquifer at the downgradient well location (m); if the calculated value of Z_d is greater than z , Z_d is made equal to the value of z ;

$l^{(cz)}$ = length of the contaminated zone parallel to the hydraulic gradient;
and

α = angle of spread of the contaminant plume in the aquifer.

For surface water pathways involving a pond, the dilution factor calculated by the present RESRAD code is adequate. For a river located at $D^{(sz)}$ from the downgradient edge of the contaminated zone, the dilution factor for the ND model may be given by the formula

$$f = IA/Q ,$$

where

Q is the discharge rate of the river (m^3/yr).

As shown by the equation above, the dilution factors for a well offsite that is located away from the edge of the contaminated zone can be significantly smaller than dilution factors estimated for a well located in or immediately adjacent to the contaminated zone.

6.3.3. Estimated Liquid Doses. Estimates were made of the doses owing to ingestion of water from the Columbia River using the mean river flow of 3400 m³ and an assumed downriver population of one million, each ingesting 510 l/yr. The nuclide K_d values used in the calculations are given in Table 6-4. Knowing the breakthrough time of a liquid release in the 200 West Area at the Columbia River permits calculation of the integrated individual dose due to ingestion of drinking water from the river, using the simple formula

$$\text{Dose} = \sum_i C_i \times F_i \times W_d \times D_i / Q ,$$

where

- C_i = curies of isotope i in the release,
- F_i = decay factor for isotope i during the breakthrough delay,
- W_d = annual quantity of water consumed by an individual, and
- D_i = dose factor for ingestion of isotope i into GI tract.

The assumption in the above calculation is that all of the released radioactive liquid eventually reaches the river, albeit with an isotope dependent delay (breakthrough) time. RESRAD is used to estimate this delay, which is then used to calculate F_i , based on the isotope half-life.

The results of the downriver population doses calculations for various spill sizes are presented in Table 6-5. Calculations were performed for infiltration rates of 0.2, 0.5, and 5.0 cm/yr. These values cover a range from current climatic conditions to possible future changes to a much wetter climate.

Figure 6.8 shows a typical RESRAD calculation result, indicating the breakthrough time, rise time to maximum individual dose rate, and decline as radioactivity is flushed through the aquifer system. The doses presented in Table 6-5 are primarily due to the isotopes ⁹⁹Tc and ¹²⁹I, which move with the groundwater with no delay due to retention. The breakthrough times for ⁹⁹Tc and ¹²⁹I are 1856, 790, and 98 yr, respectively, for infiltration rates of 0.2, 0.5, and 5.0 cm/yr. Because these nuclides have half-lives of 2.1×10^5 and 1.7×10^7 yr, respectively, the correction factor for decay is approximately unity. This means that the time integrated population doses are independent of the infiltration rate, the principal controlling parameter for the breakthrough time, for these isotopes.

TABLE 6-5
DOSE ESTIMATES FOR LIQUID RELEASES

Spill Size (gal.)	Contained Curies ⁹⁹ Tc/ ¹²⁹ I	Peak Individual Dose (mrem/yr) ^a	Population Dose person-rem ^b
100,000	74/0.34	1.0E-5	0.91
20,000	15/ 0.068	2.0E-6	0.18
5000	3.7/0.017	5.0E-7	0.045
1000	0.74/0.0034	1.0E-7	0.0091
500	0.37/0.0017	5.0E-8	0.0045

^aDepends on the geometric configuration of the initial spill; values are for a constant thickness, variable area.

^bBased on a 1,000,000-person downriver population drinking the water.

Fig. 6.8.
Individual dose rate at river for 100,000-gal. release.

For the 0.2 cm/yr breakthrough time, the ^{90}Sr and ^{137}Cs are delayed sufficiently so that they have decayed to insignificant levels by the time they breakthrough to the river. The transuranics do not appear at the river until after 10,000 yr, so they have not been included in the dose contributions.

6.4. Dose/Health Consequences for Release Categories

Having developed the release quantities given in Chap. 5 and the unit dose factors given in the previous sections of this chapter, it is possible to estimate the population doses and committant health effects for the various release categories. Because all of the population exposures are well below those where acute radiation dose effects are seen, we only need deal with the long-term LCF. Basically, this is a statistically derived factor that is an estimate of the number of persons in the exposed population that would be expected to die of an exposure-induced cancer in the future. Additionally, the exposures to toxic gas are presented as individual exposures. Because these effects do not extend offsite, only the exposures to onsite individuals relatively close to the release are of interest.

The preparation of the complete risk curves that combine all the release categories is described in Chap. 7.

6.5. Exposure to Hazardous Chemicals

In addition to radionuclides, Tank 101-SY contains a number of chemicals which are potentially harmful to humans. If these chemicals are released, through the vadose zone and the underground aquifer steams, they would ultimately reach and contaminate the Columbia River waste. This release of the chemicals to the river could occur decades after the actual spill/release of the tank contents to the ground. The contaminated river water can lead to a toxicological dose if it exceeds the safe concentration levels and is consumed by surrounding human population. Accordingly, a scoping hazards analysis was performed to evaluate the potential hazards due to the potential chemical exposure. The purpose of the scoping analysis was to determine and identify, if there is a need to perform a detailed chemical dispersion analysis and hazards evaluation for the tank.

Hazardous chemical contamination of the Hanford site groundwater and the Columbia River were comprehensively examined in the 1986 Hanford Environmental Impact Statement,⁹ App. U. This study evaluated the impacts of potential leakage from all Hanford single shell tanks (SSTs) and found that hazardous chemical concentrations in the Columbia River remained well below EPA drinking water

standards for all remediation scenarios under all site conditions. The EIS also showed that ground water within the current site boundaries would, over time, show hazardous chemical concentrations well above EPA standards with not tank remediation.

Because large leaks from double-shell tanks were not explicitly evaluated in the EIS, a scoping analysis of the potential for contamination of the Columbia River was performed for Tank 101-SY. This analysis is presented in App. I; it confirms that leaks from Tank 101-SY represent no threat to the Columbia River, based on USEPA maximum contaminant levels for drinking water. Since site boundaries were assumed to remain as is for this evaluation, as discussed in App. H, no further analysis of hazardous chemical risk was performed and no health impacts from hazardous chemical releases are included in the results reported here.

REFERENCES

1. Y. C. Yuan and D. R. MacFarlane, "AI-RISK: A Computer Program for Calculating Doses and Health Risks from Accidental Release of Radioactive Materials," Los Alamos National Laboratory document LA-UR-92-2636 (July 1992).
2. International Commission on Radiation Protection, *Limits for Intakes of Radionuclides by Workers*, ICRP Publication 30, Pergamon Press, Oxford (1979).
3. Y. C. Yuan and D. R. MacFarlane, "AP-RISK: A Computer Program for Calculating Population Doses and Health Risks from Accidental Release of Radioactive Materials," Los Alamos National Laboratory document LA-UR-93-3825 (September 1993).
4. S. Abrahamson et al., "Health Effects Model for Nuclear Power Plant Accident Consequence Analysis," US Nuclear Regulatory Commission report NUREG/CR-4214, Rev. 1 (1989).
5. Data supplied by Brit Hey, Westinghouse Hanford Company (September 1992).
6. Data supplied by Kathy Rhoades, Pacific Northwest Laboratory (February 1992).
7. T. L. Gilbert et al., "A Manual for Implementing Residual Radioactivity Material Guidelines," Argonne National Laboratory report ANL/ES-160 (June 1989).
8. J. L. Smoot, J. E. Szecsody, B. Sagar, G. W. Gee, and C. T. Kincaid, "Simulations of Infiltration of Meteoric Water and Contaminant Plume Movement in the

Vadose Zone at Single-Shell Tank 241-T-106 at the Hanford Site," Westinghouse Hanford Company report WHC-EP-0332 (November 1989).

9. US Department of Energy, "Final Environmental Impact Statement, Disposal of Hanford Defense High-Level Transuranic and Tank Wastes, Hanford Site, Richland, Washington (5 Vol.)," US Department of Energy report DOE/EIS/0113, Richland Field Office, Richland, Washington (December 1987).
10. R. C. Routson and V. G. Johnson, "Recharge Estimates for the Hanford Site 200 Areas Plateau," *Northwest Science* 64, 150–158 (1990).
11. R. J. Serne and A. B. Muller, "A Perspective on Adsorption of Radionuclides onto Geologic Media," in *The Geological Disposal of High Level Radioactive Wastes* (D. G. Brookins, ed.), pp. 407–444, Theophrastus Publications, Athens (1987).

7.0. PRESENTATION OF TOTAL RISK CURVES

The final results of the risk analysis performed for Tank 101-SY are the unconditional risk curves. The risk curves present the relationship between the frequency of occurrence of radionuclide release scenarios and the level of damage sustained owing to the release. The risk curves are presented as complementary cumulative distribution functions (CCDFs). The RISKMAN and STADIC personal computer software packages were used to generate probability distributions for the release category frequencies. AP-RISK was used to generate conditional risk curves (based on meteorology) corresponding for each release category. A Monte Carlo code was then used to combine the release category frequencies and the conditional risk curves to produce the final unconditional risk curves.

7.1. Release Category Frequencies

The scenarios contributing to the frequency of each release category were calculated by RISKMAN through the point estimate quantification of the event-tree model. The release category frequencies were then requantified using a Monte Carlo algorithm and probability distributions for the initiators and split fractions to generate probability distributions for all release category frequencies. The distributions for release categories that were dependent on double delta functions were generated using the STADIC program for release categories DCH, HEPAH, and DCLLK.

7.2. Conditional Health Risk Curves

The conditional risk curves from AP-RISK were supplied for each release category (on site and off site) in tabular form. The curves showed the relationship between consequences, defined as person-rem, and the frequency of exceeding the consequence level given the occurrence of a release. The following table shows the correspondence between each release category and the conditional risk curves.

Conditional Risk Curve	Release Categories
Onsite—Normal	BPL, DCH, HEPAH, HEPAL, DCLLK, SSP
Onsite—Fire	DCVH
Offsite—Normal	BPL, DCH, HEPAH, HEPAL, DCLLK, SSP
Offsite—Fire	DCVH

The uncertainty in the release quantity was modeled by assuming that three discrete quantities (small, medium, and large) were possible for each release category. The probability assumed for each potential release quantity was

Release Quantity		
Small	Medium	Large
0.1	0.8	0.1

There are three damage curves for each release category corresponding to the low, mean, and high release quantities in Table 5-2. Therefore, for a given release category and receptor population, there are three conditional risk curves, each with the probability weight shown in the above table.

7.3. Total Health Risk Curves

7.3.1. Airborne Releases. The release category frequencies and the conditional risk curves are used to construct unconditional risk curves. This process involves calculating unconditional risk curves for individual release categories for specific receptor populations (e.g., DCH Onsite). The total offsite and onsite risk curves are then calculated by summing the offsite and onsite contributions, respectively. Risk curves for offsite acute consequences were also calculated.

Calculation of a probability distribution for the exceedance frequency of a given damage (person-rem) level requires the merging of the three weighted conditional consequence curves and the release category frequency distribution for each release category. The distribution for the unconditional exceedance frequency per year of damage level, x , for release category A is calculated as a product of the frequency distribution for release category A and the conditional exceedance frequency vs damage level, x . The conditional exceedance frequency distribution for damage level is a three-bin distribution where the exceedance frequencies correspond to those of the three conditional damage curves generated for the three potential release quantities (i.e., small, medium, or large). The product of frequency and damage generates a distribution for the exceedance frequency of damage level for a release category A. To generate the mean risk curve with uncertainty bands for release category A, over all damage levels, probability distributions for the exceedance frequency must be calculated at a number of damage levels to sufficiently define the shape of the curve.

The curve for total onsite risk is calculated by summing the probability distributions for exceedance frequencies at corresponding damage levels for all contributing release categories. The 5th, 50th, and 95th percentile curves and the mean risk curves were calculated for total offsite consequences, acute offsite consequences, and total onsite consequences. Figure 7.1 presents the mean curves for total offsite consequences and each of the contributing release categories. Figure 7.2 shows the 5th, 50th, and 95th percentile curves for total offsite consequences. Figure 7.3 presents the mean curves for acute offsite consequences and each of the contributing release categories. Figure 7.4 shows the 5th, 50th, and 95th percentile curves for acute offsite consequences. Figure 7.5 shows the mean curves for total onsite consequences and each of the contributing release categories. Figure 7.6 shows the 5th, 50th, and 95th percentile curves for total onsite consequences. Because the contributions from release categories SSP and BPL are so small and have a negligible impact on the total risks, they are not shown in Figs. 7.1 through 7.6.

7.3.2. Liquid Releases. The procedure described above was also used to develop the conditional risk curves for the liquid release consequence categories SSP, LLK, and SLK. Because there are no onsite impacts from these releases, calculated results are presented for offsite impacts only; they are presented in Figs. 7.7 and 7.8. As shown, the radiation exposure risks posed by the liquid releases are significantly lower than those for the airborne releases given in Figs. 7.1 through Fig. 7.6. They also are significantly delayed in time compared to doses from airborne releases.

7.4. Economic Risk Curves

As discussed earlier, an objective of the PSA was to estimate the potential economic costs associated with 241SY tank farm accidents. For purposes of this analysis the following cost elements were included:

- 1 surrounding land surface decontamination (from airborne releases).
- 2 subsurface contaminated soil removal, processing, and disposal (from tank leaks).
- 3 replacement of damaged tank, and
- 4 replacement/repair of damaged tank ventilation system.

Fig. 7.1.
Mean total consequences—offsite.

Fig. 7.2.
Total consequences—offsite.

Fig. 7.3.
Mean acute consequences—offsite.

Fig. 7.4.
Acute consequences—offsite.

Fig. 7.5.
Mean total consequences—onsite.

Fig. 7.6.
Total Consequences—onsite.

Fig. 7.7.
Mean total consequences—offsite liquid releases

Fig. 7.8.
Total consequences—offsite liquid releases

The AP-RISK calculated contaminated areas for the airborne release categories are given in Sec. 6.2.4. These areas along with the surface decontamination costs given in App. J and the release category frequency distributions were used to generate the cost CCDF curves for item (1). For item (2), which applies only to the subsurface leak release categories SSP, SLK, and LLK, the mean leak sizes and excavation, treatment and disposal costs given in App. J were used to generate the CCDF curves. A similar procedure was used to generate CCDF curves for items (3) and (4). Complete details on the calculation of the cost CCDF curves are given in App. J; the procedure is basically the same as that outlined for the population doses in Sec. 7.3. Finally the total cost CCDF is developed by summing the contributions of all the cost elements. This curve, broken down by release categories is presented in Fig. 7.9.

7.5. Observations and Insights

The mean risk curves for the onsite and offsite populations are presented in Figs. 7.1, 7.5, and 7.7. The corresponding total annual LCFs for different exposure scenarios are given in Table 7-1. These estimates compare with the annual LCFs that would be expected from normal background radiation of 0.75 and 29 for the onsite and offsite (within a 50-mi radius) populations, respectively. For the postulated one-million persons downstream along the Columbia River that would be subjected to the radionuclide exposures from liquid leaks hundreds of years in the future, the expected annual background LCF is 75. Note that although the airborne and liquid pathway doses are both listed in Table 7-1, they are qualitatively quite different. The airborne doses are relatively immediate, occurring over the next 50 yr or so, whereas the liquid path doses do not even start until 1800 yr (for 0.2 cm/yr infiltration) in the future.

Thus, the incremental radiological risk posed by Tank 101-SY in its present configuration is a very small fraction of that posed by exposure to background radiation. The reason for this is that even though the hazard is high, because of the large inventory of radionuclides, there is no available energetic release mechanism that will produce a large source term. Natural phenomena, e.g., seismic, high winds, ashfall, etc., did not prove to be significant risk contributors for Tank 101-SY.

As shown by the overall economic risk curve in Fig. 7.9, there is a potential for some significant economic impacts, albeit at very low frequencies. Table 7-2 gives a summary of the release category contributions to the estimated mean economic impact of \$1.44 million/year. As in the case of the health risks it is the mid

Fig. 7.9.
Total for all release categories.

TABLE 7-1
SUMMATION OF MEAN RISK BY RELEASE CATEGORY

Release Category (mean frequency)	Airborne Path Risk—Mean Exposure (person-rem/yr)		Liquid Path Risk—Mean Exposure (person-rem/yr)	
	Onsite	Offsite	Onsite	Offsite
BPL (6.02E-2)	2.4E-5	1.8E-4	—	—
HEPAL (1.16E-1)	0.116	0.86	—	—
HEPAH (5.07E-3)	0.0187	0.147	—	—
DCH (6.98E-4)	0.0105	0.0977	—	—
DCVH (3.08E-9)	9.24E-7	6.78E-6	—	—
SSP (4.35E-5)	6.50E-7	8.80E-6	—	1.2E-7
LLK (4.46E-4)	—	—	—	4.9E-4
SLK (2.0E-4)	—	—	—	5.4E-6
Totals	0.145	1.11		4.9E-4
Annual LCFs	7.25E-5	5.5E-4		2.5E-7

- Notes: 1. Mean release quantities taken from Table 5-2.
2. Mean onsite and offsite doses from AP-RISK (person-rem) are:
BPL - 3.9E-4, 2.9E-3;
HEPAL - 1.0, 7.4;
HEPAH - 3.7, 29;
DCH - 15, 140;
DCVH - 300, 2200.
3. Liquid path doses based on releases in Table 5-2 and factors in Table 6-7.

severity range categories with moderately high frequencies (HEPAL, HEPAH) that dominate the economic risk.

As shown by the results presented in this report, the calculated risks are dominated by the burp/burn sequences. Therefore, actions that eliminate the periodic burps and/or reduce the possibility of hydrogen ignition will reduce the risk further. In fact, the uncertainty in the accident sequence frequencies for the burp events is large for the question of hydrogen ignition in the tank or ventilation system following a burp event. Better knowledge about the crust searing and other aerosol-generating processes, probably from experiments, is needed to reduce this source-term uncertainty. However, in view of the extremely low mean health risks

TABLE 7-2
SUMMATION OF MEAN COSTS BY RELEASE CATEGORY

Release Category (Mean Frequency)	Surface Cleanup Mean Cost (\$)	Tank Replace Mean Cost (\$)	Vent Replace Mean Cost (\$)	Below Surface Cleanup Mean Cost (\$)	Mean Frequency x Mean Cost (\$/yr)
BPL (6.02E-2)	—	—	1.0E+6	—	60,200
HEPAL (1.16E-1)	680	—	10.8E+6	—	1,252,900
HEPAH (5.07E-3)	2190	—	10.8E+6	—	54,800
DCH (6.98E-4)	8360	96E+6	—	—	67,000
DCVH (3.08E-9)	504,000	96E+6	—	—	—
SSP (4.35E-5)	—	—	—	637,700	28
SLK (2.0E-4)	—	—	—	887,200	180
LLK (4.46E-4)	—	—	—	11,698,000	5200
Total					1,440,300

(four orders of magnitude, below background radiation for the population at risk), it is difficult to justify further refinements in the calculations as they would not change the overall conclusions.

Comparing the results presented in Tables 7-1 and 7-2, it appears that the economic risks are more significant than the health risks. Efforts to reduce the frequency or eliminate burping in the tank should be viewed in that context.

APPENDIX A

GLOSSARY

Active Tank	A tank being used, or planned for use, for the storage of liquid in excess of a minimum supernatant liquid heel in connection with production and/or waste processing.
Aging Waste Neutralized Current Acid Waste (NCAW)	The high-level, first-cycle solvent extraction waste from PUREX.
Airlift Circulator	A device used to introduce air into the bottom of a waste storage tank to provide agitation and minimize bumping.
Annulus	The space between the primary and secondary liners in a double-wall tank.
Assumed Leaker	A tank for which there is an indication of a breach of integrity. Such a tank exhibits surveillance parameter changes that exceed stated criteria limits and less than 95% confidence that it is sound.
Availability	The availability of a component or system is the probability that it will be able to operate successfully at a random point in time.
Breathing	Of tanks, drawing in or giving out vapor or air due to changes in temperature or pressure.
Breathing Air	Separate air supply for fresh air masks.
Burial Ground	A land area specifically designated to receive packaged contaminated waste and equipment for burial.
CAM	Continuous air monitor. Instrumentation for measuring airborne radioactive contamination.
Cascade	Equipment arrangement where process streams flow by gravity from vessel to vessel, column to column; also, radioactive decay scheme.
CASS	Computer-Automated Surveillance System.

Catch Station	Short-term waste storage facility that consists of a double-contained receiver tank and related equipment. It is used for interim storage of liquid wastes and as a valve pit for waste transfer operations. Transfer lines are drained to a catch station.
Catch Tank	Small-capacity single-wall tank, primarily associated with diversion boxes and diverter stations. The tanks collect liquid from diversion boxes, diverter stations, catch stations, and other facilities.
Common-Cause Event	A common-cause event is a single, shared event that adversely affects the performance of two or more components at the same time. When the performance degrades to the extent that component failures result, the event is referred to as a common-cause failure. When the consequences of the event include the occurrence of an accident-sequence initiating event, the event is called a common-cause initiating event.
Complexant Concentrate	The product of concentrating complexed waste.
Complexed Waste	Dilute waste material containing relatively high concentrations of chelating agents (EDTA/HEDTA) from B Plant waste fractionization operation. This waste is stored separately from other waste.
Conductivity Probe	Liquid-level detection device for leak-detection pits, waste storage tanks, catch tanks, etc.
Confirmed or Declared Leaker	The designation of any underground waste storage tank that has been confirmed as a leaker by a review of accumulated data.
Constant Monitoring	Continuous determination of the amount of ionizing radiation or contamination present in a specified place.
Continuous Air Monitor	(CAM) Instrumentation for measuring airborne radioactive contamination.
Cover Block	Removable concrete shields over cell openings and diversion boxes, valve pits, etc.
Crib	A subsurface drainage field used to dispose of low-activity streams.

Critical	The state of a system of fissile material when the effective multiplication factor is equal to unity, i.e., $K_{\text{effective}} = 1$. The neutron gains exactly balance the neutron losses.
Crust	A hard surface layer that has formed in many waste tanks containing concentrated solutions.
DASC	Data acquisition and signal conditioning system.
DCRT	Double-contained receiver tank.
Deentrainer	Usually a densely packed mesh screen that removes droplets and/or particulates from vapor. Also known as moisture separator or demister.
Dependent Events	Two or more events are dependent when the probability of any event in the set is dependent on the occurrence or nonoccurrence of any other event in the set. The two events A and B are independent events if and only if: <div style="text-align: center;"> $\text{Prob}[A \text{ and } B] = \text{Prob}[A] \bullet \text{Prob}[B].$ </div> This requires that: <div style="text-align: center;"> $\begin{aligned} \text{Prob}[B A] &= \text{Prob}[B], \text{ and} \\ \text{Prob}[A B] &= \text{Prob}[A]. \end{aligned}$ </div>
Dilute Double-Shell Slurry Feed (DDSSF)	NCPLX waste, consisting of diluted saltwell liquor and process and laboratory building waste that serves as feed for the production of DSSF.
Dip Tube or Leg	A pipe or combination of pipes extending into a vessel as the suction leg for solution sampling, either for transfer of vessel contents or sensing lines for instrumentation.
Diversion Box	A below-grade concrete structure that contains jumpers and nozzles for routing liquid wastes to designated transfer or storage facilities.
Diverter Station	Similar to a diversion box except waste transfers are made by gravity flow, not under pressure. Solutions enter a station tank and are routed through an outlet spout that leads to the receiving tank.

Double-Shell Slurry (DSS)	The product of concentrating DDSSF to a solid-liquid matrix containing interstitial liquid. The interstitial liquid may not be drainable. For reporting purposes, DSS is considered a solid because it represents a final product form.
Double-Shell Slurry Feed (DSSF)	Noncomplexed waste that has been concentrated until the sodium aluminate in solution is at or near saturation.
Double-Shell Slurry Holding Tank	A tank that is designated for long-term storage of DSS.
Double-Shell Tank	The newer 1-million-gal. capacity underground waste storage tank consisting of a concrete shell and two concentric carbon-steel liners separated by an annulus.
Drainable Interstitial Liquid	Applies to the interstitial liquid that is not held in place by capillary forces and will therefore migrate or move by gravity.
Dry Well	A steel casing, generally 6 in. in diameter or greater, drilled into the ground to various depths and used for access of monitoring instruments to measure the presence of radioactivity or moisture content.
Dry Well (in Tank)	A sealed casing within a tank that is attached to a riser and used for access of a neutron or an acoustical probe to determine the level of drainable interstitial liquor.
End State	The set of conditions at the end of an event sequence that characterizes the impact of the sequence on the plant or the environment.
Evaporator Cystallizers	242-A and 242-S waste concentration facilities that operated at a reduced pressure (vacuum) and were capable of producing a slurry containing about 30 vol % solids at a specific gravity of greater than 1.6.
Evaporator Feed	Any liquid that forms acceptable saltcake with further concentration (e.g., low-heat waste, dilute interstitial liquor, aged waste, and other radioactive waste solutions).

Event Sequence Diagram (ESD)	A logic block diagram that defines event sequence progression from the initiating event to an ultimate end state. The ESD documents the PSA analysts' understanding about how event sequences develop in terms of system responses, plant conditions, and operator actions. They are used as a communication tool with plant operations personnel to elicit their input into the PSA model development and its quantification. The ESD is a precursor to the development of event trees for quantification.
Event Tree	A logical network of event sequences formed to quantify accident frequencies. It contains much of the same information as in the ESD but reflects key modeling assumptions that are needed to support risk quantification. In this PSA, event trees were developed graphically with the PSA workstation software called RISKMAN.
Event-Tree Top Event	Conditions that are considered at each branch point of an event tree. They may address system behavior or operability, human actions, or phenomenological events. A particular event-tree sequence can be described in terms of the status of the plant relative to each top event.
External Event	An event that initiates outside of the plant, although it can affect the operability of plant systems. An earthquake or a missile generated by a tornado are examples of external events.
Failure Rate	The failure rate of a component is the conditional probability of failure on the next demand (for a standby component) or in the next period of operation (for an operating component), given that the component has not already failed.
Fault Tree	A logic diagram that is used to determine the logical combination of causes that will produce an undesired event.
Fault-Tree Top Event	The event at the very top of the fault tree, sometimes referred to as the undesired event, for which the fault tree determines the causes.
FDM	Facility description manual.

FIC Gauge	A Food Instrument Corporation automatic liquid-level gauge based on a conductivity probe. Installed in approximately 85 underground waste storage tanks and, in most cases, electrically connected to a computer for data transmission, analysis, and reporting. Field readings may also be obtained using the LIT.
Fission Product Deposition	A fission product transport process where fission products are removed from the gas phase. Vapors can be removed by adsorption onto solid surfaces or by condensation. Aerosols can be removed by particle agglomeration, turbulent deposition, molecular diffusion, thermophoresis, or sedimentation.
Frequency	The number of occurrences of an event per trial or per unit time. In principle, frequency can be experimentally measured.
Hazard	The source of a danger or consequence.
High-Efficiency Particulate Air (HEPA)	An air filter designed to achieve 99.95% minimum efficiency in the containment of radioactive particulates greater than 0.3 micrometers in size.
Inactive Tank	A tank that has been removed from liquid processing service, pumped to a minimum supernatant heel, and is awaiting, or is in the process of, stabilization and isolation. Includes all tanks not in active or active-restricted categories.
Independent Events	See dependent events.
Initiating Event	An initiating event is any occurrence that perturbs the steady-state condition of the tanks. Initiating events trigger accident sequences that challenge the radionuclide barriers and safety systems.
Interim Isolation	Completion of the physical effort required to stop the addition of liquids into an inactive storage tank, process vault, sump, catch tank, or diversion box.

Interim Stabilized	The condition of an inactive waste storage tank after all liquid technically practical has been removed by a saltwell system using a jet pump. Tanks not requiring saltwells and jet pumps will be interim stabilized by other methods that are to be defined by specific tank studies.
Interstitial Liquor	The liquid that fills the voids in the solids in the waste tank. This liquid is estimated to be about 50% of the solids volume. In saltcake, approximately 60% of the liquor is drainable and about 40% is held in place by capillary forces (nondrainable). In the sludge portion of the tank farm waste, this liquor is not considered pumpable or drainable but may contain pockets of liquid that cannot be estimated.
Intrusion	The entry of any liquid into a facility or structure not intended for storage of the liquid.
Jet Pump	A modified, commercially available jet pump used as a saltwell pump. A centrifugal pump in the pit recirculates a stream to serve as the motive fluid for the jet located at the bottom of the well. The jet pump draws additional solution into the loop at a rate equal to the discharge rate that is controlled by a diaphragm-operated valve.
Jumper	A short pipe used to connect process lines, auxiliary lines, instrument lines, or electrical lines. Most commonly, a rigid or flexible jumper used to connect pit nozzles.
Knuckle	Area where the sides of the tanks are welded to the top and bottom heads.
Lance	A long steel pipe, usually 2 to 3 in. in diameter. The top is bent at a 90° angle and contains a check valve, gate valve, and hose connection. The bottom end of the lance is tapered to a 1/2-in. diam.
Lancing	A lance is placed into a tank containing sludge/solids. Water enters the top of the lance and is forced out the bottom at high pressure. Also, for special purposes, air lancing has been employed.
Lateral	Horizontal drywell under A Farm and certain SX Farm waste storage tanks used for leak detection instruments.

Leak Detection Pit	Collection point for any leakage from waste tanks and DS tanks. The pits are equipped with radiation and liquid-detection instruments.
Operating Limits	Volume, concentration, or weight limits in process vessels or areas designed to preclude personnel hazards, equipment damage, or processing upsets.
Liquid-Level Well (LLW)	A small 3-in. saltwell screen in which dip tubes are placed to measure interstitial liquid level.
Liquid Observation Well (LOW)	A fiberglass drywell placed in the tank that can be used to measure interstitial liquid level.
Liquid Waste	Solutions contaminated with radionuclides in concentrations greater than environmental discharge limits.
Manual Tape	Device used to manually take waste tank liquid level readings.
Mission Time	The time required for a system or component to operate to successfully perform its function.
Monitoring Wells	Holes drilled into the ground to various depths, used to determine presence of radioactivity by instruments lowered into the well or by water samples.
Nonaging Waste	Radioactive liquid waste that is cool enough to permit further processing, primarily as evaporator feed.
Noncomplexed Waste (NCPLX or NCW)	A general waste term applied to all Hanford liquors not identified as complexed or complexed waste.
Occurrence Report	A report to DOE-RL covering an off-standard condition, accident, or incident.
Open-Hole Saltwell	A pump inserted into a waste tank with the suction at or below the solids level; frequently used to remove the bulk of the liquid, particularly in tanks containing less than 2 ft of sludge.
Partial Interim Isolation	Completion of the physical effort required for interim isolation except for isolation of risers and piping required for jet pumping or for other methods of stabilization.

Primary Stabilization	The condition of an inactive waste storage tank after all liquid above the solids (other than isolated surface pockets) has been removed. Isolated surface pockets of liquid are those not pumpable by conventional techniques.
Probability	A numerical measure of a state of knowledge, a degree of belief, or a state of confidence about the outcome of an event.
PUREX Plant	Plutonium-Uranium Reduction Extraction (Plant).
Questionable Integrity	Any tank that has a small decrease in liquid level or a radiation increase in an associated drywell for which the data are insufficient to support a conclusion that the tank is sound.
Raffinate	Material from which some soluble substance has been extracted.
Raw Water (RW)	Untreated and unfiltered water.
Resource Conservation Recovery Act (RCRA)	A federal program requiring cradle-to-grave accounting by owners and operators of facilities that generate, transport, treat, store, or dispose of hazardous materials after November 19, 1990.
Release Category	Characterize major classes of accident sequences in terms of the nature, timing, and magnitude of the release of radioactive or toxic material from the tanks during an accident. The factors addressed in the definition of the release categories include the response of the tank structure, timing, and mode of tank failure; timing, magnitude, and mix of any releases of radioactive material; thermal energy of release; and key factors affecting deposition and filtration of radionuclides. Release categories can be considered the end states of the PSA.
Reliability	The probability that a component will operate successfully over a specified mission time, given that it is successfully operating at the start of the mission.
Riser	The upright pipe projection from the top of a tank.

Risk	The frequency of and consequence of specified accident scenarios. Risk can be quantified by identifying potential scenarios, quantifying the frequency of those scenarios, characterizing the consequences of the scenarios, and quantifying the uncertainties in the frequency and damage estimates.
RISKMAN	A PC-based PSA software system for developing and evaluating models for PSA. Following a qualitative analysis phase early in this project, all model building, database development, and event sequence quantification tasks in the PSA are performed using RISKMAN.
Saltcake	Nondeliquescent crystals (at average Hanford Site air conditions) formed by evaporation, cooling, and/or settling.
Saltwell	A screened well casing inserted into waste tank solids, extending to near the bottom of the tank. The well may contain a jet pump to remove interstitial liquid that drains into the well from surrounding solids.
Saltwell Pump	A low-capacity pump used to remove interstitial liquor from saltwells.
Saltwell Receiver Tank	Receives liquid that has been jet pumped from saltwells.
Seismic Fragility	The seismic fragility of a structure or component relates to the fraction of seismic events of a specified intensity that results in failure of the structure or component.
Seismic Hazard	The seismic hazard is normally defined in terms of a curve of the frequency of seismic events as a function of the earthquake intensity measured in units of peak horizontal ground acceleration at the plant site grade level. The curve accounts for all events in the seismic region of the plant corrected for attenuation between the epicenter and the plant site.
Single-Shell Tanks (SSTs)	Tanks constructed of a concrete shell (wall) and one steel liner, used to contain high-level wastes.

Source Term	The radiological source term for a given accident sequence or release category consists of the release fractions for various radionuclide groups and the timing, elevation, and energy of the release.
Split Fraction	A parameter used in quantifying an event tree. It is the fraction of the time within which each possible outcome, or branch, of a particular top event may be expected to occur. Depending on the meaning of the event-tree top event, the split fraction can be a frequency or a probability. Split fractions are, in general, conditional on precursor events. At any branch point, the sum of all the split fractions representing all possible outcomes must be unity.
Stabilized	The condition of an inactive waste storage tank following removal of all supernatant (free-standing) and interstitial liquid that it is technically practical to remove.
STADIC	A computer code to determine the probability distribution of the value of a function by statistically combining the probability distributions that describe the independent parameters that define the function. STADIC utilizes Monte Carlo sampling techniques to combine the parameters.
Tank Farm	Grouping of a number of storage tanks (e.g., the chemical tank farm, which stores chemicals used in a plant, or the underground waste tank farm, which stores radioactive waste).
Transfer Box	A type of diversion box usually associated with sluicing operations.

APPENDIX B

PROBABILISTIC CAPACITY OF THE 241-SY-101 UNDERGROUND WASTE STORAGE TANK TO WITHSTAND SEISMIC EXCITATION AND HYDROGEN BURN

August 1992

Prepared for:

PLG, INC.
Newport Beach, California

PROBABILISTIC CAPACITY OF THE 241-SY-101 UNDERGROUND WASTE STORAGE TANK TO WITHSTAND SEISMIC EXCITATION AND HYDROGEN BURN

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EQE Project Number: 52172.01

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1. INTRODUCTION

A probabilistic risk assessment of the Hanford 241-SY-101 underground waste storage tank is being conducted by PLG, Inc. to evaluate the probability of radioactive release. In this study, systems models, event trees, and fault trees are used to determine the risk. EQE Engineering is under contract to PLG, Inc. to establish the capacity of the tank structure for both earthquake and pressure loadings resulting from a hydrogen burn. For hydrogen burn, the probability of failure as a function of internal pressure has been developed for critical failure modes of the tank. The variability in the probability of failure is also included. For seismic excitation, the probability of failure is developed as a function of peak free field ground acceleration.

The 241-SY-101 underground storage tank is used for long term storage of high level radioactive wastes. The tank has an outside diameter of approximately 83 feet and is about 56 feet high overall. A double wall tank configuration is used as shown in Figure 1-1, with a primary tank of 75 foot diameter used to contain the waste. The primary tank wall thickness varies from 7/8 inch at the base knuckle to 3/8 inch at the dome. The concrete wall is 1'-6 thick in the cylinder to 1'-3 thick in the dome, reinforced with ASTM A-615-68 Grade 60 reinforcing steel and the concrete 28 day design compressive strength is 4500 psi. A 3/8 inch thick secondary liner is used for the concrete base and cylinder into the haunch region as shown in Figure 1-2. The secondary liner and primary tank are not welded. Both are fabricated from ASTM 516 Grade 65 carbon steel plate. The primary tank is separated from the secondary tank liner on the base slab by an 8 inch thick insulating concrete slab. The base slab is 11-1/2 inches thick locally thickened to 2 foot around the periphery and the center. The cylinder-base slab interface is a sliding connection with graphite between steel plates as shown in Figure 1-3. A steel angle curb limits outward radial motion of the cylinder with respect to the base slab. A minimum of 6'-6 of overburden is placed above the dome.

A considerable amount of analysis has previously been conducted to establish both the seismic behavior of the tank, as well as investigate the capacity of the tank to withstand a hydrogen burn. References 1 through 4 evaluate the seismic capacity at design basis acceleration including the effects of soil-structure interaction. References 5 and 6 consider the effects of a hydrogen burn. Maximum utilization

of these existing results was made wherever possible in the current evaluation. As such, most of the effort reported here was to obtain estimates of tank seismic acceleration and internal pressure failure capacities rather than just satisfying nonfailure at the design basis. In this sense, it was necessary to assure that all results were consistent and in a form readily usable by the risk analyst, including a representation of the uncertainty in the reported capacities.

Figure 1-1: 241-SY-101 Tank Configuration

Ref.: Automation Industries, Inc.
Dwg. H-2-37706, Rev. 2

Figure 1-2: Haunch Reinforcing and Liner

Ref.: Automation Industries, Inc.
Dwg. H-2-37706, Rev. 2

Figure 1-3: Cylinder-Base Slab Interface

2. PROBABILISTIC DESCRIPTION OF INTERNAL PRESSURE CAPACITY

In order to fit into the PRA context, a probabilistic description of the pressure capacity of the tank is required. Also, since the pressure capacity is treated as a random variable, it is possible for more than one failure mode to significantly contribute to the risk. Therefore, several failure modes must be evaluated. This section discusses how the capacities are described in a probabilistic form.

It should be noted that in the current investigation, stresses are not categorized as primary membrane, primary bending, etc., which are then compared with different allowables depending on the load condition as is required in a code or design calculation. Rather, failure is based on expected ultimate strengths and elongations using median material properties and associated variabilities.

2.1 DEVELOPMENT OF FAILURE PROBABILITIES

The pressure capacities are evaluated using limit state analyses for the various failure modes considered. The capacities are dependent on several factors, including the material properties, modeling assumptions, and the postulated failure criteria. A major source of uncertainty in the failure criteria is the expected strain resulting in failure. All welds are full penetration and the probability of failure at membrane strains of either the primary tank or the secondary liner below yield is considered to be quite low. On the other hand, biaxial strains and gage length effects as well as strain concentrations and bending significantly reduces the expected membrane strain at failure when compared to elongation data developed from standard specimen ultimate tests. Since test data from vessel tests are extremely limited, especially for dynamic load conditions, considerable variability is introduced not only in the failure criteria, but in analytical modeling and other assumptions. Since many of the base parameters are random and the methods used to evaluate the capacities are subject to some uncertainty, the pressure capacity for any failure mode is also considered to be a random variable. It is assumed that the pressure capacities have a lognormal distribution. This assumption is made because a lognormal distribution has been shown to be a valid description of the variability in material strengths. In addition, for a random variable

that can be expressed as the product and quotient of several random variables, the distribution of the dependent variable tends to be lognormal regardless of the distributions of the independent base variables.

Variability in the pressure capacity of a closed vessel results from a number of sources including material properties, pressure pulse shape and duration, and analytical modeling assumptions. Material properties and analytical modeling uncertainties were included in the current investigation. The latest hydrogen burn pressure pulse shows a rise time in the order of 0.3 seconds or more and virtually constant pressure for several seconds. In order to develop any appreciable increase in dynamic yield strength over static strength of either reinforced concrete or steel, rise times in less than about 100 milliseconds are required (Reference 7). Also, the constant pressure period after the rise results in essentially a static condition for the tank (except that the overburden may be thrown in the air at high internal pressures). Thus, essentially no randomness in material properties results from using the Reference 6 pulse shape shown in Figure 2-1 as median centered. Some variability results from the dynamic amplification of the tank, which is combined with the variabilities from the static material properties and analytical modeling uncertainty. Different assumed values of friction between the concrete cylinder and surrounding soil were used in the Reference 6 analysis. Although the actual friction values were not included in Reference 6, the variation of this parameter appears to influence the magnitude of the internal pressure much more than the shape of the pulse.

The pressure capacity assumed to be a lognormal random variable and denoting it as P , the probability of failure occurring at a pressure less than a specific value p is expressed as:

$$P_f = \text{Prob}(P \leq p) = \Phi \left(\frac{\ln(p/\hat{P})}{\beta_c} \right) \quad (2-1)$$

Where

P_f = probability that failure occurs at a pressure $P \leq p$

P = random pressure capacity

β_c = logarithmic standard deviation of P

$\hat{P}$ = median pressure capacity

$\Phi(\cdot)$ = cumulative distribution function for a standard normal random variable

In Equation (2-1), the pressure capacity for a given failure mode is probabilistically described by the following expression.

$$P = \hat{P} \cdot M \cdot S \quad (2-2)$$

in which $\hat{P}$ is the median pressure capacity, M is lognormally distributed random variable having a unit median and a logarithmic standard deviation β_M representing the uncertainty in modeling, and S is also a lognormally distributed random variable with a unit median value and a logarithmic standard deviation β_S representing the uncertainty in the material properties. The overall uncertainty in the median capacity is obtained by taking the square root of the sum of the squared of β_M and β_S .

The median pressure capacity represents the internal pressure level for which there is a 50% probability of failure (leakage) for a given failure mode. The median values are evaluated from limit state analyses for the different failure modes. The uncertainties, β_M and β_S , are associated with variability due to a lack of knowledge related to differences between the analytical model and the real structure.

Modeling uncertainties are associated with the assumptions used to develop analytical models and their ability to properly represent the failure condition. The strength uncertainties are associated with variabilities related to the material resistance. Examples of the sources of such uncertainties include: variability in concrete strength, steel yield strength, and stress-strain relationships.

2.2 VARIABILITY IN MATERIAL PROPERTIES

Code values of material strengths typically are minimum values whereas actual material properties and associated variabilities are required for the type of evaluation considered here. Reference 6 uses the following values for ASTM 516 Grade 65 as "typical" properties:

$$\begin{aligned}\sigma_Y &= 51 \text{ ksi} \\ \sigma_U &= 80 \text{ ksi} \\ \epsilon &= 31\%\end{aligned}$$

Assuming the elongation corresponds to a 2 inch gage length, the above values may be considered as essentially median values. Based on test data for similar materials and assuming a lognormal distribution, the following median values and variabilities were used for ASTM 516 Grade 65 plate for the current evaluation:

$$\begin{aligned}\hat{\sigma}_Y &= 51 \text{ ksi} & \beta &= 0.09 \\ \hat{\sigma}_U &= 80 \text{ ksi} & \beta &= 0.07 \\ \hat{\epsilon} &= 31\% & \beta &= 0.24\end{aligned}$$

Based on information available in the literature (Reference 8) the following median strength values and variabilities were used for the ASTM 615-68 Grade 60 reinforcing bars:

$$\begin{aligned}\hat{\sigma}_Y &= 71 \text{ ksi} & \beta &= 0.09 \\ \hat{\sigma}_U &= 110 \text{ ksi} & \beta &= 0.13 \\ \hat{\epsilon} &= 12\% & \beta &= 0.14\end{aligned}$$

The concrete is also expected to exhibit strengths above the 4500 psi 28 day design value. In addition, concrete can be expected to increase in strength with time after the 28 day test. Site specific data on the concrete was not available at the time of this investigation. Based on comparison with tests from other 4500 psi design concrete, a median value of f_c' equal to 5640 psi with a lognormal standard deviation of 0.11 was estimated.

In addition to the variabilities in the yield stress, ultimate stress, and elongation, variability exists in the post yield stress-strain relationships, the crack spacing in the concrete and corresponding average strain in the reinforcing steel, and the failure strain in the primary tank and secondary liner. Since all credible failure modes of the tank involve some degree of inelastic deformation, these sources of variability must also be accounted for.

2.3 MODELING VARIABILITY

Uncertainties will exist in the estimated pressure capacities due to differences between the analytical idealization of the structure and the real conditions. There are numerous possible sources of modeling uncertainties. Examples of the sources of modeling uncertainties include: assumptions used to develop the internal force distributions, failure criteria, and the use of empirical formulae. Moreover, since they are dependent on the particular failure mode under consideration, they must be evaluated on a case-by-case basis. Bounding analytical assumptions such as different boundary conditions can often be used to establish an estimate of the modeling variability. However, in many instances, the evaluation of these uncertainties would require very detailed analysis and/or extensive data which may not be available. As a result, it was necessary to use subjective evaluation and engineering judgment to estimate these uncertainties. The evaluation of the modeling uncertainties associated with the estimated pressure capacities is included in the discussion of the specific failure modes in the next section.

2.4 PRESSURE CAPACITY

The expected pressure capacity was calculated for several modes of failure including the primary tank, secondary tank, and the dome. Failure was defined as breach of the pressure boundary. Results of existing analyses (References 5 and 6) were used to the extent possible, supplemented by hand calculations where required.

In addition to the hydrogen burn pressure capacities, pressure capacities for static conditions were also developed as a comparison for several failure modes.

In order to estimate the membrane capacities, several issues must be considered, which include: the median failure criteria including median strains expected for failure, the stress-strain behavior of the reinforcing and plate steel, and the variabilities associated with these parameters. No credit was taken for the tensile strength of the concrete. The failure strain of the reinforcing steel was estimated by assuming uniform bond stress per unit length of the reinforcement and linear bar stress between points of maximum stress (at concrete crack locations) and

minimum stress. Average reinforcing strain at bar fracture was estimated at about 4.5% based on an average crack spacing of 24 inches as determined in Reference 9.

The expected failure strain of the primary and secondary liners is more complex. The ASME Code minimum uniaxial elongation is 19% in a 2 inch gage specimen, with expected median uniaxial elongation of about 31% as shown in Section 2.2. Reference 5 notes that hydrogen embrittlement was considered and was found to be unlikely. However, a biaxial stress state, gage length effects, and strain concentration effects will substantially decrease this value when compared to uniaxial test data. Manjoine (Reference 10) suggests a triaxial reduction factor of the form

$$T.F. = \frac{\sqrt{2}(\sigma_1 + \sigma_2 + \sigma_3)}{[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2]^{1/2}}$$

For an unrestrained cylinder and sphere, a reduction in uniaxial strain of 1.73 and 2.0 respectively results.

Another factor which can influence the failure strain is the effective gage length. Part of the elongation reported for a 2 inch uniaxial test specimen results from necking. For longer specimens, the necking portion of the elongation remains essentially constant so that the total elongation for longer length specimens is less (i.e., the elongation for a uniaxial 8 inch test specimen is less than for a 2 inch specimen). In addition, strain concentrations such as around the nozzles in the dome will further reduce the expected global strain at failure. Based on these considerations, a median failure strain of 9% with a lognormal standard deviation of 0.38 was assumed to correspond to failure for the primary and secondary cylinder portions of the tank, with a median failure strain of about 7.5% and lognormal standard deviation of 0.40 for the dome.

A value of 0.015 inches corrosion was assumed for the primary tank in Reference 5, and the same value was used for both the primary tank cylinder and dome in the current investigation. This may introduce some conservatism in the dome. Failure in the primary tank cylinder is expected to occur in the nominal 3/8 inch thick upper course. Based on the material properties discussed above, static yielding in this region is expected to occur at about 41 psig with a lognormal standard deviation of

0.10. The strain in the cylinder required to close the 30 inch gap between the primary and secondary tank is 6.67%. The secondary tank has a median static yield capacity (independent of the primary tank) of about 63 psig. If the primary tank has not failed prior to closing the annular gap, some strain hardening of the primary tank will occur resulting in a median static pressure of about 110 psig at yield of the secondary tank and 6.7% strain in the primary tank. Note, however, that based on the variability in failure strain in the primary tank, there is about 24% probability of failure before the primary tank contacts the secondary tank wall. If the primary tank fails before the secondary tank reaches the 4.5% median strain corresponding to rebar failure, the median static failure pressure of the secondary tank is about 76 psig with a lognormal standard deviation of 0.11. If the primary liner remains intact up to the median failure strain of the rebar, the median static capacity of the combined primary and secondary tanks is 130 psig. However, there is a 76% probability that rupture of the primary tank will have occurred prior to developing the median secondary tank rebar failure strain.

The dome failure capacity is determined only by the primary tank and reinforced concrete since the secondary tank liner is discontinued above the haunch. A median static yield pressure of about 42 psig and a median static failure pressure of about 51 psig, each with a lognormal standard deviation of 0.10 for the dome were calculated.

Based on the static failure pressures discussed above, the controlling failure mode is expected to be the dome. A similar location is expected for the dynamic hydrogen burn condition. Assuming a pulse shape similar to that shown in Figure 2-1 with a rise time in the order of 0.3 seconds and essentially a constant pressure dwell for several additional seconds, the median dynamic failure pressure in the dome was estimated to be 46 psig with a lognormal standard deviation of 0.27. This failure pressure includes consideration of the dynamic response characteristics of the tank including the fact that of the overburden above the dome is likely to be thrown into the air at pressures approaching failure. Impact of the soil on the dome after being thrown in the air above is unlikely to cause failure unless internal tank pressure has resulted in tearing the primary dome liner. However, above ground components immediately above the tank will likely be failed, and assuming failure of

the dome due to internal pressure, impact of the falling soil will likely result in collapse of the dome and soil into the tank with sloshing of liquids out of the tank as well as airborne release.

MAX OP BURP / VENT SYS INOP / RISER CLSD

CASE 10

FULL FRICTION

Figure 2-1: Pressure-Time Relation (Reference 6)

3. PROBABILISTIC DESCRIPTION OF SEISMIC CAPACITY

The probabilistic seismic capacity of the tank and selected above ground components was determined in much the same manner as the hydrogen burn pressure capacity was determined. Maximum use was made of existing seismic analysis results (Reference 1, 2, 3 and 4). Where analysis results were not available, as in the case of the above ground equipment, estimates of seismic capacities were developed based on performance of similar equipment to earthquake excitation.

Seismic fragility of the tank or above ground component is defined as the conditional frequency of its failure for a given value of the ground motion parameter (for example, peak ground acceleration). Thus, the fragility evaluation is based on the estimation of the median ground acceleration value for which the seismic response of a given component exceeds its capacity, resulting in failure. Because there are many sources of variability in the estimation of the median ground acceleration capacity, the component fragility is described by means of a family of fragility curves. Figure 3-1 depicts such curves, showing the median (50 percent confidence) curve with its shape governed by randomness variability, (β_R), and showing the relative position of the curve for other confidence levels greater than or less than 50 percent. The properties of the fragility curves and the general approach to their development are defined in previous works (References 11 and 12). Employing the characteristics of the lognormal distribution as described in these references, the entire family of fragility curves for any mode of failure is defined in terms of a median estimate of the ground acceleration capacity, $\hat{A}$ (Figure 3-1), times the product of randomness and uncertainty variables, ϵ_R and ϵ_U , which have unit median values and are lognormally distributed with logarithmic standard deviations of β_R and β_U , respectively.

$$A = \hat{A} \epsilon_R \epsilon_U \quad (3-1)$$

The median ground acceleration capacity, $\hat{A}$, is computed as:

$$\hat{A} = \hat{F} \cdot A_R \quad (3-2)$$

where $\hat{F}$ equals the median overall factor of safety based on response to the reference earthquake, and A_R equals the peak ground acceleration of the reference earthquake.

In this study, the guidelines used to estimate the values of β_R and β_U for each variable affecting the fragility were based on considering the inherent randomness, β_R , to be associated primarily with the earthquake characteristics themselves, and the uncertainty, β_U , to be associated with lack of knowledge of the model and material parameters. Thus, the variability resulting from earthquake response spectra shape and amplification, earthquake duration, numbers and phasing of peak excitation cycles, together with their contributions to structure ductility and response characteristics was attributed to randomness. In general, it is not considered possible to significantly reduce randomness by additional analysis or test based on current state-of-the-art techniques. Uncertainty, on the other hand, is considered to result primarily from analytical modeling assumptions and other knowledge gaps concerning variables such as material strength and damping that could, in many cases, be reduced by additional study or test.

The lognormal distribution can be justified as a reasonable distribution since the statistical variation of many material properties (References 13 and 14) and seismic response variables (Reference 15) may reasonably be represented by this distribution. In addition, the central limit theorem states that a distribution consisting of products and quotients of distributions of several variables tends to be lognormal even if the individual distributions are not lognormal.

3.1 SEISMIC FRAGILITY OF THE TANK

In the evaluation of the seismic fragility of the tank, several potential failure modes were investigated. Two levels of failure were included. First, the fragility of the primary tank shell was evaluated. This involved an evaluation of a breach of the primary tank shell. Second, the capacity of the outer concrete shell was evaluated to arrive at a fragility associated with a gross leakage from the tank. The various existing soil-structure interaction analyses were used as a basis for developing relationships between the seismic input and the tank response.

As previously noted, the seismic fragility is described in terms of a median free field ground acceleration capacity and logarithmic standard deviations associated with

randomness and uncertainty. By anchoring the median ground acceleration capacity to a reference motion, the fragility can then be expressed in terms of a series of probabilistic factors of safety and their associated logarithmic standard deviations. These factors of safety are evaluated for the various parameters that affect the strength and response of the structure.

The configuration of the primary steel tank is such that it can be considered as a cylindrical, flat bottom tank supported at both the top and bottom. The soil-structure interaction analyses results contained in Reference 4 included response spectra at various elevations of the tank. These spectra were developed from time history analyses which had an input ground surface motion with a peak acceleration of 0.2g. Using these spectra and the analysis methods presented in References 16 and 17, the response of the steel tank shell could be evaluated including both the impulsive and convective fluid responses. Since the tank fluid level is approximately at the haunch, the available freeboard is not adequate for the fluid free surface sloshing and thus, the tank dome partially restrains the sloshing response. As a result, in evaluating the primary tank shell response, the median fluid response was assumed to be bounded by a totally impulsive response (convective response restrained) and the combined impulsive and convective responses. For the impulsive and the convective fluid response, median damping ratios of 5% and 0.5%, respectively, were used.

The critical failure mode for the inner primary tank was found to be shear buckling of the 3/8" steel shell at the top of the tank where it joins the dome. Median factors of safety referenced to the 0.2g ground acceleration were evaluated for the capacity and the response as affected by the spectral shape, damping, modeling, earthquake component combination, and soil structure interaction. The median factors of safety and the corresponding logarithmic standard deviations are shown in Table 3-1. Also shown in Table 3-1 are the median ground acceleration capacity and the HCLPF capacity of the shear buckling failure of the primary tank.

In the evaluation of the fragility of the outer concrete tank, the critical failure mode was found to be a flexural failure of the dome at the haunch. This failure mode was judged to be primarily due to the vertical seismic input. The internal force distribution for the concrete tank in Reference 1 was used to estimate the maximum dead load and seismic moments at the haunch. However, the vertical seismic response in Reference 1 was based on an assumed rigid structure in the

vertical direction. Therefore, in estimating the median seismic demand loads, the results from Reference 1 were adjusted to reflect a median vertical ground spectral shape consistent with NUREG/CR-0098 (Reference 18) and a median damping ratio 7% for the reinforced concrete tank. In evaluating the strength factor of safety, it was assumed that the peak vertical ground acceleration is 2/3 of the peak horizontal ground acceleration. Since the failure mode is associated with a ductile flexural response, additional capacity beyond the static capacity can be accounted for through inelastic energy absorption. Table 3-2 shows the median factors of safety, the corresponding logarithmic standard deviations, and the overall seismic fragility parameters for the failure of the reinforced concrete dome.

3.2 ABOVE GROUND COMPONENTS

Seismic fragilities were estimated for several above ground components. These included:

1. Offsite power
2. Electric cabinet
3. Instrument rack/pump start controls (anchored)
4. Above ground piping and ducts

The fans were not included in the current evaluation since no information was available for the fans at the time the current investigation was completed. Provided the fans have adequate anchorage and are not mounted on vibration isolator supports, it is expected they will have fairly high seismic capacities.

In general, engineering drawings with sufficient detail to calculate accurate seismic fragilities were not available. For instance, Automation Industries, Inc. Dwg. H-2-37746, Rev. 2, "Ventilation Equipment Plan and Details" calls out concrete anchor bolts 6" o.c. (minimum) for the electrical cabinet, but does not specify the bolt size or embedment depth. No results of any previous seismic analyses were available, nor were any weights available.

The approach adopted to estimate the fragilities for the above ground components was based on comparisons of the seismic behavior of similar equipment to actual earthquakes (Reference 19). These results were supplemented by hand calculations to develop the component seismic response and expected capacity

where sufficient information was available. This approach introduces considerable uncertainty but is expected to yield acceptable results. Table 3-3 shows the seismic fragilities for the above ground components. Included in Table 3-3 are the median acceleration, the lognormal standard deviation for randomness, β_R , the lognormal standard deviation for uncertainty, β_U , and the high confidence of low probability of failure (HCLPF) acceleration which is arbitrarily defined as 95% confidence of less than 5% probability of failure.

Table 3-1

SEISMIC FRAGILITY FOR PRIMARY TANK SHELL

Failure Mode: Shear Buckling at the top of Primary Tank Shell

Factor	$\check{F}$	β_R	β_U
Strength	3.6	0	0.22
Spectral Shape	1.0	0.25	0
Damping	1.0	0	0.11
Modeling	1.0	0	0.23
Earthquake Component Comb.	1.0	0.05	0
Soil Structure Interaction	1.31	0.10	0.13
	4.7	0.27	0.36

$$\check{A} = 4.7 \times 0.2g = 0.94g$$

$$HCLPF = 0.94e^{-1.65(0.27 + 0.36)} = 0.33g$$

Table 3-2

SEISMIC FRAGILITY FOR THE REINFORCED CONCRETE SHELL

Failure Mode: Flexural Failure of the Dome

Factor	$\check{F}$	β_R	β_U
Strength	8.0	0	0.19
Inelastic Energy Absorption	1.68	0.07*	0.13
Spectral Shape	1.0	0.25	0
Damping	1.0	0	0.11
Modeling	1.0	0	0.15
Earthquake Component Comb.	1.0	0.05	0.10
	13.44	0.26	0.31

$$\check{A} = 13.44 \times 0.2g = 2.7g$$

$$HCLPF = 2.7e^{-1.65(0.26 + 0.31)} = 1.05g$$

Table 3-3

ABOVE GROUND COMPONENT SEISMIC FRAGILITIES

Component	Median Seismic Acceleration (g)	β_r	β_u	HCLPF (g)
Offsite Power	0.3	0.25	0.50	0.10
Electric Cabinet	0.5	0.25	0.34	0.19
Instrument Rack/Pump Start Controls	0.8	0.25	0.17	0.4
Above Ground Piping and Ducts	> 1

Figure 3-1: Typical Fragility Curve Representation

4. REFERENCES

1. ARH-R-172, "Analysis of Underground Waste Storage Tanks 241-SY at Hanford, Washington," prepared by URS/John A. Blume and Associates, Engineers, for Atlantic Richfield Hanford Company, Richland, Washington, October 1974.
2. RHO-C-59, "Additional Analysis of Underground Waste Storage Tanks 241-SY, Hanford, Washington," prepared by URS/John A. Blume and Associates, Engineers, for Vitro Engineering, Richland, Washington, July 1981.
3. Becker, D.L., et al, "Summary Status of the Seismic Evaluations on the Hanford Site Radioactive Waste Storage Tanks," WHC-EP-0373 UC-703, September 1990.
4. Giller, R.A. and E.O. Weiner, "Soil Structure Interaction Analysis for Hanford Site 241-SY-101 Double-Shell Waste Storage Tanks," WHC-EP-0504, Volume 1 and 2, September 1991.
5. Fox, G.L., et al, "Response of Tank 241-SY-101 to a Postulated Hydrogen Burn," WHC-SD-WM-TI-426, Rev. 0, May 1990.
6. Appendix P: Structural Consequences of a Hydrogen Burn, Preliminary Draft, APP P-1, June 1992.
7. Kinney, G.F. and K.J. Graham, Explosive Shocks in Air, 2nd Edition, Springer Verlag, New York, 1985.
8. Mirza, S.A. and J.G. MacGregor, "Variability of Mechanical Properties of Reinforcing Bars," Journal of the Structural Division, ST5, ASCE, May 1979.
9. Park, P. and T. Paulay, Reinforced Concrete Structures, John Wiley & Sons, New York 1975.
10. Manjoine, M.H., "Ductility Indices at Elevated Temperature," J. Engineering Materials and Technology, Trans. ASME, Vol. 97, Series H, No. 2, 1975, pp. 156-161.

11. Kennedy, R.P., et al., "Probabilistic Seismic Safety Study of an Existing Nuclear Power Plant," Nuclear Engineering and Design, Vol. 59, No. 2, pp. 315-338.
12. Kennedy, R.P., and M.K. Ravindra, "Seismic Fragilities for Nuclear Power Plant Risk Studies, Nuclear Engineering and Design, Vol. 79, No. 1, pp. 47-68.
13. Freudenthal, A.M., J.M. Garrelts, and M. Shinozuka, "The Analysis of Structural Safety," Journal of the Structural Division, ASCE, ST 1, pp. 267-325, February 1966.
14. Kennedy, R.P., "A Statistical Analysis of the Shear Strength of Reinforced Concrete Beams," Technical Report No. 78, Department of Civil Engineering, Stanford University, Stanford, California, April 1967.
15. Newmark, N.M., "A Study of Vertical and Horizontal Earthquake Spectra," WASH 1255, Nathan M. Newmark Consulting Engineering Services, prepared for USAEC, April 1973.
16. Veletsos, A.S. and Shivakumar, P., "Hydrodynamic Effects in Tanks with Different Conditions of Support," Proceedings, Third DOE Natural Phenomena Hazards Mitigation Conference, 1991, pp. 578-587.
17. "Draft Seismic Design and Evaluation Guidelines for the Department of Energy High Level Waste Storage Tanks," February 1992.
18. Newmark, N.M. and Hall, W.J., "Development of Criteria for Seismic Review of Selected Nuclear Power Plants," NUREG/CR-0098, May 1978.
19. Horstman, N.G. and S.W. Swan, "Summary of the Seismic Adequacy of Twenty Classes of Equipment Required for the Safe Shutdown of Nuclear Plants," prepared for the Seismic Qualification Utility Group, February 1989.

APPENDIX C

EXTERNAL EVENTS ANALYSIS

1.0. INTRODUCTION

A PSA must include a comprehensive analysis of external events, such as earthquakes, because of their ability to start an accident while simultaneously compromising the ability of safety systems to mitigate these accidents. Past probabilistic safety analyses (PSA) have shown that external events can contribute significantly to the overall risks.

The potential external events identified in the USNRC's "Procedures Guide"¹ were reviewed for their applicability to Hanford. The results of this screening are presented in Table C-1.

The next step in the external events analysis was to conduct a quantitative screening analysis of the external events retained in Table C-1. The objective of the quantitative screening analysis was to eliminate from further consideration any external events that could either be shown to be incapable of producing a release from the Hanford Tank Farms or whose release-frequency was much lower than the frequency of comparable releases from internal events. The methodology for this approach was comprised of the following major steps:

1. Readily available information was used to estimate the occurrence frequencies and impacts of the external events that were determined by the screening procedure to be applicable to the tank farm.
2. The specific tank facilities that may be subject to damage or malfunction from the external-event hazard were identified and assigned a conservative conditional resultant unavailability probability.
3. The possible ways in which event damage could lead to releases of radionuclides or toxic gases were logically, but qualitatively determined.
4. For damaging scenarios that could lead to tank leakage, a conservative estimate of the annual tank release frequency was made.

Where it was unclear whether the damage caused by an external event could be extensive or when possible consequences were unknown, as in the case of seismic and dome overload events, a second approach involving more detailed analysis was used to estimate release frequency.

TABLE C-1
NATURAL AND MAN-INDUCED EXTERNAL EVENTS TO BE
CONSIDERED IN THE HTF PSA^a

Events	Remarks
Aircraft Crash	Discussed in Sec. C.6.
External Flooding	Discussed in Sec. C.4.
Extreme Winds and Tornadoes	Discussed in Sec. C.5.
External Fire	Discussed in Sec. C.3.
High Tide, Lake Level, River Stage	Included with external flooding, Sec. C.4.
Industrial or Military Facility Accident	Discussed in Sec. C.9.
Internal Flooding	Included with water intrusion; Sec. D 3.8.
Lightning	Discussed in Sec. C.7.
Intense Precipitation	Included with tank dome overload; Sec. D 3.2.
Release of Chemicals in Onsite Storage	Included with accidents at other Hanford Area facilities, Sec. C.9.
Sandstorm	Included with extreme winds, Sec. C.5.
Seiche	Included with external flooding, Sec. C.4.
Seismic	Discussed in Sec. C.2.
Storm Surge	Included with external flooding, Sec. C.4.
Transportation Accidents	Included with accidents at other Hanford Area facilities, Sec. 9.9.
Tsunami	Included with external flooding, Sec. C.4.
Toxic Gas	Included with accidents at other Hanford Area facilities, Sec. C.9.
Volcanic Activity	Discussed in Sec. C.8.
Waves	Included with external flooding, Sec. C.4.
Avalanche	Not on an avalanche site.
Coastal Erosion	Not on coast.

^aModified from Ref. 1, App. C.

TABLE C-1 (CONT)

Events	Remarks
Forest Fire	No forests in the Hanford Area. Range fire is included in Sec. C.3.
Hurricane	Not in a hurricane area (321 km from the ocean).
Landslide	Not on a landslide site.
Fog	Internal initiating events data include any effects of fog.
Drought	Internal initiating events data include any effects of drought.
High Summer Temperature	Internal initiating events data include any effects of high summer temperature.
Frost	Internal initiating events data include any effects of frost.
Low Winter Temperature	Internal initiating events data include any effects of low temperature.
Pipeline Accident	Internal initiating events data include pipeline accident.
Snow	Internal initiating events data include any effects of snow.
Ice Cover	No body of water is used as a heat sink for the Hanford Tank Farm.
Low Lake or River Water Level	No body of water is used as a heat sink for the Hanford Tank Farm.
River Division	No body of water is used as a heat sink for the Hanford Tank Farm.
Soil Shrink-Swell Consolidation	Controlled by tank design codes. Internal initiating events data include any effects of soil failure.
Hail	Risk bounded by extreme winds.
Meteorite	Risk bounded by aircraft crash.

^aModified from Ref. 1, App. C.

In the course of this evaluation, many judgments were made with regard to the importance of these external events. Following the general recommendation in the "PRA Procedures Guide,"¹ which states that an event with a mean frequency of occurrence of much less than that for other events may be excluded as important to risk, we excluded from further consideration all external events that contribute less than 1% to an internal initiating event frequency.

A draft report from an in-progress Hanford Waste Vittrification Plant (HWVP) safety study was also used to identify external events.² Because the planned HWVP will be located on the 200 East Area near the tank farm, most external events are common to both HWVP and the tank farm. Since the draft HWVP safety study report evaluated almost the same spectrum of external events that are considered important for the tank farm, the analysis documented in the draft safety report for the HWVP was used wherever possible.

2.0. SEISMIC RESPONSE ANALYSIS

A seismic response assessment was performed on a double-walled waste storage tank, associated equipment pits, tank gas exhaust ductwork system, and support facilities. The assessment consisted of the five separate analyses discussed below.

1. **Seismic Hazard Analysis.** Determination of the frequency of various potential peak ground accelerations at the site.
2. **Fragility Analysis.** Determination of the seismic-initiated peak ground acceleration at which plant structures and components are predicted to fail.
3. **Logic Analysis.** Development of a logic model that depicts the potential component failure scenarios, including consideration of possible combinations of associated equipment or structure failures.
4. **Preliminary Quantification and Results.** Assembly of seismic hazard, fragilities, and models; the quantification of the frequency of a seismic event causing sufficient damage to release hazardous materials, and identification of dominant contributors. The quantification process requires results from the previous seismic hazard, fragility, and logic analyses.
5. **Final Quantification.** Calculation of uncertainty in the damage and release frequency. This seismic uncertainty analysis was not performed in this study because the contributions to total risk from seismic events was negligible

when compared to nonseismic events. The quantification process requires results from the previous seismic hazard, fragility, and logic analyses.

The approach taken in each of these steps and the findings are discussed in the following sections.

2.1. Seismic Hazards

A seismic hazard analysis was performed by WCC in April 1989, for a number of nonreactor locations at the Hanford Reservation.³ In addition, a seismic hazard evaluation was performed by SNL in November 1990 as part of an analysis of external events effects at the DOE N Reactor site.⁴ Rather than initiate new seismic hazard studies for this tank assessment project, we chose to use both of the earlier studies, being satisfied that within the uncertainty of seismic hazard predictions, the use of these studies should be quite acceptable.

The SY Tank Farm is located in Site 1 at Hanford. The WCC study predicted peak ground acceleration frequencies at six Hanford Sites, including Site 1 and Site N, the location of the N Reactor, which is the subject of Ref. 4. As in other contemporary probabilistic seismic hazard studies, the WCC results were based on (1) the location and geometry of earthquake sources relative to the site, (2) the recurrence of earthquakes of various magnitudes on the sources up to the maximum magnitudes for each source, and (3) the attenuation of ground motions from the sources to Site 1. The source models and attenuation relationships that were developed earlier by WCC in the seismic hazard studies for the WNP-2 nuclear power plant, which is located in the region, and for the N Reactor studies performed earlier in 1987, were used in the WCC 1989 study. The uncertainty in the source models and attenuation relationships in these studies was embedded in the 1989 study.

Figure C.1 presents the overall site plan and indicates the proximity of Site 1 and N Site to each other. Table C-2 presents the annual mean number of events exceeding the peak accelerations at Site 1 and N Site. Figure C.2 presents the mean hazard curve for Site 1 in graphical form. These three exhibits were taken directly from Ref. 3. It can be seen from this information for Site 1 that, although the curve is represented as the mean curve, the uncertainty about the curve is not represented because it was neither included in Ref. 3 nor available from Ref. 5. However, the 1990 SNL study calculated an uncertainty distribution about the mean for the N Reactor site. By comparing, in Table C-2, the results for Site 1 and N Site, it can be seen that there is a similarity in the annual probability of exceedance between the two sites. Therefore, it was judged

Fig. C.1.
Location map.

TABLE C-2
ANNUAL MEAN NUMBER OF EVENTS EXCEEDING PEAK ACCELERATIONS

Peak Acceleration (g)	Site 1	Site N
0.05	1.51×10^{-3}	1.45×10^{-3}
0.10	5.76×10^{-4}	5.68×10^{-4}
0.15	2.94×10^{-4}	2.77×10^{-4}
0.20	1.71×10^{-4}	1.49×10^{-4}
0.25	1.07×10^{-4}	8.47×10^{-5}
0.30	7.02×10^{-5}	4.96×10^{-5}
0.35	4.74×10^{-5}	2.98×10^{-5}
0.40	3.27×10^{-5}	1.81×10^{-5}
0.50	1.62×10^{-5}	6.92×10^{-6}
0.60	8.29×10^{-6}	2.71×10^{-6}
0.70	4.37×10^{-6}	1.08×10^{-6}
1.00	6.91×10^{-7}	4.95×10^{-8}

to be reasonable to apply the uncertainty distribution about the N Site mean curve to the Site 1 mean curve. This is seen in Fig. C.3, which also shows the extrapolation to an exceedance frequency of 1×10^{-7} .

To develop point estimates of scenario frequencies, it is necessary to divide the mean frequency curve into a number of incremental ranges of acceleration. Five ranges were judged to be ample to reflect the curve shape. Table C-3 presents the mean frequency for the increments of acceleration ranges. These ranges are each given a designated acceleration for ease of reference, which was used in the analysis, along with the mean frequency within the range. The lower bound acceleration is discussed below under "Structure and Equipment Fragilities." The upper bound is limited by the mean frequency of 1×10^{-7} per year because values lower than this are of little interest in the tank farm risk assessment.

2.2. Fragility Analysis

A fragility analysis of Tank 101-SY and of associated facilities is included as App. B to this report. A summary of that analysis and the results are presented here. The approach adopted in assigning peak ground acceleration capacities to safety-related structures, equipment, and other components was to first determine the median

Fig. C.2.
Mean seismic hazard curve, Site 1.

Fig. C.3.
Seismic hazard curves, Site 1, used in analysis.

TABLE C-3
MEAN ANNUAL FREQUENCIES OF ACCELERATION RANGES

Acceleration Range (g)				
0.10–0.20	0.20–0.30	0.30–0.50	0.50–0.70	0.70–1.0
Designated Acceleration				
0.15	0.25	0.40	0.60	0.85
4.05×10^{-4}	1.01×10^{-4}	5.40×10^{-5}	1.18×10^{-5}	3.68×10^{-6}

factor of safety against failure and its statistical variability. In general, the factor of safety against failure of a structure or component from seismic-initiated ground motion can be defined as the ratio of the ground motion causing the failure to the maximum ground motion used in design that maintained acceptable elastic stress limits in the component materials. For the tank farm site, the ground motion for which the J. A. Blume & Associates (1981)⁶ and WHC (1991) evaluations⁷ were performed was 0.20-g free field peak ground acceleration. Margins of safety were determined using that design basis.

The overall safety factor was determined by evaluating the factors for a number of parameters that fell into three categories: strength, ductility, and response. For structures, the parameters influencing the factor on structural strength are the stresses at structure failure compared with the design stress level. Ductility is the inelastic energy absorption capacity of a structure to carry load beyond yield as compared with the capacity used in the design. The most significant parameters for response to a given ground acceleration include:

- earthquake characteristics,
- system damping,
- load combinations,
- modal combination,
- combination of responses for earthquake directional components, and
- structural modeling considerations.

The overall safety factor for equipment and other plant components is derived from similar parameters for the component. However, component response also depends on the structure in which the component is located and its location within the structure. Therefore, the overall safety factor for components is composed of component strength and response relative to its support, in addition to the structure response to ground accelerations. A best estimate of the actual value for each parameter was established as being the median of a distribution of possible values. A combination of generic and plant-specific information was used for these estimates. The ratio between the best-estimate value and the value used in the design was determined for each parameter for each critical component. The product of the parameter safety factors represents the overall safety factor. When combining these median factors for contributing parameters, variabilities were also combined to define the variability in the overall safety factor. From this overall safety factor, the median acceleration capacity, or peak ground acceleration at failure, was determined by multiplying the safety factor by 0.20 g.

Definition of Failure. For purposes of this analysis, structures and tanks are considered to have failed when inelastic deformations under seismic load have the potential to interfere with the operability of equipment supported by the structure and, in this case, the integrity of the tank. These limits on inelastic energy absorption capacity (ductility limits) are estimated to correspond to the onset of significant structural damage and not necessarily to structure collapse. Piping, electrical, mechanical, and electromechanical equipment are considered to fail when they can no longer perform their designated functions, whether as a result of supporting structure failure or direct failure from the earthquake. Also, ruptures of pressure boundaries are considered failures. In most cases, however, the equipment will lose its ability to function at lower accelerations before pressure boundaries fail because the pressure boundaries for equipment, such as pumps and valves, usually are very conservatively designed.

Fragility Curve Formulation. Seismic-induced failure data are generally unavailable for specific plant components or structures. Thus, the peak ground acceleration at which the component is expected to fail must be determined primarily from analysis and engineering judgment supported by limited test data.

Earthquakes causing the same peak ground acceleration at the HTF site can have different energy contents and durations. The magnitude of these factors varies randomly, and therefore, the effects on structures and components at the same acceleration but from different earthquakes differ. So while the median acceleration capacity can be determined for structures and components, even if their strengths, ductilities, and responses are well known, it is still necessary to assign a random variability to the

capacity owing to differences only in earthquake characteristics. Therefore, because of this uncertainty, great precision in attempting to define the shape of fragility curves is neither possible nor warranted. In addition, the strengths and response characteristics of the structures and components are not exactly known, so our uncertainty about these also needs to be expressed. The median acceleration capacity, random variability, and uncertainty can be expressed by $\hat{a}$, β_R , and β_U , respectively. Then the acceleration capacity, a , at designated levels of confidence is given by

$$a = \hat{a} \epsilon_R \epsilon_U , \quad (C.2.1)$$

where ϵ_R and ϵ_U are logarithmic because the statistical variations of many material properties and seismic response variables are well represented by logarithmic distributions. It is assumed that both ϵ_R and ϵ_U have lognormal standard deviations of β_R and β_U , respectively. This representation is believed to be inappropriate near the tails of the distributions because experience tells us that there are practical lower bounds on accelerations at which failures of engineered facilities can occur, as will be discussed shortly. Therefore, the acceleration capacity, a , can be expressed in terms of

$$a = \hat{a} \exp(f' \beta_U) \exp(f \beta_R) , \quad (C.2.2)$$

where

- $\hat{a}$ = median acceleration capacity;
- f' = variate of a standard normal distribution representing the uncertainty in the acceleration capacity that, with additional information, might be reduced;
- β_U = lognormal standard deviation applied to f' to adjust the uncertainty distribution and is based on specific knowledge about the building or component;
- f = variate of a standard normal distribution representing the randomness in the acceleration capacity. This randomness results from earthquakes yielding the same acceleration at the site but having different energy content and duration and, therefore, different effects on plant components. This is a random variable that additional information would not affect; and
- β_R = lognormal standard deviation applied to f to adjust the distribution on the randomness for the evaluated parameters.

A graphical representation of Eq. (C.2.2) for the fragility of buildings and equipment can be seen in Fig. C.4, which shows $\hat{a}$ and the median curve through it (shown dashed), as well as the 5th (left-dashed) and 95th (right-dashed) percentile curves, representing the range in uncertainty. Actually, the 5th and 95th percentile curves bound a family of curves that reflect the uncertainty represented by β_U . The shape of each curve is a reflection of β_R , the variability caused by the randomness of earthquake characteristics at given accelerations. The mean fragility curve can be seen as the solid curve through $\hat{a}$. Any point, a , on the mean curve is represented by the expression

$$a = \hat{a} \exp(f'' \beta_C) , \quad (C.2.3)$$

where f'' is a standard normal distribution, and

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2} . \quad (C.2.4)$$

Fig. C.4
Typical fragility curve.

The mean acceleration capacity, $\dot{a}$, is given by

$$\dot{a} = \hat{a} \exp \frac{\beta_c^2}{2} . \quad (C.2.5)$$

Furthermore, the mean value of the failure fraction, $F(\hat{a})$, on the mean fragility curve is obtained for point estimate calculations from the expression

$$F(\dot{a}) = \phi \left(\frac{1}{\beta_c} \ln \frac{\dot{a}}{\hat{a}} \right) , \quad (C.2.6)$$

where $\phi(\bullet)$ is the standard Gaussian cumulative distribution from which $F(\dot{a})$ is determined. Fragilities expressed by $\hat{a}$, R , and U are developed for components where failures could initiate or result in a release of hazardous materials.

In the following sections, the specifics of the fragility analysis, as they apply to the tank farm, are described.

Structures and Equipment Fragilities. The approach used to analyze fragilities relied on existing reports, drawings, photographs taken by others in the field, and seismic capacity calculations performed by others. The following components were evaluated:

- primary tank,
- secondary tank,
- exhaust ductwork,
- exhaust fan,
- electrical panels,
- instrument and control panels,
- offsite power, and
- piping

Possible failure modes were evaluated for each of the components, recognizing that for a single component, alternative failure modes are not independent; that is, one failure mode will likely influence other failure modes of that component. Therefore, the capacity of a component was determined to be that of the most likely failure mode that would result in the same type of release as other modes.

A review of the mean seismic hazard curve in Fig. C.3 indicates that the annual frequency of a 1.0-g peak ground acceleration is less than 1×10^{-6} . This frequency is too low to be of interest in this risk assessment because of the much higher release frequency from nonseismic events. Therefore, where it could be shown that the median capacity of a component is greater than 1.0 g, no further analysis was conducted.

The results of the fragility analysis is presented in Table C-4. Besides the values of $\hat{a}$, β_R , and β_U that define the fragility family for each component, the HCLPF value is also shown. The HCLPF is the value at which there is a 95% probability that there is no greater than a 5% chance of failure, or essentially less than a 1% chance of failure. By scanning the components for the lowest HCLPF value, it was determined that there is no need to include failure contributions below 0.10 g because none of the components would fail below that value. Thus, 0.10 g was established in Table C-3 as the lower bound acceleration of interest.

TABLE C-4
COMPONENT FRAGILITIES

Component	$\hat{a}$ (g)	β_R	β_U	HCLPF (g)	Failure Mode
1. Offsite Power	0.30	0.25	0.50	0.10	Substation Transformer Insulators
2. Electrical Panel	0.50	0.25	0.34	0.19	Component Function
3. Instrument/Control Panels	0.80	0.25	0.17	0.40	Instrument Function
4. Primary Tank	0.94	0.27	0.36	0.33	Shear Buckling and Cracking at Knuckle (dome collapse > 1.0 g).
5. Exhaust Ducts	> 1.0				
6. Exhaust Fan	> 1.0				
7. Above-Ground Piping	> 1.0				
8. Secondary Tank	> 1.0				

2.3. Logic Analysis

It can be seen from the fragility analysis that only offsite power, electrical panels, instrument racks, and the primary tank can fail within the possible acceleration levels. On this basis, a simple event tree is constructed to reflect these potential seismic failures. This tree can be seen in Fig. C.5. Components can be unavailable owing to seismic failures, as well as from nonseismic failures and other nonseismic unavailabilities. To account for the nonseismic events, the seismic tree is linked to the nonseismic event tree, thereby simultaneously evaluating the combination of seismic and nonseismic events. After linking the trees, a point estimate quantification is performed for each designated acceleration frequency. For these point-estimate quantifications, the mean fragility of each component at the designated acceleration represents the top event probability in the seismic tree. The probability of failure for each top event in the nonseismic tree is the same as was used in the nonseismic analysis. This value is constant for all initiating event frequencies; i.e., designated acceleration frequencies. The frequencies of like scenarios from each designated acceleration run are added to determine the total seismic frequency over all accelerations.

Earthquake Frequency	Primary Tank Failure	Loss Offsite Power	Electric Panel Failure	Instrument/Control Panel Failure	Seq. #	Frequency Per Year	Release Category
IE(g) (Table 4-7)	SPT(n) (Table 4-5)	SOP(n) (Table 4-5)	SEP(n) (Table 4-5)	SIP(n) (Table 4-5)	1	Depends	Feeds to
				SIP(n) (Table 4-5)	2	upon	BURP
				SIP(n) (Table 4-5)	3	earthquake	event
				G/F	4	severity	tree
				G/F	5		(Fig. 4.6)
					6		
				SIP(n)	7		
				SEP(n)	8		
				SIP(n)	9		
				G/F	10		

LEGEND:

G/F = Guaranteed Failure

Fig. C.5.
Seismic event tree.

This analysis assumes that a bound hydrogen gas release event will occur in the tank following a seismic event. Therefore, the internal event tree used to evaluate the effects from a BURP initiating event is linked to the seismic event tree for quantification of seismic events. The BURP event tree, presented as Fig. 4.6, reflects all the events that could follow the potential seismic failures. Some seismic failures will directly cause events in the nonseismic event tree to be unavailable. Therefore, it was necessary to prepare a dependency table that correlates these failures as rules for inclusion in the quantification process. The dependency table can be seen in Table C-5.

2.4. Preliminary Quantification and Results

The five designated accelerations and their mean frequencies can be seen in Table C-3. The failure fractions, or conditional failure probabilities, for the seismic failures at each of these designated accelerations were calculated from Eq. (C.2.6) and can be seen in Table C-6. Using RISKMAN, the linked event trees were quantified to determine scenario frequencies. Release category frequencies can be seen in Table C-7. The total frequency for all seismic-initiated releases is 5.7×10^{-4} , which is substantially lower than for the nonseismic initiating events. Even comparing individual release category frequencies with those from nonseismic initiating events, we find that seismic-initiated events are not significant.

TABLE C-5
DEPENDENCY MATRIX

Seismic Failure	Nonseismic Top Event (BURP Event Tree)							
	H2HI ^a	VOP	TBRN	VBRN	PROP	DOMES	PSI SSI	LI
Primary Tank							X	
Offsite Power		X						X
Electrical Panel		X						X
Instrument/ Control Panels		X						X

^aHydrogen concentration in the dome space is assumed to be greater than 4% following seismic initiated bound gas release events.

TABLE C-6
CONDITIONAL SEISMIC FAILURE PROBABILITIES

Component	Designated Acceleration (g)				
	0.15	0.25	0.40	0.60	0.85
SOP—Offsite Power	1.08×10^{-1}	3.72×10^{-1}	6.97×10^{-1}	8.92×10^{-1}	9.69×10^{-1}
SEP—Electrical Panel	0.00	5.03×10^{-2}	2.98×10^{-1}	6.67×10^{-1}	8.96×10^{-1}
SI—Instrument/Control Panels	0.00	0.00	0.00	1.71×10^{-1}	5.79×10^{-1}
SPT—Primary Tank	0.00	0.00	2.88×10^{-2}	1.59×10^{-1}	4.12×10^{-1}

TABLE C-7
RELEASE FREQUENCIES

Release Category	Seismic-Initiated Events		Internal Events
	Dominant Scenarios	Annual Mean Frequency ^a	Annual Mean Frequency
TG	(no failures)	5.7×10^{-4}	3.5
HEPAL	VBRN1	2.6×10^{-6}	1.2×10^{-1}
HEPAH	$SOP \cap BRRN1 \cap PROP2$	1.7×10^{-6}	5.1×10^{-3}
DCH	$SOP \cap VBRN1 \cap PROP2$ $\cap COLAP2$	2.3×10^{-7}	7.0×10^{-4}
LLK	—	1.2×10^{-9}	4.5×10^{-4}
DCLLK	—	1.5×10^{-10}	2.4×10^{-8}

As shown in Table C-7, the dominant seismic-initiated release category is a toxic release (release category TG). Category TG, which accounts for essentially all of the seismic-initiated release, is dominated by the scenario whereby an earthquake occurs and causes a toxic gas burp in the tank that is released through the stack. Thus, the dominant seismic contributions to release involve only the earthquake and no seismic-caused failures.

The dominant scenario contributing to a normal aerosol release, release category HEPAL, starts when a seismic event causes a toxic gas burp in the tank. This gas is

released to the ventilation duct, where an explosion results in a release that contains a nominal amount of radioactivity.

An enhanced aerosol release, HEPAH, is caused by an earthquake-induced failure, of offsite power, which causes failure of the ventilation system. An explosion in the vent system propagates back to the tank, thereby causing failure of the HEPA filter from the pressure pulse. This releases toxic gas, which contains some radioactivity, through the stack or the failed exhaust duct. The frequency for the HEPAH category is about half the HEPAL frequency.

At a significantly lower frequency than the foregoing releases but with more severe consequences, release category DCH is caused by an earthquake and burp of toxic gases in the tank, seismic failure of offsite power followed by an explosion in the vent system propagating to the primary tank, collapse of the secondary tank dome, and a major release of the tank contents into the atmosphere and onto the ground.

3.0. FIRE

This section discusses both the conservative estimation for the frequency of an external fire impact on the 101-SY Tank Farm and the existing facilities fire mitigation capability. The potential consequences of an external fire on the tank farm are postulated to be LOSP and LOTV (see Sec. 4.3). The contributions of external fires to the overall risk can be obtained by merging the initiating frequency contributed by the fire with the internal event frequencies.

3.1. Frequency of External Fire

The SY Tank Farm external-fire frequency is influenced by the local climate, which is arid to semiarid because the site is located in the rain shadow of the Cascade mountain range. Because of the arid environment and prevailing winds, the site is blanketed by a thin veneer of wind-blown sediments. Vegetation on the site consists of sagebrush and other common, central Washington desert plant species. Range or grass fires are likely occurrences at the Hanford Site in the late summer when vegetation and wind-blown sediments become extremely dry. Once started, these range fires can burn out of control if they are driven by strong winds (Ref. 2, p. 2-7).

The following equation, which is a function of the parameters discussed above, was developed to evaluate the frequency of the impact of an external fire on the tank farm.

$$\lambda_{\text{fire}} = \sum_j \sum_i \lambda_j f_{i|j} f_{s|i} f_{wv|s} f_{wd|s} f_{B|s,wv,wd} f_{h|B} \quad , \quad (\text{C.3.1})$$

where

- λ_{fire} = annual occurrence frequency of external fire on tank farm;
- λ_j = occurrence frequency of range fire;
- $\lambda_j f_{i|j}$ = fraction of range fires that occur in area;
- $f_{s|i}$ = conditional probability that a fire in area i has a fire size of S ,
which is considered to be the minimum fire size to impact tank farm;
- $f_{wv|s}$ = conditional probability of a strong wind given a size S fire;
- $f_{wd|s}$ = conditional probability of having a wind direction that pushes a
fire toward the tank fire, given a size S fire;
- $f_{B|s,wv,wd}$ = conditional probability of fire barrier failure, given a size S fire
in area i concurrent with a properly directed strong wind; and
- $f_{h|B}$ = the probability that fire fighters fail to control the fire given
failure of fire barriers.

The split fractions listed above are introduced to account for the conditional factors that are required for a range fire to impact the tank farm. Because of the lack of sufficient information, engineering judgment and conservative estimates were used to estimate the frequency of an external fire impacting Tank 101-SY, as documented below.

3.2. Range Fire and High Wind Speed at Tank 101-SY

The estimated occurrence frequency of range fire, λ_j , calculated from the historical data at the Hanford Site is about 0.85/yr.² However, no information is available on the size and location of these range fires. Because range-fire spatial and impact information are not available, the following process was used to estimate $f_{s|i}$ for Tank 101-SY; this process is the conditional frequency of fire in the Tank 101-SY Area having the minimum size necessary to impact Tank 101-SY.

To estimate the spatial distribution of the range fires, the tank farm site was divided into three equal-width annular areas centered on Tank 101-SY. The proportion of the area enclosed by each annulus, starting from the center, is therefore 1:3:5. Assuming fires are spatially distributed as a function of area, 1/9 of the random fires would occur in the annulus nearest Tank 101-SY. Furthermore, if every range fire is assumed to be of minimum size S , the product of $f_{i|j}$ and $f_{s|i}$ is 1/9. Lastly, the frequency of a

range fire in the Tank 101-SY Areas sufficient to cause an impact was calculated as the product of λ_j , $f_i | j$, and $f_s | i$. This value of 0.85/9 is conservative.

A strong wind is needed to cause a range fire to spread quickly. For this analysis, a large range fire in combination with a wind speed > 20 mph is assumed to be a potential threat. Table C-8 shows the historical wind speed distribution at the Hanford Site. As can be seen from this table, $f_{wv | s}$ for winds stronger than 20 mph is < 0.059.

To estimate the relationship between the wind direction and range fire, the historical data of range fire, as well as the prevailing wind direction of the Hanford farm tank is needed. The prevailing wind direction at Hanford is known to be WNW (Ref. 2, Table 3.3-1); however, as previously mentioned, no information is available regarding the location of range fires. For a conservative estimate, $f_{wd | s}$ is assigned a value of 2/16. This assignment partitions the wind into 16 directions and assumes 2 of them push fire toward Tank 101-SY. The following section discusses the last two parameter values required to estimate the frequency of fires that impact Tank 101-SY.

3.3. Fire Prevention and Mitigation at the SY Tank Farm

The last two parameters, $f_{B | s, wv, wd}$ and $f_{h | B}$, are more difficult to estimate. Historical data for the effectiveness of fire barriers are not available, so $f_{B | s, wv, wd}$ cannot be determined exactly. Furthermore, effectiveness of fire suppression depends on fire fighter response, which can only be qualitatively judged. As discussed below, conservative estimates were provided for $f_{B | s, wv, wd}$ and $f_{h | B}$ to bound the impact frequency of an external fire on the tank farm.

Because the Hanford Site houses many facilities that are at risk from external fires, precautions are regularly taken against the potential risks from range fire. Two precautions are to (Ref. 2, p. 2-7):

- remove vegetation from facility sites, and
- create fire breaks by the roadways in the vicinity of the tank farm.

TABLE C-8
PERCENTAGE FREQUENCY DISTRIBUTION OF 15m (50 FT) WIND SPEED^a

Wind Speed	<3	>3	>7	>12	>18	>24	>31
Percentage	25.4	74.6	41.2	17.4	5.9	1.8	0.7

^aModified from Table 3.3-3 of Ref. 2.

The removal of vegetation from facility sites (the major combustible materials at the site) has two effects. First, the severity of a range fire would be significantly decreased. Second, because less combustible materials are available, the effectiveness of the road-way fire breaks is increased because of the resulting decrease in fire size.

In addition to these two factors, the experience of the nearby Hanford Fire Department in dealing with range fires has the potential to further reduce the danger of range fire impact on the tank farm. It is judged that the combined effect of precautions and fire suppression experience will reduce the external fire impact on the tank farm by at least a factor of 10.

The analysis discussed in this section indicates the λ_{fire} for Tank 101-SY can be estimated to be

$$\lambda_{\text{fire}} < 0.85/9 \times 0.059 \times 2/16 \times 1/10 = 6.97 \times 10^{-5}/\text{yr}$$

from equation C.3.1.

3.4. Impact of External Fires

The possible consequences of an external fire are postulated to be LOSP and LOTV (Sec. 4.3). An intensive range fire at or near the tank farm can burn utility poles, and smoke can degrade or even damage ventilation equipment.

The conditional probabilities of LOSP and LOTV, given a fire at or near the tank farm, are assumed to be lognormally distributed with a conservatively assigned median value of 0.3 and an error factor of 5. The calculated mean for this distribution is approximately 0.5. Therefore, the frequency of Tank 241-101-SY LOSP and LOTV owing to external range fires is estimated to be $3.48 \times 10^{-5}/\text{yr}$.

Compared with the contribution to LOSP and LOTV of other events (Sec. 4.3), it is expected that the risk contribution from the range fire will be insignificant.

It is to be noted that although the frequency discussed above is per tank year for Tank 101-SY, it is likely that an external fire will impact many tanks simultaneously. A risk assessment of the entire tank farm needs to account for the potential simultaneous impact on multiple tanks owing to range fires.

3.5. Uncertainties

There are large uncertainties regarding the numerical results obtained by this external fire modeling. Although uncertainties exist for both the model and the model parameters, it is judged that the uncertainties in parameter values overwhelm the model

uncertainty. Some of the uncertainty factors that impact parameter values and their correlations are discussed below.

Most parameters defined in Eq. (C.3.1) are correlated. In contrast, the dynamics of inner- and outside-annulus fires are very different. For example, a range fire far from the site requires a high-wind and a specific-wind direction to impact the tank. The distant range fire provides a longer warning time for fire fighters to prepare and suppress the fire. All these factors decrease the chance of a fire impact on the tank farm.

However, for a fire started from within the inner annulus, the factors discussed above work to increase the chance of an impact on the tank farm. Fortunately, because there are few combustibles in the tank farm's immediate vicinity, the frequency of and severity from a nearby fire is lower than those resulting from a distant fire.

More accurate assessments and more data will improve the estimates provided in the range fire analysis. However, because the overall estimate is conservative, more accurate results probably will not significantly alter the overall conclusion.

4.0. FLOOD

In this section, the potential accident sequences initiated by external floods at the SY Tank Farm are investigated, and the frequencies of the floods are calculated. It is concluded that the possible scenarios involving external floods are highly unlikely and that tank water intrusion is dominated by other events.

The location of the tank farm (200-West and 200-East Areas) within the Hanford Site can be seen in Fig. C.6. The ground level of the tank farm site is about 214 m (700 ft) above mean sea level (MSL). The major sources of external flooding at the site, which will be addressed sequentially, are:

1. abnormal increase in the river water level at the site owing to causes other than dam failure; e.g., heavy rainstorms;
2. failure of Grand Coulee Dam, which is located upstream of the Columbia River; and
3. others, such as precipitation or surge and seiche flooding.

4.1. Frequency of Abnormal Increase of River Water Level

The Columbia, Snake, Yakima, and Walla Walla rivers are the only perennial streams in the Pasco Basin within which the Hanford Site is located. However, because

Fig. C.6.
Land use features at the Hanford Site

of their relative locations, flooding of only the Columbia and the Yakima rivers may have an impact on the Hanford Site. The Columbia River will be considered first.

Engineering judgment and historical data indicate that the largest flooding threat from an abnormal increase in the river water is the Columbia River. The normal level of the Columbia River is 110 m MSL (360 ft) around the site. According to an earlier (1950) Army Corps Engineering analysis (see Sec. C.4.2), a flooding discharge volume of 230,000 m³/s at the Hanford Site (Fig. C.7) would still leave a sufficient safety margin for the site (elevation difference of 74 m). Table C-9 provides the average, minimum, and maximum historical discharge data of the Columbia River at the site since 1917.²

Note also that the largest possible discharge volume that has occurred at the Columbia River was estimated to be 21,000 m³/s (January 7, 1894).

It has been demonstrated that annual maximum discharges (flood) from a river can be described by the a Type I extreme value function whose cumulative distribution function, F, is described by⁸

$$P(V > v) = F^*(v) = 1 - \exp\left[-e^{-\alpha(v-\beta)}\right] ; \quad (C.4.1)$$

where v is the discharge volume of interest, and α and β can be calculated from the following two equations:

$$\alpha^2 = \frac{1.645}{\sigma^2} , \quad (C.4.2)$$

and

$$\beta = \mu - \frac{0.577}{\alpha} ,$$

where μ is the mean and σ is the standard deviation of the yearly maximum discharge volume.

Monte Carlo simulations were carried out to determine the μ and σ of the annual maximum discharge. In this simulation, the underlying distribution of discharge was taken as lognormal, with an average of 3400 and an error factor of 6.* Ten 365-point samples were drawn, each with 365 points to represent daily discharge. The average

*Other distributions have also been used. The results agreed with the overall conclusions reached later in this section.

Fig. C.7.
Flooded area resulting from a 50% breach of Grand Coulee Dam.

TABLE C-9
HISTORICAL DISCHARGE VOLUME (m³/s) OF THE COLUMBIA RIVER
AT FARM TANK SITE SINCE 1917²

Average	Minimum	Maximum
3400	117	19,000

of the maximum from these 10 samples is 4.49×10^4 m³/s, and the standard deviation, σ is 9.04×10^3 . The μ and σ then were used to calculate the α and β , which were: $\alpha = 1.419 \times 10^{-5}$, and $\beta = 4.083 \times 10^4$. The probability of the discharge volume, V , that exceeds 230,000 m³/s then is calculated to be

$$P(V > 230,000) < 10^{-6} . \quad (C.4.3)$$

Because this probability was calculated on a yearly basis, the annual occurrence frequency of a discharge volume that exceeds 230,000 m³ is $< 10^{-6}$ /yr, a negligibly small value.

The most severe flood of the Yakima River was recorded on December 23, 1933, and had a peak discharge of 1900 m³/s. The best-estimate frequency of floods of this size is 5.9×10^{-3} per year.² Because most of the Hanford Site is physically isolated from the Yakima River by the Rattlesnake Hills, potential water level increases of the Yakima River are not a threat to the tank farm site.

4.2. Flooding owing to Grand Coulee Dam Failure

There are nine dams on the Columbia River upstream from the Hanford Site. The largest upstream dam and impoundment and the principal flow-regulating structure on the Columbia River is the Grand Coulee Dam. The other eight dams are small compared with the Grand Coulee Dam; their failures pose little threat to the Hanford Site owing to the large difference between the MSL of the site and the Columbia River.

The annual frequency of failure of a single concrete dam is calculated by summing rates from two categories of failure.⁹ The first category (rupture) has a frequency of 1 in 50,000 dam-years. The second category (all other causes of failure) has a frequency of 1 in 100,000 dam-years. Therefore, the annual frequency of a single concrete dam failure owing to all causes is the sum of the two category frequencies, or 3×10^{-5} /yr. This value, 3×10^{-5} /yr, approximates the combined US and worldwide failure

frequency experience of 10^{-4} /yr. Because most dam failures occur during the first five years of operation, the above failure rate for the Grand Coulee Dam (which has passed the 5-yr wear-in period) is judged as appropriate for a screening value.

The US Army Corps of Engineering evaluated a number of scenarios that might result in a failure of the Grand Coulee Dam.² One scenario postulated a 50% breach of Grand Coulee Dam as a result of damage expected from a direct-hit detonation of a nuclear warhead. This scenario is believed to represent the largest realistic flow resulting from a break caused by either human or natural events (i.e., seismically induced breaching). The resulting discharge at the outfall of the dam would be $5.7 \times 10^5 \text{ m}^3/\text{s}$, which would result in a flow of approximately $2.3 \times 10^5 \text{ m}^3/\text{s}$ adjacent to the Hanford Site. The resulting Columbia River water level at the site would be approximately 140 m MSL; the tank farm site (approximately 214 m MSL) would remain well above the water level, even for this catastrophic flood.

Based on the estimated frequency and the impact from the worst-case scenario, it is believed that dam failures pose a negligible threat to the tank farm.

4.3. Other Flooding Scenarios

- **Surge and Seiche Flooding.** Surge and seiche flooding are not credible because the tank farm site is located about 321 km from the ocean, and there are no large bodies of inland water near the site.
- **Tsunami Flooding.** Tsunami flooding is not credible because the tank farm site is located about 321 km from the ocean.
- **Ice Flooding.** Ice flooding is not credible because the tank farm site is located about 61 m above the Columbia River level.
- **Probable Maximum Flood (PMF) on Streams and Rivers.** For the Columbia River, the PMF was evaluated to produce a flow of $4.0 \times 10^4 \text{ m}^3/\text{s}$ at the Hanford Site.¹⁰ As was shown in this report, a discharge of this size would pose no threat to the tank farm site. Skaggs and Walters (1981)² reported preliminary estimates of PMF conditions for Cold Creek.* This report projected that the conservatively estimated Cold Creek PMF would drain a small portion of the southwest corner of the West 200 Area (see Fig. C.8).

Because the 200 West Area Tank Farms are located at the central to south part

*The historical flood flow information is not available for Cold Creek. The best-point estimation of a 100-yr peak discharge is $178 \text{ m}^3/\text{s}$. The estimated 100-yr flood of Cold Creek would not affect the tank farm.²

Fig. C.8.
Extent of probable maximum flood in Cold Creek Area [after Skaggs and Walters (1981)].

of the area (see Fig. C.9), the credible Cold Creek floods cannot become a threat to the tank farm.

- **Precipitation.** The maximum historical intense precipitation at the Hanford Site was 4.85 cm (1.91 in.) in a 24-h period. The probable maximum 24-h precipitation is 28 cm (11 in.), which has an estimated frequency of 10^{-6} per year. Thus, water intrusion is dominated by other events.

5.0. HIGH WINDS

This analysis has evaluated the fragility of the tank structure to the high-speed wind loads estimated to have the potential to impact the tank farm. The resulting conclusion is that the contribution from high-speed wind to tank releases is insignificant when compared to other events. This analysis is discussed in the following sections.

5.1. Frequency of Gust Wind

At the Hanford Site, the weather phenomena that occurs most frequently and has the greatest impact on routine operations are dust storms. The average frequency of dust storms is 8/yr, with storms occurring most often from January through May and also in September. The maximum recorded peak gust speed at 15 m (50 ft) above ground level at the Hanford Site is 128.8 km/h (80 mph).² Table C-10 lists historical (1945–1980) monthly maximum gust speed data at the Hanford Site (Ref. 2, Table 3.3-1).

Literature¹¹ indicates that the extreme value distribution of Type I can be used to accurately describe the distribution of maximum wind speed. The probability of gust speed exceeding v_0 , the gust speed of interest, is calculated using the following Type I extreme value distribution:

$$P(v > v_0) = F^*(V_0) = 1 - \exp\left[-e^{-\alpha(v-\beta)}\right], \quad (C.5.1)$$

where α and β values can be calculated using the following equations:

$$\alpha^2 = \frac{1.645}{\sigma^2}, \quad (C.5.2)$$

and

$$\beta = \mu - \frac{0.577}{\alpha}. \quad (C.5.3)$$

Fig. C.9.
Hanford Waste Vitrification Plant location within the Hanford Site 200 Area.

TABLE C-10
MONTHLY PEAK GUSTS AT 15 m ABOVE GROUND LEVEL
AT THE HANFORD SITE^a

Date	Speed (mph)
July 1979	69
April 1972	73
January 1972	80
February 1971	65
August 1961	66
June 1957	72
March 1956	70
December 1955	71
September 1953	65
October 1950	63
November 1949	64
May 1948	71

^aModified from Table 3.3-3 of Ref. 2.

The μ and σ , the average and standard deviation of the maximum gust speed, respectively, are calculated to be 69.1 mph and 4.6 mph, respectively, using data contained in Table C-10.

Substituting μ and σ into these two equations, we obtain α and β values of 0.28 and 67.0. These values are used in Eq. (C.5.1) to calculate the following conditional probability of gust speeds larger than the velocities contained in Table C-10.

$$\begin{aligned}
 P^*(\text{gust speed} > 80 \text{ mph}) &= 2.7 \times 10^{-2}, \\
 P^*(\text{gust speed} > 86 \text{ mph}) &= 5.2 \times 10^{-3}, \\
 P^*(\text{gust speed} > 90 \text{ mph}) &= 1.7 \times 10^{-3}, \\
 P^*(\text{gust speed} > 117 \text{ mph}) &= 9.6 \times 10^{-7}, \text{ and} \\
 P^*(\text{gust speed} > 135 \text{ mph}) &= 9.5 \times 10^{-9}.
 \end{aligned}$$

To calculate the yearly frequency of gust speed exceeding some velocity, V , Table C-10 data needs to be examined. Ideally, if the data contained in Table C-10 were annual

peak gusts, the calculated probability result would be the same as the frequency per year value. However, because of their temporal distribution, the relationship between the extreme value distribution and frequency for this case is more complicated. However, as discussed below, the peak gusts in Table C-10 may be used to approximate yearly-occurrence exceedence frequencies.

As shown in Table C-10, the maximum recorded peak gust at the tank farm site over 35 yr was 80 mph. The resulting maximum likelihood estimate for the occurrence frequency of gust speed > 80 mph is $1/35 = 0.0286/\text{yr}$. In comparison, the extreme value distribution F gives the 80-mph exceedance probability as 0.027. A 100-yr return period peak gust of 86 mph has also been calculated for the site.¹² For comparison, the extreme value distribution equation calculates the same 100-yr return period peak gust as about 84 mph. Because the extreme value distribution probabilities have approximately the same magnitude as the likelihood estimators, this analysis assumes the extreme value distribution probabilities can roughly approximate the frequency per year.

Other equations have been developed by researchers to calculate the extreme value distribution parameters. However, as discussed below, these equations yield results that are too conservative. For example, the following equations have been proposed for α and β :¹³

$$\alpha = \frac{\sqrt{6}}{\pi \times \sigma} , \quad (\text{C.5.4})$$

and

$$\beta = \mu - \frac{0.577}{\alpha} . \quad (\text{C.5.5})$$

Evaluating these equations using the data in Table C-10 gives α and β as 0.17 and 65.7, respectively. The following exceedence probabilities are calculated using these parameters.

$$\begin{aligned} P(\text{gust speed} > 80 \text{ mph}) &= 8.53 \times 10^{-2}, \\ P(\text{gust speed} > 86 \text{ mph}) &= 3.19 \times 10^{-2}, \text{ and} \\ P(\text{gust speed} > 90 \text{ mph}) &= 1.64 \times 10^{-2}. \end{aligned}$$

It is judged that these estimates are too conservative for serious consideration.

5.2. Impact of Gust Wind on Tank Farm

Future Hanford Site HLW facilities will be designed to withstand sustained 90-mph wind loads.¹⁴ Because the quality of construction may vary and the specification of construction materials is not continuously distributed, most designs have an additional safety margin. If the U.S. Uniform Building Code were used in the tank farm design, a safety factor of 1.3 could be assumed. If we assume that past construction activities adhered to the 1990 design criteria,¹³ the actual capacity for wind load would be 117 mph; the yearly exceedance frequency is estimated to be 9.6×10^{-7} , assuming a safety factor of 1.3. If a safety factor of 1.5 were assumed, the actual capacity for wind load would be 135 mph; the corresponding exceedance frequency is estimated to be 6.5×10^{-9} . Because the site design is specified for sustained wind loads, even much higher gust speeds probably can be withstood.

The most likely consequences of an extremely high-speed gust on a tank farm are: LOSP, LOTV, annulus vent line breach, and exhaust vent line breach (Table 4-2). However, because the exceedance frequency of a gust speed greater than the assumed actual capacity of 117 mph is negligibly small, any wind-gust risk contributions, assuming the tank facilities were designed properly, can be neglected.

5.3. Uncertainty

This section discusses the uncertainties associated with the wind-gust exceedance frequencies calculated in the previous section. Because the average and standard deviations resulting from Table C-10 were used as if they were generated from the annual maximum gust speeds, this discussion focuses on differences between the distribution determined from Table C-10 data and the one expected from actual annual maximum gust speeds.

The average deviation obtained from Table C-10 would very likely be larger than the one generated by averaging the maximum yearly gust speed. Also, the actual standard deviation would very likely be smaller than the one generated from the maximum yearly gust speed data. Whereas a larger mean tends to increase exceedance frequency, a smaller standard deviation decreases frequency so that the overall impact of these differences is mixed. Although the opposing impacts of the standard deviation and mean are not likely to cancel, it is judged that uncertainties will not change the conclusion that wind gusts are not likely contributors to risk.

6.0. AIRCRAFT CRASH

The potential risks associated with Tank 101-SY contents release caused by aircraft impacts are evaluated in this section. The analyses that support the conclusion that aircraft crashes are not significant risk contributors are detailed below.

6.1. Commercial Aircraft Crash

6.1.1. Screening Analysis. A previous study,² performed using the methodology established in Ref. 15, concludes that the frequency of a commercial aircraft crash into the HWVP is less than 1×10^{-7} /yr. The same study states that the frequency of an aircraft crash into a Safety-Class 1 structure is significantly smaller than 10^{-7} /yr. Because Tank 101-SY is smaller than a Safety-Class 1 structure by at least a factor of 8, the frequency of commercial aircraft crash into Tank 101-SY is $\leq 10^{-8}$ /yr. Even if the entire tank farm is considered, the crash frequency is still probably $\leq 1.77 \times 10^{-6}$ /yr (177×10^{-8} /yr).

Based on the expected frequency, it seems reasonable to screen commercial aircraft crashes from further consideration. However, because of the potential severity of the consequences of this event, further examination is required.

If an aircraft crash results in the failure of the 101-SY tank dome structure and the released jet fuel ignites the waste material, the resulting release could be far more severe than any release category defined for internal-accident sequences. A detailed analysis of this possible high-consequence accident follows.

6.1.2. Detailed Aircraft Crash Analysis

6.1.2.1. Airports and Airport Operations. Two relatively large airports and landing facilities are located in the vicinity of the Hanford Site. These are Richland Airport, which is 20 m from the site, and Tri-City Airport (Pasco), which is 30 m from the site. Richland Airport is a small general aviation facility that handles an estimated 17,500 air operations per year.¹⁶ The Tri-City Airport is used for local commercial aircraft and for small, general aviation purposes. Table C-11 lists the total airport and instrument operations at the Tri-City Airport in 1991.¹⁷ Because Richland Airport's instrument operations are handled by the Tri-City Airport, Table C-11 also includes the secondary instrument operations for Richland Airport.

6.1.2.2. Consequences of Large Aircraft Crash on a Tank. Early studies and aircraft crash tests concluded that only high-velocity, large aircraft can cause waste tank collapse. One study in particular addressed the issue of collapse of the Hanford

TABLE C-11
AIRCRAFT OPERATIONS FOR TRI-CITY AIRPORT IN 1991

Type of Operation	Total	Air Carrier	Air Taxi	General	Military
Itinerant Operations	5.45E+04	2.25E+03	2.81E+04	2.37E+04	4.78E+02
Local Operations	2.19E+04			2.14E+04	5.50E+02
Total Operations	7.64E+04	2.25E+03	2.81E+04	4.51E+04	1.03E+03
Instrument Operations					
Primary Operations	3.15E+04	2.22E+03	2.41E+04	4.86E+03	3.34E+02
Secondary Operations ^a	1.72E+04	9.00E+00	1.02E+04	6.23E+03	7.24E+02
Overflights	1.70E+03	6.70E+01	2.64E+02	8.61E+02	5.10E+02
Total Instrument Operations	5.04E+04	2.30E+03	3.45E+04	1.20E+04	1.57E+03
Large Aircraft ^b	3.82E+04				

^aRichland Airport Operations handled by the Tri-City Airport.

^bIncludes air carriers, air taxis, and 10% of general and military operations.

waste tank, given a large aircraft crash on the tank. The characteristics of the airplane studied are:¹⁸

airplane type: Boeing 707-320;

total gross weight: 200,000 lb;

engine weight: 3100 lb;

engine effective diameter: 44 in.;

terminal velocity: 600 mph (880 ft/s); and

crash angle: 22.5° from target surface.

Because these aircraft characteristics are similar to those for the commercial airlines operated around the tank site, these results can be directly applied to the waste tank. Considering the brittle response of a tank, this study concluded that both the aircraft engine and the aircraft fuselage perforate the tank structure. For a tank ductile response, this study concluded that the postulated aircraft-impact load would cause the tank structure to collapse completely.²⁰

Given the above information, it was judged credible that the waste tank would collapse, given a large aircraft crash on it. However, the study gave no information concerning the results of a smaller aircraft crash. This analysis conservatively assumes that an impact by any aircraft having a gross weight $\geq 75,000$ lb causes tank collapse.

Other studies have also addressed the issue of military-aircraft-induced collapse of earth-covered facilities at other DOE sites. One such study addressed weapon storage buildings¹⁹ that were topped by 5 ft of topsoil having an approximate density of 100 lb/ft^3 . The roof of these buildings were 150 lb/ft^3 density, 1-ft-thick concrete, which is quite similar to the Hanford Waste Tank (HWT) dome concrete.

This study concluded that the weapons storage buildings would collapse if the minimum crash velocities were 130 ft/s for a B720 and 60 ft/s for a T38 trainer, where the equivalent gross weights are 156,000 lb and 39,300 lb, respectively. Impact velocities of larger than 1000 ft/s are required for these aircraft to penetrate into the weapons storage buildings.

Note that the normal altitude range for smaller general aviation aircraft near the Hanford Site is about 1000 to 10,000 ft. If such aircraft free fell from 10,000 ft, their terminal velocity would reach about 800 ft/s. Also, normal flight speed for smaller aircraft is in the range of 150 to 300 mph (220 to 440 ft/s). Neglecting all resistance force, the maximum terminal crash velocity for smaller aircraft thus would be the square root of $(800 \times 800 + 440 \times 440) = 913$, which is less than the minimum penetration velocity for buildings having protective coverings similar to those for the waste tanks. Therefore, it was concluded that a smaller aircraft crash on the tank might cause the tank dome breach but that no collapse would occur. Because the tank dome breach had a much larger frequency (see Table 4-6) than the small aircraft crash frequency (see Sec. 4.2.8), the risk contributions made by crashes of small aircraft are negligible and are not considered for the remaining analysis.

As shown in Table C-11, the approximate number of large aircraft (75,000 lb or heavier, or having 30 or more seats) operating near the tank farm site was obtained by summing the air carriers, air taxi, and 10% of the general and military aircraft that were handled by instrument operations in 1991. For the last 30 yr in the US, the average annual increase of airport operations was about 3.0%, and instrument operations were about 6.6%. The projected mean and median number of yearly aircraft operations near the tank farm site for the next 10 yr, assuming the percentages remain constant, are listed as follows.

Type of Aircraft Operation	Mean	Median
Total Airport Operations	9.03E+4	9.00E+5
Large Air Carrier	5.52E+4	5.43E+4

6.1.2.3. Analytical Model. The frequency of aircraft crashes into various tanks at the Hanford Site was estimated using the following model:²⁰

$$f_k = \sum_i^M \sum_j^L N_{ij} \times \lambda_j \times d_j \times \frac{A_{kj}}{A_{pj}} , \quad (C.6.1)$$

where

- f_k = annual frequency of aircraft impact on the kth tank (events/yr),
- N_{ij} = annual number of operations of aircraft of type j to or from airport i or along airway i,
- λ_j = crash rate of aircraft of type j (accidents/mi flown),
- d_j = distance traveled by the aircraft while the Hanford Site is within its potential impact area (mi),
- A_{pj} = effective impact area for aircraft type j (mi²),
- A_{kj} = effective impact area of the kth tank for aircraft of type j (mi²),
- M = number of different flight paths that take aircraft past the site or number of different airports, and
- L = number of different types of aircraft that pass the site.

Because only the crashes of large aircraft operating from the Tri-City Airport are important, the above equation is simplified to

$$f_k = N \times \lambda \times d \times A_k / A_p . \quad (C.6.2)$$

The product $N \times \lambda \times d$ is the yearly number of aircraft accidents within the defined distance segment, d , that could potentially affect the tank farm from the Tri-City Airport. The ratio A_k / A_p is the random probability of hitting a particular tank, given that the aircraft accident is in the vicinity of the tank farm.

The quantities d and A_p can be calculated by assuming that if a crash-initiating malfunction occurs, there is an equal possibility of the resulting crash terminating any-

where in a sector of radial length gh and angular width $\varnothing$ located directly in front of the aircraft, where g is the glide distance per unit of altitude lost, and h is the altitude.

From Fig. C.10, it can be seen that the distance d is given by

$$d = [(gh)^2 - b^2]^{1/2} + b/\tan \beta .$$

If d is averaged over all allowable values of b , the result is

$$d = 1/2 \times gh \times (\varnothing/2)/\sin(\varnothing/2) . \quad (C.6.3)$$

A_p is the area of the sector defined by the angle $\varnothing$ and radius gh :

$$A_p = (gh)^2 \times (\varnothing/2) . \quad (C.6.4)$$

6.1.2.4. Determination of Parameter Values. The values necessary to calculate the frequency of aircraft crashes into the tank farm are determined in this section.

Crash Rates. Table C-12 shows statistics for 9 yr of fatal accidents involving 75,000 lb or heavier aircraft.^{21,22} Additionally, Table C-13 shows air carrier air miles flown for the same 9-yr period.¹⁷ The in-flight crash rate distribution parameters calculated by using the accident and miles-flown data were derived by considering accidents for cruise, climb, and descent operational phases. Aircraft destroyed (the 5th column of Table C-12) was used as the 5th percentile of the in-flight crash. Aircraft with substantial damage, destroyed, and destroyed during the maneuvering phase were also assumed to the distribution 50th percentile. Assuming a lognormal distribution, the resulting characteristics of the distributions for aircraft of 75,000 lb or heavier are

5th percentile 1.34×10^{-10} /in-flight mi,
 50th percentile: 6.20×10^{-10} /in-flight mi, and
 95th percentile: 2.90×10^{-9} /in-flight mi.

The corresponding mean and the variation of the annual in-flight crash rates are 9.62×10^{-10} and 9.3×10^{-18} , respectively.

Geometric Parameters. Normal jet route altitudes are between 18,000 and 45,000 ft MSL, but according to Pasco FAA control tower personnel, an average altitude of between 22,000 and 23,000 ft is appropriate for commercial traffic around the Pasco Area.²³ According to the same reference, it takes about 60 to 70 m for departing

Fig. C.10.
Geometry for Impact Probability Model.

TABLE C-12
AIRCRAFT CRASH INVESTIGATION DATA (1983–1991)

Phase of Operation	Aircraft Damage			Destroyed	Total	Percent of Total
	None	Minor	Substantial			
Standing	17	4	2	1	24	10.1
Taxi	5	3	18	1	27	11.3
Takeoff	2	3	13	13	31	13
Initial Climb	0	0	1	0	1	0.4
Climb	6	0	5	0	11	4.6
Cruise	31	4	5	0	40	16.8
Descent	17	4	3	5	29	12.2
Approach	0	2	5	4	11	4.6
Landing	2	2	44	9	57	23.9
Maneuvering	1	0	0	4	5	2.1
Other	0	0	1	0	1	0.4
Unknown	0	0	0	1	1	0.4
Total	81	22	97	38	238	
Percentage of Total	34	9.2	40.8	16		100.0

TABLE C-13
AIR MILES FLOWN BY AIRCARRIERS

Year	Miles Flown
1983	3.07E+09
1984	3.43E+09
1985	3.63E+09
1986	4.02E+09
1987	4.36E+09
1988	4.50E+09
1989	4.61E+09
1990	4.97E+09
1991	4.76E+09
Average	4.15E+09
Standard Deviation	7.24E+08

Tri-City Airport commercial aircraft to reach this altitude range. Because the HTF Site is only 30 mi from this airport, air crashes are more likely in the climbing and descending operational modes.

To calculate h , it was assumed that aircraft reach an altitude of 10,000 ft MSL, roughly half their cruising altitude, by the time they reach the site. Because the MSL is about 700 ft, the point estimate for h is 9300 ft. To account for the uncertainty associated with this estimate, h was assumed to be a uniform distribution in the range of 8300 to 10,300 ft.

Because statistics for glide ratios for aircraft that are descending toward a crash landing are not available, it was necessary to construct a distribution for the glide ratio, g , the glide distance per unit of altitude lost. This distribution was determined by choosing upper- and lower-bound values, as well as the distribution type for g . Details on the selection criteria used for these choices are given below.

The approach angle for an aircraft making a normal landing is typically 4° , which corresponds to a glide ratio of 15. Any aircraft descending at this ratio probably is not in an imminent crash situation, so 15 was chosen as an upper bound on g . Other analysis¹⁸ has determined that the maximum credible tank-impact angle is 22° , corresponding to a glide ratio of 2.41. This value was used as the lower bound for g . Because there is no evidence that favors any specific value for g , g was treated as a uniform distribution in the range of 2.41 to 15.

The impacted tank area for the j th accident, A_{kj} , is represented by the tank size multiplied by a factor of 5 to account for the glide effect. Even though the Tank 101-SY surface area is about 4415 ft², a typical tank size is about 8831 ft². Therefore, a conservative site value for A_{kj} is about $8831 \times 5 = 4.42 \times 10^4$ ft² (1.59×10^{-3} mi²).

Finally, the angle ϕ is the last geometric parameter requiring assessment before calculating the aircraft crash/frequency estimate. Based on other analyses,²⁴ it was assumed that the $\phi/2$ was about 90° .

Substituting parameter distributions into Eq. (C.6.3) gives the following distribution characteristics for d :

mean = 3.86 mi,
5th percentile = 1.35 mi,
50th percentile = 3.80 mi, and
95th percentile = 6.48 mi.

Likewise, evaluating Eq. (C.6.4) gives the resulting characteristics for A_p

mean = 141 mi²,
5th percentile = 14.7 mi²,
50th percentile = 115 mi², and
95th percentile = 336 mi².

6.1.2.4. Impact Frequency of Large Aircraft. Finally, by substituting the estimated distribution values for N , λ , d , A_p , and A_k into a Monte Carlo simulation model for the crash-frequency, the mean value for f_k was determined to be 3.08×10^{-9} crashes/tank-yr. Other characteristics of the distribution for f_k , the large aircraft impact frequency, are:

5th percentile: 3.39×10^{-10} crashes/tank-yr,
50th percentile: 1.82×10^{-9} crashes/tank-yr, and
95th percentile: 1.04×10^{-8} crashes/tank-yr.

The analysis results presented in this section indicate that aircraft crashes are not significant contributors to external-event Tank 101-SY risk. It should be noted that the mean crash frequency for 177 tanks would be about 5.45×10^{-7} crashes/yr.

7.0. LIGHTNING

The conclusion of the tank farm lightning strike evaluation is that the risk contribution of a tank lightning strike is insignificant. The details that support this conclusion are discussed in this section.

7.1. Frequency of Lightning Strike

The general empirical relationships between flashes (cloud-to-ground) and annual thunderstorm days for regions in the US are shown in Table C-14,²⁵ where T is the number of thunderstorm days for the locality of interest.

TABLE C-14
EMPIRICAL FUNCTIONS RELATE THUNDERSTORM DAYS
AND GROUND FLASH DENSITY*

Location	Ground Flash Density
Northern US	$0.11T / (\text{km}^2\text{-yr})$
Southern US	$0.17T / (\text{km}^2\text{-yr})$
US	$0.1T / (\text{km}^2\text{-yr})$
US	$0.15T / (\text{km}^2\text{-yr})$

*See Ref. 10.

It has also been observed that the proportion of cloud-to-cloud flashes increases as latitude decreases. Pierce et al.²⁵ proposed the following relationship for cloud-to-ground flash density in terms of latitude, λ , and thunderstorm days per year, T , for the locale of interest:

$$N_g = [0.1 + 0.35 \times \sin(\lambda)] \times (0.40 \pm 0.20) \times \frac{T}{\text{km}^2 - \text{yr}}, \quad (\text{C.7.1})$$

where N_g is the number of ground strikes per km^2 .

Substituting the tank farm latitude of about 47° in the equation yields the N_g values of $0.22T$ and $0.07T$. The number of thunderstorm days per year, T , for Hanford is 10.²⁵

The frequency of a lightning strike on a tank farm is the product of N_g and tank area. The area of a typical tank, which has a diameter of 75 ft, is about $4.1 \times 10^{-4} \text{ km}^2$. Combining the thunderstorm days and the tank size with the empirical value for N_g gives a range of the occurrence frequency of lightning strikes on a tank between 2.87×10^{-4} and $8.61 \times 10^{-4} / \text{yr}$.

7.2. Consequences of a Lightning Strike

The most likely consequences of lightning in terms of tank safety would be LOSP, range fire, and possibly LOTV. Recall that the estimated range fire frequency is about 0.85/yr, the estimated frequency of LOSP is about 0.418/yr, and the estimated LOTV is about 0.566/yr. Because the estimated frequency of lightning strike on a tank

is only a small percentage of these values, the contribution of lightning to the range fire, LOSP, and LOTV can be neglected.

Lightning also is a potential ignition source for hydrogen released from the tank waste. For Tank 101-SY, there are approximately 3.65 releases/yr with ignition exposure time windows of up to 8 h for each release. This results in an exposure time of about 29 h/yr and a yearly ignition frequency of 3×10^{-7} from lightning. Because the estimated ignition likelihood from internal sources is about 1×10^{-3} /release, this lightning risk also is judged to be insignificant.

8.0. VOLCANISM

Lava flows and volcanic ashfall, two types of potential hazards associated with volcanic activity, are evaluated in this section. This evaluation concludes that the probability of an impact from lava is negligibly small and that the frequency of an ashfall impact on the tank farm is insignificant. The potential consequences of an ashfall can be incorporated into this risk analysis by modifying the internal initiating event frequencies for LOSP and LOTV to include the frequency of an ashfall event.

8.1. Lava

With regard to the tank farm site, lava can arise only from Cascade Range volcanic activity. Because there is no evidence that lava or mud flows from the Cascade Range have reached the Pasco Basin during the last 2 to 3 million years, the nearest Cascade Range volcano is more than 100 km (62 m) from the Hanford Site, and because no stream or river drainage runs directly from the Cascades to the site, the probability of a lava flow hazard impacting the tank farm site is considered very low.² The Cascade Range is also the only potential volcanic ash source. The frequency of and potential impacts from ashfall are discussed below.

8.2. Frequency of the Ashfall

The frequency of ashfall on the Hanford Site from Cascade Range volcanoes depends on both the likelihood of renewed eruptive activity and on proper wind direction at the time of eruption. To estimate the frequency of ashfall at the tank site, the following equation was developed:

$$\lambda_{\text{ash, tank}} = \lambda_{\text{erupt}} \times f_{\text{wd | ash}} \times f_{\text{wv | wd}} \quad , \quad (\text{C.8.1})$$

where

- $\lambda_{\text{ash, tank}}$ = the frequency of volcanic ashfall on the tank site,
- λ_{erupt} = the frequency of volcanic eruption in the vicinity of the tank site,
- $f_{\text{wd}|\text{ash}}$ = the conditional probability that wind direction pushes the ashfall toward the tank site, and
- $f_{\text{wv}|\text{wd}}$ = the conditional probability that the wind speed is large enough to carry volcanic ashfall to the tank site.

The estimated frequency of eruption of some Cascade Range volcanoes is in the range of 10^{-4} to 10^{-5} /yr.^{2,26} However, it appears that Mt. St. Helens, which caused ashfall in May 1980, may be slightly more active. The estimated eruption point-value frequency for Mt. St. Helens is 2.1×10^{-3} /yr (Ref. 2, pp. 9-90). This more conservative frequency is used as λ_{erupt} in Eq. (C.8.1).

Mt. St. Helens is about 120 mi west (slightly west-southwest direction) of the tank farm site. Given an eruption, a west (slightly toward west-southwest) wind is required to carry the ashfall to the site. Wind direction data contained in Table 3.3-3 of Ref. 2 shows that on average, the site wind direction is from the west 9.7% of the time and from the west-southwest 8.5% of the time. Assuming the volcanic eruption is randomly distributed in time, summing these two percentages give a conservative value of $f_{\text{wd}|\text{ash}} = 0.182$.

The determination of the wind speed required to deposit the ash from a Mt. St. Helens eruptions at the tank farm is very complex. The required wind speed is dependent on the height to which the tephra (low-temperature ash) is ejected during the eruption and the tephra particle size and density. Given that the required wind speed could be determined, the conditional probability [i.e., $f_{\text{wv}|\text{wd}}$ from Eq. (C.8.1)] of this wind speed, given that the wind is blowing toward the tank farm, could be determined based on meteorological data and an extrapolation of ground level wind speed to wind speed at a given elevation of interest, such as the height of the ejected tephra.

Rather than quantitatively determine the actual wind speed required to deposit Mt. St. Helens eruption ash at the tank site (i.e., $f_{\text{wv}|\text{wd}}$), a decision was made to assign this parameter a value of 1.0 in order to calculate the upper-bound frequency of ashfall at the tank as

$$\lambda_{\text{ash, tank}} = 2.1 \times 10^{-3} \times 0.182 \times 1.0 = 3.82 \times 10^{-4} .$$

8.3. Impact of the Ashfall

The tank farm site experienced a volcanic ashfall on May 8, 1980. In the first 9 h following the eruption, approximately 1 mm (0.04 in.) of uncompacted ash was recorded at the Supply System WNP-2 meteorological station, which is about 25 km (15 m) south-southeast of the tank farm site.

The possible consequences this and other potential instances of tank farm volcanic ashfall depend on the amount of air-fall tephra that may reach the tank farm site, which in turn depends on the dispersal characteristics and volume of material erupted, the tephra characteristics, and the distance of the site from the source. Dispersal patterns of ejecta from eruptions are determined by the wind direction and velocity and the altitude to which the ash cloud rises. Furthermore, given the distance between the tank site and Mt. St. Helens, the ashfall needs to stay in the air for quite a while to be carried to the tank site.

The postulated impacts of ashfall on the tank farm are an LOSP and an LOTV. Estimates of the amount of ashfall required to impact the tank farm and the wind speed needed to cause this level of deposition are not quantified in this analysis. Instead, it is conservatively assumed that, given an eruption with the wind blowing from the west or west-southwest direction, an LOSP and an LOTV will occur. Based on Eq. (C.8.1) the unconditional maximum annual frequency of this event is 3.82×10^{-4} , which is much smaller than the internal initiating-event frequencies for LOSP and LOTV. Therefore, the contributions to the LOSP and LOTV initiating event frequencies and to risk owing to ashfall are not considered in the model.

9.0. ACCIDENTS AT OTHER HANFORD SITE FACILITIES

Accidents may occur at other Hanford Area nuclear, industrial, or transportation facilities or at military installations at or near the Hanford Site. It is judged that if these facilities are designed and operated according to their corresponding safety standards, the contribution of these accidents to the risks of the tank farm is insignificant.²

9.1. Nuclear Reactors

The Hanford Site houses three US DOE reactors: N Reactor in the 100 Area; the Fast Flux Test Facility (FFTF) in the 400 Area; and the SP-100 space nuclear test assembly in the 300 Area. There are also two commercial nuclear reactors: WNP-1 and WNP-2, owned by the Washington Public Supply System and located across from the

400 Area. Because these five reactors may be operating during the remaining lifetime of the tank farm, their potential tank-farm impacts must be considered.

These reactors must comply with the safety and radiation standards of the DOE or the USNRC for protection of the public during both routine operations and accidental or unplanned-release situations. The distances between each of these reactors and its exclusion-area boundary (i.e., allowable nearest distance to a resident member of the public) is considerably less than the distance from each reactor to the tank farm site. Because these reactors pose insignificant risk to the offsite public, these reactors also are judged to have an insignificant potential impact on the operation of the tank farm.

9.2. Nonreactor Nuclear Facilities and Nonnuclear Facilities

In general, all Hanford nonreactor facilities are responsible for ensuring that the potential from onsite accident consequences are within published risk acceptance guidelines. No existing analyses determine radiological consequences at the tank farm from nonreactor and nonnuclear facility accidents, but facilities believed to be representative of operations that present the most risk to the safe operation of the Hanford Waste Vitrification Plant (HWVP) were selected for review and are listed in the following table. Because the HWVP is located in the 200 East Area adjacent to the tank farm, it is judged that results from the following analyses can be applied to the tank farm.

Facility	Distance from HWVP
PUREX Plant	2.4 km (1.5 mi)
Essential Materials Warehouse (Building 275-EA)	2.4 km (1.5 mi)
Nonradioactive Dangerous-Waste Storage Facility (NRDWSF)	2.4 km (1.5 mi)
Plutonium Finishing Plant (PFP)	8 km (5.0 mi)
Waste Encapsulation and Storage Facility (WESF)	0.4 km (0.24 mi)
Aging Waste Facility (AWF)	2.4 km (1.5 mi)

The postulated worst-case accident situations at nuclear facilities in the above table yield the following calculated radiological dose commitments:

Facility	Accident	Radiological Consequences
PUREX	Cooling coil leak to B pond	0.028-Sv (2.8 rem) whole-body dose at facility boundary
PFP	Plutonium release following seismic event	0.11-Sv (11 rem) whole-body dose 550 m (1840 ft) from release point
WESF	Package solid waste fire in truck port	0.078-Sv (7.8 rem) whole-body at facility boundary
AWF	Seal-loop ventilation failure	0.062-Sv (6.2 rem) whole-body dose 100 m (300 ft) from release point

When these worst-case accident dose commitments are extrapolated to the HWVP location (or to the tank farm location) on the basis of engineering judgment, they are less than the allowable dose limits for occupational exposures to maximally exposed onsite individuals (i.e., 5-rem annual EDE for stochastic effects; 50-rem annual EDE for organs, extremities, and skin; and 15-rem EDE for the lens of the eye).

For the two nonnuclear facilities (Building 275-EA and NRDWSF), worst-case chemical release accidents yield maximum concentrations of chemicals at the tank farm site below the threshold limit value (TLV) or immediately dangerous to life and health (IDLH) concentration.

9.3. Ground Transportation Facilities

It is judged that potential impacts from non-Hanford Site truck accidents involving missile, shock wave, or toxic chemical release are negligibly small because of the large distance between the site and public highway (Highway 240). At its closest point, this distance is about 3.9 km (2.5 mi).

With regard to hazards associated with a Hanford Site truck or railcar accident in which toxic or hazardous chemicals are released, it is judged that the most important impact on the tank may be the evacuation of the facility and the resulting loss of monitoring capability for the period of evacuation. The risk contribution from the evacuation is judged to be insignificant.

Trucks and railcars can also accidentally knock down utility poles and other facilities. The historical data for other initiating event frequencies have already included the impact of such truck and railcar accidents.

9.4. Military Facilities

The only significant military activity near the tank farm site is on the US Army Yakima Firing Range, which is located more than 32 km (20 mi) west of the Hanford Site. The most significant hazard associated with the firing range is the potential for an incident to start a range fire that could spread to the tank farm site. (See Sec. C.3 for possible impacts caused by range fire.) Another postulated hazard associated with the firing range is that of a misdirected artillery shell hitting the tank farm. It is judged that the likelihood of this accident is negligible because the frequency of a misdirect is low and the distance between these two sites is large.²

REFERENCES

1. US Nuclear Regulatory Commission, "PSA Procedures Guide," NUREG/CR-2300 (1983).
2. Westinghouse Hanford Company, "Hanford Waste Vitrification Plant Preliminary Safety Analysis Report," WHC-EP-0250, Rev. 1 (January 1991).
3. Woodward-Clyde Consultants, "Evaluation of Seismic Hazard for Non-Reactor Facilities, Hanford Reservation," Westinghouse Hanford Company report WHC-MR-0023 (July 1989).
4. Sandia National Laboratories, "Analysis of Core Damage Frequency due to External Events at the DOE N-Reactor," SAND89-1147, UC-610 (November 1990).
5. Telephone communication, A. M. Tallman, Westinghouse Hanford Company, and H. F. Perla, PLG, Inc. (May 29, 1992).
6. URS/J. A. Blume & Associates, "Additional Analysis of Underground Waste Storage Tanks 241-SY," RHO-C-59 (July 1981).
7. Westinghouse Hanford Company, "Soil Structure Interaction Analysis for the Hanford Site 241-SY-101, Double-Shell Waste Storage Tanks," WHC-EP-0504, Vols. 1 and 2 (September 1991).
8. E. J. Gumbel, *Statistics of Extremes*, Columbia Press, New York (1958).

9. A. Goubet, "Risques Associes aux Barrages," La Houille Blanche/No. 8-1979.
10. US Department of Energy, "Final Environmental Impact Statement: Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes," DOE/EIS-0113, US Department of Energy Headquarters, Washington, D.C. (1987).
11. E. Simiu and J. J. Filliben, "Statistical Analysis of Extreme Winds," Technical Note No. 868, National Bureau of Standards, Washington, D.C. (1975).
12. W. A. Stone, J. M. Thorpe, O. P. Gifford, and D. J. Hoitink, "Climatological Summary for the Hanford Area," Pacific Northwest Laboratory report PNL-4622 (1983).
13. D. W. Coats and R. C. Murray, "Natural Phenomena Hazards Modeling Project: Extreme Wind/Tornado Hazard Models for Department of Energy Sites," US Department of Energy report UCRL-53526, Rev. 1 (1985).
14. R. P. Kennedy et al., "Design and Evaluation Guidelines for Department of Energy Facilities Subject to Natural Phenomena Hazards," US Department of Energy report UCRL-15910 (June 1990).
15. *Standard Review Plan for Nuclear Power Plants*, US Nuclear Regulatory Commission Guide 0800 (1981).
16. D. A. Smith, "Aircraft Impact on the Hanford Waste Vittrification Plant," Westinghouse Hanford Company report WHC-SD-HWV-RA-001 (April 1990).
17. "FAA Air Traffic Activity, FY 1991," US Department of Transportation, Federal Aviation Administration (1991).
18. Hanford Defense High-Level Waste Management Studies, Kaiser Engineers report 77-09-RE, under Contract EY-76-C-06-2195.
19. Final Report, Hanford Defense High-Level Waste Management Studies, Kaiser Engineers report 77-09-RE (September 1977).
20. "Aircraft Consideration Preapplications Site Review by the Directorate of Licensing, U. S. Atomic Energy Commission," in the matter of Portland General Electric Company, Boardman Nuclear Plant, Boardman, Oregon, Project Number 485.
21. "FAA Statistical Handbook of Aviation, Calendar Year 1991," US Department of Transportation, Federal Aviation Administration (December 1992).
22. National Transportation Safety Board, "Annual Review of Airport Accident Rates, Calendar Year 1980," NTSB-ARG-80-1 (May 1980).

23. Telephone conversation with FAA Pasco control tower personnel (January 26, 1993).
24. PLG, Inc., "Seabrook Station Probabilistic Safety Assessment," PLG-0300 (December 1983).
25. "Lightning Problems and Protection at Nuclear Power Plants," Electric Power Research Institute report NSAC/41 (December 1981).
26. S. Shipley and A. M. Sarna-Wojcicki, "Maps Showing Distribution, Thickness and Mass of Late-Pleistocene and Holocene Tephra from Major Volcanoes in the Pacific Northwest of the United States: A Preliminary Assessment of Hazards from Volcanic Ejecta to Nuclear Reactors in the Pacific Northwest," MAP MF-1435, US Geological Survey, Washington, D.C. (1983).

APPENDIX D

DATA ANALYSIS

1.0. HTF UNUSUAL OCCURENCE REPORT EVENT FREQUENCIES

Table D-1 gives the reported incidents of unusual occurrences involving waste tanks at Hanford, based on data from the 17-yr period 1974 to 1990. If the component of interest is at risk during continuous time intervals, the data obtained for the event are in terms of the number of occurrences (denoted X) and the accumulated time at risk for the component (denoted T). If events are functions of demands rather than time, then T represents the number of times the component was at risk from the specified unusual occurrence. The data are obtained from Refs. 1 and 2. Various assumptions and calculations were used to determine actual time on the test for each occurrence, as discussed in the following paragraphs.

The frequencies for occurrences are described using a Bayesian framework. A noninformative Gamma prior distribution with parameters $(0.5, 0)$ is used to model initial uncertainty for the frequency rates of the various occurrences because low-frequency events are modeled well with the Gamma distribution. These prior distributions were updated with the appropriate unusual occurrence report (UOR) frequency data (X, T) to obtain the final "posterior" distribution for the frequency of occurrences, which is Gamma $(X+0.5, T)$. From the posterior distribution, useful statistical moments and quantiles, such as the mean, median, and standard deviation, are obtained. Results for each occurrence of interest are found in the table. This method of estimation is described in Chap. 7 of Ref. 3. Prior distributions were not constructed for those events for which no time interval or demand information exists.

For each event, frequencies are tabulated, along with the corresponding total time on testing for the family of components at risk. Most events are measured in time (e.g., tank years), but a few are rendered as per demand probabilities. For these demand cases, the population data is either estimated from operational considerations or based on operational data such as in the case of transfer errors and tank leaks. Finally, conservative bounds were used when specific time-interval data were unavailable.

Misroutings Per Year: A misrouting is defined as the routing of waste to an unintended location. This can include a tank, pit, catch tank, crib, or transfer directly to the environment. It is assumed that only the 28 DS tanks would be

**TABLE D-1
HANFORD WASTE TANK FARM UNUSUAL OCCURRENCE REPORT EVENT FREQUENCIES**

Category	Event	UOR Data		Posterior Gamma Parameters		Posterior Moments and Quantiles π					Comments
		x	T	α	β	Q(05)	Median	Mean	Q(95)	Std Dev	
Misroutings (per year)	Tank-to-tank misroutings	28	286.7 tank-yr	28.5	286.7	7.1E-02	9.8E-02	9.9E-02	1.3E-01	1.9E-02	Per DS tank per yr
	Misrouting to a valve pit or diversion box	3	286.7 tank-yr	3.5	286.7	3.8E-03	1.1E-02	1.2E-02	2.5E-02	6.5E-03	Per DS tank per yr
	Misrouting to a crib	2	17 yr	2.5	17	3.4E-02	1.3E-01	1.5E-01	3.3E-01	9.3E-02	Per yr
	Misrouting to a blanked line	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
	Misrouting to the environment	2	17 yr	2.5	17	3.4E-02	1.3E-01	1.5E-01	3.3E-01	9.3E-02	Per yr
	Inadvertent pumped transfer of waste	2	286.7 tank-yr	2.5	286.7	2.0E-03	7.6E-03	8.7E-03	1.9E-02	5.5E-03	Per DS tank per yr
	Inadvertent gravity drain of waste from a tank	1	286.7 tank-yr	1.5	286.7	6.1E-04	4.1E-03	5.2E-03	1.4E-02	4.3E-03	Per DS tank per yr
Misroutings (per transfer)	Tank-to-tank misroutings	28	~16,150 transfers	28.5	16150	1.3E-03	1.7E-03	1.8E-03	2.3E-03	3.3E-04	Per DS tank per transfer; assumes an average of ~1000 transfers per year, and ~95% of transfers involve DS tanks
	Misrouting to a valve pit or diversion box	3	~16,150 transfers	3.5	16150	6.7E-05	2.0E-04	2.2E-04	4.4E-04	1.2E-04	Per DS tank per transfer; assumes an average of ~1000 transfers per year, and ~95% of transfers involve DS tanks
	Misrouting to a crib	2	~16,150 transfers	2.5	16150	3.5E-05	1.3E-04	1.5E-04	3.4E-04	9.8E-05	Per DS tank per transfer; assumes an average of ~1000 transfers per year, and ~95% of transfers involve DS tanks
	Misrouting to a blanked line	1	~16,150 transfers	1.5	16150	1.1E-05	7.3E-05	9.3E-05	2.4E-04	7.6E-05	Per DS tank per transfer; assumes an average of ~1000

TABLE D-1 (CONT.)

Category	Event	UOR Data		Posterior Gamma Parameters		Posterior Moments and Quantiles π					Comments
		x	T	α	β	Q(05)	Median	Mean	Q(95)	Std Dev	
Mistransfer	Misrouting to the environment	2	~16,150 transfers	2.5	16150	3.5E-05	1.3E-04	1.5E-04	3.4E-04	9.8E-05	transfers per year, and ~95% of transfers involve DS tanks Per DS tank per transfer; assumes an average of ~1000 transfers per year, and ~95% of transfers involve DS tanks
	Overfill of tank	8	286.7 tank-yr	8.5	286.7	1.5E-02	2.8E-02	3.0E-02	4.8E-02	1.0E-02	Per DS tank per yr
	Excessive transfer waste temperature	1	286.7 tank-yr	1.5	286.7	6.1E-04	4.1E-03	5.2E-03	1.4E-02	4.3E-03	Per DS tank per yr
	Undesired reaction after transfer	1	286.7 tank-yr	1.5	286.7	6.1E-04	4.1E-03	5.2E-03	1.4E-02	4.3E-03	Per DS tank per yr
	Fissile inventory exceeded by transfer	0	286.7 tank-yr	0.5	286.7	6.9E-06	7.9E-04	1.7E-03	6.7E-03	2.5E-03	Per DS tank per yr
	Other concentration limit exceeded by transfer	5	286.7 tank-yr	5.5	286.7	8.0E-03	1.8E-02	1.9E-02	3.4E-02	8.2E-03	Per DS tank per yr
Intrusions	Surface water intrusion	8	1343 tank-yr	8.5	1343	3.2E-03	6.1E-03	6.3E-03	1.0E-02	2.2E-03	Per tank per yr; considers only the partially interim isolated and active tank populations
	Raw water leak intrusions	4	1343 tank-yr	4.5	1343	1.2E-03	3.1E-03	3.4E-03	6.3E-03	1.6E-03	Per tank per yr; considers only the partially interim isolated and active tank populations
	Intrusions through transfer piping	5	476 tank-yr	5.5	476	4.8E-03	1.1E-02	1.2E-02	2.1E-02	4.9E-03	Per tank per yr; considers only the active tank population
	Intrusions from interfacing systems	4	476 tank-yr	4.5	476	3.5E-03	8.8E-03	9.5E-03	1.8E-02	4.5E-03	Per tank per yr; considers only the active tank population
	Intrusions into an interim isolated tank	1	833 tank-yr	1.5	833	2.1E-04	1.4E-03	1.8E-03	4.7E-03	1.5E-03	Per tank per yr; considers only the interim isolated tank population
	Valve pit/diversion box flooding by water	11	357 pit (box)-yr	11.5	357	1.8E-02	3.1E-02	3.2E-02	4.9E-02	9.5E-03	Per pit (box) per yr; assumes a valve pit population of 21

TABLE D-1 (CONT.)

Category	Event	UOR Data		Posterior Gamma Parameters		Posterior Moments and Quantiles π					Comments
		x	T	α	β	Q(05)	Median	Mean	Q(95)	Std Dev	
Tank Pressurization or Excessive Vacuum	Valve pit/diversion box flooding by waste	2	357 pit (box)-yr	2.5	357	1.6E-03	6.1E-03	7.0E-03	1.6E-02	4.4E-03	Per pit (box) per yr; assumes a valve pit population of 21
	Surface flooding by raw water without intrusion	8	17 yr	8.5	17	2.6E-01	4.8E-01	5.0E-01	8.1E-01	1.7E-01	Per yr
	Surface flooding by other sources without intrusion	0	17 yr	0.5	17	1.2E-04	1.3E-02	2.9E-02	1.1E-01	4.2E-02	Per yr
	Transfer-caused overpressure	9	286.7 tank-yr	9.5	286.7	1.8E-02	3.2E-02	3.3E-02	5.3E-02	1.1E-02	Per DS tank per yr
	Accidental loop seal filling	1	68 tank-yr	1.5	68	2.6E-03	1.7E-02	2.2E-02	5.7E-02	1.8E-02	Per tank per yr; applicable only to the aging waste tanks
	Vaporization	1	286.7 tank-yr	1.5	286.7	6.1E-04	4.1E-03	5.2E-03	1.4E-02	4.3E-03	Per DS tank per yr
	Loss of ventilation fan	29	72 vent fan-yr	29.5	72	2.9E-01	4.1E-01	4.1E-01	5.4E-01	7.5E-02	Per ventilation fan per yr; of the 29 occurrences, one was a mechanical spark (thus, a conditional prob. of 0.03 per fan loss)
	Interfacing system pressurizes tank	2	286.7 tank-yr	2.5	286.7	2.0E-03	7.6E-03	8.7E-03	1.9E-02	5.5E-03	Per DS tank per yr
	Inadequate ventilation	2	286.7 tank-yr	2.5	286.7	2.0E-03	7.6E-03	8.7E-03	1.9E-02	5.5E-03	Per DS tank per yr
	Excessive vacuum in tank	1	286.7 tank-yr	1.5	286.7	6.1E-04	4.1E-03	5.2E-03	1.4E-02	4.3E-03	Per DS tank per yr
	Filter plugging	6	72 vent system-yr	6.5	72	4.1E-02	8.6E-02	9.0E-02	1.6E-01	3.5E-02	Per ventilation system per yr
	Deentrainer plugging	2	72 vent system-yr	2.5	72	8.0E-03	3.0E-02	3.5E-02	7.7E-02	2.2E-02	Per ventilation system per yr

TABLE D-1 (CONT.)

Category	Event	UOR Data		Posterior Gamma Parameters		Posterior Moments and Quantiles π					Comments
		x	T	α	β	Q(05)	Median	Mean	Q(95)	Std Dev	
Filter Bypass or Blowthrough	Filter blowthrough	5	72 vent system-yr	5.5	72	3.2E-02	7.2E-02	7.6E-02	1.4E-01	3.3E-02	Per ventilation system per yr
	Filter frame damage	1	72 vent system-yr	1.5	72	2.4E-03	1.6E-02	2.1E-02	5.4E-02	1.7E-02	Per ventilation system per yr
	Duct condensate leakage	1	72 vent system-yr	1.5	72	2.4E-03	1.6E-02	2.1E-02	5.4E-02	1.7E-02	Per ventilation system per yr
	Failure to restore	1	72 vent system-yr	1.5	72	2.4E-03	1.6E-02	2.1E-02	5.4E-02	1.7E-02	Per ventilation system per yr
	Loop seal pot loss	0	72 vent system-yr	0.5	72	2.7E-05	3.2E-03	6.9E-03	2.7E-02	9.8E-03	Per ventilation system per yr
	Riser leaks	2	286.7 tank-yr	2.5	286.7	2.0E-03	7.6E-03	8.7E-03	1.9E-02	5.5E-03	Per DS tank per yr
Irradiations	Failure to notify of transfer	5	17 yr	5.5	17	1.3E-01	3.0E-01	3.2E-01	5.8E-01	1.4E-01	Per yr
	Failure to heed notification of transfer	2	17 yr	2.5	17	3.4E-02	1.3E-01	1.5E-01	3.3E-01	9.3E-02	Per yr
	Uncovering of high-radiation component by flooding	2	17 yr	2.5	17	3.4E-02	1.3E-01	1.5E-01	3.3E-01	9.3E-02	Per yr
	Uncovering of high-radiation component by excavation	4	17 yr	4.5	17	9.8E-02	2.5E-01	2.6E-01	5.0E-01	1.2E-01	Per yr
Tank Mechanical Damage	Tank riser damaged by a vehicle	4	3009 tank-yr	4.5	3009	5.5E-04	1.4E-03	1.5E-03	2.8E-03	7.0E-04	Per tank per yr
	Drilling contacts tank	1	3009 tank-yr	1.5	3009	5.8E-05	3.9E-04	5.0E-04	1.3E-03	4.1E-04	Per tank per yr
	Excavation contacts tank	1	3009 tank-yr	1.5	3009	5.8E-05	3.9E-04	5.0E-04	1.3E-03	4.1E-04	Per tank per yr

TABLE D-1 (CONT.)

Category	Event	UOR Data		Posterior Gamma Parameters		Posterior Moments and Quantiles π					Comments
		x	T	α	β	Q(05)	Median	Mean	Q(95)	Std Dev	
External Events	Volcanic ashfall	1									
	Range fire	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
Spills of Radioactive Material	Crane handling leads to spill	6	17 yr	6.5	17	1.7E-01	3.6E-01	3.8E-01	6.6E-01	1.5E-01	Per yr
	Truck movement	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
	Surveillance operations	1	476 active tank-yr	1.5	476	3.7E-04	2.5E-03	3.2E-03	8.2E-03	2.6E-03	Per active tank per yr
	Water intrudes into contaminated equipment	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
	Other	3	17 yr	3.5	17	6.4E-02	1.9E-01	2.1E-01	4.1E-01	1.1E-01	Per yr
Transfer Leaks	Stabilization line	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
	Transfer line	8	17 yr	8.5	17	2.6E-01	4.8E-01	5.0E-01	8.1E-01	1.7E-01	Per yr
	Slurry line	5	17 yr	5.5	17	1.3E-01	3.0E-01	3.2E-01	5.8E-01	1.4E-01	Per yr
	Jumper leaks	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
Violations											
	Respirator not used when required	1	6205 entries	1.5	6205	2.8E-05	1.9E-04	2.4E-04	6.3E-04	2.0E-04	Per entry
	No personnel contamination check upon exiting	10	6205 entries	10.5	6205	9.3E-04	1.6E-03	1.7E-03	2.6E-03	5.2E-04	Per exit; assume one exit per day from a controlled area; only two incidents actually observed (assume a THERP stress multiplier of 5)
	Readings missed (other than equipment failure) ^a	5									
	Gundecked readings ^a	1									

TABLE D-1 (CONT.)

Category	Event	UOR Data		Posterior Gamma Parameters		Posterior Moments and Quantiles π					Comments
		x	T	α	β	Q(05)	Median	Mean	Q(95)	Std Dev	
Loss of Electrical Power	Failure to follow procedure ^a	7									
	Unauthorized maintenance ^a	4									
	All causes	3	34 side-yr	3.5	34	3.2E-02	9.3E-02	1.0E-01	2.1E-01	5.5E-02	Per side per yr
	All causes	1	17 yr	1.5	17	1.0E-02	7.0E-02	8.8E-02	2.3E-01	7.2E-02	Per yr
	All causes	16	72 vent system-yr	16.5	72	1.4E-01	2.2E-01	2.3E-01	3.3E-01	5.6E-02	Per ventilation system per yr
	All causes	16	34 DS tank-yr	16.5	34	3.1E-01	4.8E-01	4.9E-01	7.0E-01	1.2E-01	Per DS tank per yr
	Failure of backup system to start	8	16 demands	8.5	16	2.7E-01	5.1E-01	5.3E-01	8.6E-01	1.8E-01	Per demand
	Ventilation fan unavailable	14.5	630,720 h	15	630720	1.5E-05	2.3E-05	2.4E-05	3.5E-05	6.1E-06	Probability; assume 0.5 h mean downtime; unavailability has a (rescaled) gamma distribution; $29 \times 0.5 = 14.5$ h downtime
	Portable fan shutdown	3	43,800 h	3.5	43800	2.5E-05	7.2E-05	8.0E-05	1.6E-04	4.3E-05	Per h
	Pipe Leaks		Drain line leaks from the secondary concrete mat			8.0E-03	7.5E-02	1.4E-01	5.5E-01	1.8E-01	Unreliability for 15 yr; assume a pipe (60 ft) lognormal median failure rate of 6E-7/h and an EF of 10; $T = 365(24)(15) = 131,400$ h, unreliability = $1 - \exp(-\lambda \times T)$, and use simulation

Source: Refs. 1 and 2

^aDemand information does not exist.

connected to the transfer system during the 17-yr period. This is not completely true because some SS tanks were not partially isolated until partway through this period; thus, this is a conservative assumption about DS tanks. During the 17-yr period, the number of DS tanks increased from 3 to 28 so that approximately 287 tank years have accumulated. Occurrence frequencies for DS tanks are calculated based on 287 tank years.

Misroutings Per Transfer: The number of transfers per year is assumed to be 1000 (which is approximately the statistical average over the 17-yr period), of which 95% are assumed to involve DS tanks. The 17-yr total is 16,150 transfers involving DS tanks. The frequency of misrouting to any specific pit or box is based on the estimated population total of 21, which was determined from Fig. 8.8 of the Tank Farm Surveillance Report.⁴

Mistransfers: A mistransfer is defined as a waste transfer that reaches its desired destination but for which an undesired situation results. The time on test, in tank-years, is estimated to be the same as the events of misroutings.

Intrusions: An intrusion is defined as the unintended entry of water into a tank. Three populations are considered: tanks that are interim isolated (II), tanks that are partially interim isolated (PI), and active tanks that are connected to the transfer system. Some previously active tanks have been transferred to II and PI tanks during the period of interest. Assuming the current population of II and PI tanks, we have 98 II tanks, 51 PI tanks, and 28 active tanks. Using active and PI tanks for surface water and raw water leak intrusions, there have been $(51 + 28) \times 17 = 1343$ tank-years on test. For intrusions through transfer piping and from interfacing systems, only active tanks are at risk; thus, $28 \times 17 = 476$ tank years are observed. Years-on-test for intrusions into an II tank are calculated assuming 49 tanks are at risk, which is the average number at risk assuming tanks were II uniformly during the 17-yr period. Intrusions involving pits or boxes are measured using $21 \times 17 = 357$ yr on test.

Tank Pressurization and Filter Bypasses/Blowthroughs: Active tanks are considered at risk for these events; thus, 287 tank-years are used to calculate occurrence frequencies. Ventilation data is accumulated from five ventilation systems having one fan operating at all times. Accounting for the time when the tank farm came on line, there have been about 72 vent-years of operations.

Irradiation: Frequencies for all events in this category are described in occurrences per year, independent of the number of tanks on line.

Tank Mechanical Damage: All tanks are considered at risk, so it is estimated that $177 \times 17 = 3009$ tank-years have elapsed.

External Events, Spills, and Transfer Leaks: For surveillance operations, only active tanks are considered at risk; thus, this estimate is based on 476 tank-years. Other events are tabulated independently of the number of tanks on line at the time.

Violations: An average of one entry into a respirator area per day for 17 yr is assumed to accumulate 6205 entries. The same assumption applies to exiting. The number of entries were not determined for the remaining events in this category.

Loss of Electrical Power: Three losses have occurred for one (of two) sides of the area (for $17 \times 2 = 34$ yr at risk), one general outage has occurred (in 17 yr), and 16 local faults have occurred for 5 ventilation systems (based on 72 vent-years of operations). In 8 of the 16 fan faults, the backup generator did not start on demand. The ventilation fan was unavailable 29 times (for no more than 30 min each time), for a total of 14.5 h. Loss of electrical power event frequencies are calculated based on 72 vent-years and 8760 h/yr except for events involving portable fans, which have accumulated 5 yr (or 43,800 h) at risk.

Pipe Leaks: Posterior moments and quantiles are based upon the assumption that the pipe leak rate (λ) is lognormal with median $6E-7/h$ with an error factor of 10. Unreliability is calculated using the equation $1 - \exp(-T \times \lambda)$ for $T = 15$ yr (131,400 h). The moments are found using simulation.

2.0. SYSTEM UNAVAILABILITY ANALYSIS

2.1. General Description

In general, each Hanford Tank Farm contains independent active systems for tank ventilation, instrumentation, mixing, and waste transfers. The unavailability of systems such as these to perform their respective functions is typically determined from actual facility performance data or from analytical models quantified with generic component failure rates. For the Hanford Tank Farms, comprehensive performance data is not available. Although analytical models (e.g., fault trees) could be constructed for each system for each tank farm, this was not judged to be a cost-effective approach for the HTF PSA. Discussions with WHC indicate that system unavailability in the Hanford Tank Farms is dominated by extended maintenance outages rather than by random hardware failures or human errors that typically control unavailability in well-maintained systems. Therefore, a simple

approximation of system unavailability based on a qualitative WHC assessment of system conditions was employed to quantify system unavailability for the HTF PSA. Where active systems are shown by the PSA results to be important to risk, additional modeling or performance data analysis will be considered.

The system availability is approximated from the WHC short-term equipment condition report (see Table D-2) by use of the following scale. The distributions are assumed to be lognormal with a range factor of 5:

Condition Code	Unavailability			
	Mean	5%	50%	95%
1 or 2	1	1	1	1
3	0.1	0.012	0.062	0.31
4	0.01	0.001	0.006	0.031

A condition code of 1 requires that the equipment be nonfunctional, whereas a condition code of 2 suggests that the primary and/or backup systems have failed and that labor intensive alternatives are required. A condition code of 3 ranks the equipment as marginal but currently operable, and a condition code of 4 is for equipment that is in good working condition. A listing of the approximations for relevant system unavailabilities is found in Table D-3.

2.2. Ventilation System Unavailability Analysis Approach

An analytical model for the ventilation system was constructed because the PSA results showed this system to be important to risk. The fault-tree model was constructed based on a WHC study for the likelihood per year of hydrogen explosions in Tank 101-SY following a burp with no ventilation flow.⁵ The fault-tree model used in this analysis is found in Fig. D.1.

The ventilation-system fault tree was used with the PC version of the RISKMAN computer code to quantify the system unavailability frequency. The system analysis results are obtained by propagating point estimate values through the system equations, which are developed by determining the fault tree minimal cut sets. Results are displayed in "cause tables" that show the contributors in terms of major groups of cut sets and individual cut sets as needed to make appropriate use of the results. The numerical output of this analysis becomes the input for the event tree quantification and for the final uncertainty analysis.

TABLE D-2

TANK FARMS SHORT TERM EQUIPMENT C

		ELECTRICAL							INSTRUMENTATION										
TANK FARMS FACILITIES	SAFETY CLASS	PRIORITY OF FARM	ELECTRICAL PNL'S	GENERATORS	CATHODIC PROTECTION	GROUNDING	MASTER PUMP SHUT DN CKT	MCC'S	ALARMS	DATA ACC & MANAGEMENT	FLOW	GAS SAMPLING	TEMPERATURE	LEAK DETECTORS	LEVEL/ INTRUSION	PRESSURE/ VACUUM	RADIATION	SP GRAVITY/ WEIGHT FAC	CONV
A FARM	1	3 6	2 4	3 9	3 9	3 6	3 6	3 6	3 6	3 6	4 16	3 6	2 4	3 6	2 6	3 6	3 6	2 8	2 8
AN FARM	1	4 8	N/A	1 3	4 12	3 6	4 8	3 6	3 6	3 12	3 6	2 4	3 6	3 6	3 6	2 4	3 12	4 12	4 12
AP FARM	4	4 32	N/A	4 48	4 48	4 32	4 32	4 32	3 24	3 48	4 32	4 32	4 32	3 36	4 32	3 24	4 64	4 48	4 48
AW FARM	3	4 24	N/A	4 36	4 36	3 18	4 24	4 24	3 18	3 36	4 24	4 24	3 18	3 27	4 24	3 18	4 48	2 16	2 16
AX FARM	1	3 6	N/A	3 9	3 9	3 6	3 6	3 6	3 6	4 16	3 6	2 4	3 6	2 6	3 6	3 6	2 8	N/A	N/A
AY FARM	2	4 16	N/A	3 18	3 18	3 12	4 16	3 12	3 12	4 32	3 12	2 8	3 12	2 12	3 12	3 12	2 16	N/A	N/A
AZ FARM	2	4 16	N/A	3 18	3 18	3 12	4 16	3 12	3 12	4 32	3 12	2 8	3 12	2 12	3 12	3 12	2 16	3 16	3 16
B FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	3 6	4 16	3 6	2 4	3 6	3 9	3 6	3 6	3 12	1 3	1 3
BX FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	3 6	4 16	3 6	2 4	3 6	3 9	3 6	3 6	3 12	2 8	2 8
BY FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	3 6	4 16	3 6	2 4	3 6	3 9	3 6	3 6	3 12	N/A	N/A
C FARM	1	3 6	N/A	1 3	3 9	3 6	3 6	3 6	3 6	4 16	4 8	2 4	3 6	3 9	4 8	4 8	3 12	4 12	4 12
S FARM	1	3 6	N/A	1 3	3 9	3 6	3 6	3 6	3 6	3 12	N/A	3 6	3 6	3 9	3 6	3 6	1 4	2 6	2 6
SX FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	3 6	N/A	N/A	3 6	N/A	3 9	N/A	3 6	N/A	2 6	2 6
SY FARM	1	3 6	2 4	1 3	4 12	3 6	3 6	3 6	3 6	1 4	3 6	3 6	3 6	3 9	4 8	3 6	4 16	2 6	2 6
T FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	2 4	3 6	N/A	N/A	3 6	3 9	N/A	3 6	N/A	1 3	1 3
TX FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	N/A	N/A	N/A	3 6	N/A	3 9	N/A	3 6	N/A	1 3	1 3
TY FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	N/A	N/A	N/A	N/A	3 6	N/A	3 9	N/A	3 6	N/A	N/A	N/A
U FARM	1	3 6	N/A	1 3	4 12	3 6	3 6	3 6	3 6	N/A	N/A	3 6	N/A	3 9	N/A	3 6	N/A	3 9	3 9
CATCH TKS	3	N/A	N/A	1 9	4 36	N/A	N/A	3 18	N/A	3 36	N/A	3 18	3 18	3 27	3 18	N/A	3 36	N/A	N/A
DCRT'S	2	N/A	4 16	1 8	4 24	N/A	N/A	3 12	3 12	3 24	4 16	1 4	3 12	4 24	3 12	3 12	3 24	N/A	N/A
242-A EVAP	1	3 6	4 8	3 9	3 9	3 6	3 6	4 8	4 8	3 12	4 8	4 8	4 8	4 12	4 8	3 6	4 16	3 9	3 9
242-S & T EVAPS	4	3 24	N/A	1 12	3 36	1 8	3 24	3 24	N/A	3 48	4 32	4 32	N/A	N/A	3 24	3 24	1 16	4 48	4 48
VALVE PITS	3	N/A	N/A	4 36	4 36	3 18	N/A	N/A	N/A	N/A	N/A	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A
VAULTS	3	3 18	4 24	4 36	4 36	3 18	3 18	4 24	3 18	4 48	4 24	N/A	3 18	4 36	4 24	3 18	3 36	N/A	N/A
CROSS SITE XFR LINES	3	N/A	N/A	1 9	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A
200 EAST XFR LINES	3	N/A	N/A	3 27	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A
200 WEST XFR LINES	3	N/A	N/A	1 9	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A	3 18	N/A	N/A	N/A	N/A	N/A	N/A

CONDITION STRATEGY

MECHANICAL					MISCELLANEOUS		LEGEND	
LESSORS	PORTABLE EXHAUSTERS	HVAC	JUMPERS	PIPING	PUMPS/MOTORS	AS-BUILT DRAWINGS	LABELING	SAFETY DOCUMENTATION
2	2	4	2	3	4	3	2	
3 6	3 6	2 8	3 6	N/A	3 12	2 6	2 4	
B,D,E,G	B,D,J	A			B	C	B	
N/A	4 8	4 16	3 6	4 12	3 12	2 6	2 4	
G	G			J,K	B	C	B	
N/A	4 32	4 64	3 24	4 48	3 48	2 24	2 16	
G	G			J,K	B	C	B	
N/A	4 24	2 24	3 18	4 36	3 36	2 18	2 12	
G	A,H,J			B,J,K	B	C	B	
N/A	N/A	2 8	3 6	N/A	3 12	2 6	2 4	
		B			B	C	B	
N/A	3 12	3 24	3 12	3 18	3 24	2 12	2 8	
B,D,J	G			H,J,K	B	C	B	
N/A	3 12	3 24	3 12	4 24	3 24	2 12	2 8	
B,D,J	G			J,K	B	C	B	
N/A	N/A	2 8	3 6	N/A	3 12	2 6	2 4	
		A,B,J			B	C	B	
N/A	N/A	2 8	3 6	N/A	3 12	2 6	2 4	
		A,B,J			B	C	B	
N/A	N/A	2 8	3 6	N/A	3 12	2 6	2 4	
		A,B,J			B	C	B	
1 2	3 6	2 8	3 6	N/A	3 12	2 6	2 4	
B,E	B,D,J	A,B,J			B	C	B	
N/A	1 2	3 12	3 6	N/A	3 12	2 6	2 4	
H	A,G				B	C	B	
N/A	3 6	2 8	3 6	N/A	3 12	2 6	2 4	
	A,D	A,G			B	C	B	
3 6	3 6	3 12	3 6	3 9	3 12	2 6	2 4	
C,E,G	B,G,J	A,G		B,J,K	B	C	B	
N/A	N/A	1 4	3 6	N/A	3 12	2 6	2 4	
	A,G,H				B	C	B	
N/A	N/A	3 12	3 6	N/A	3 12	2 6	2 4	
	A,G				B	C	B	
N/A	N/A	1 4	3 6	N/A	3 12	2 6	2 4	
	A,G,H				B	C	B	
N/A	N/A	2 8	3 6	N/A	3 12	2 6	2 4	
	A,G				B	C	B	
N/A	3 18	1 12	3 18	3 27	3 36	2 18	2 12	
E,G	A,B			E,K	B	C	B	
N/A	3 12	3 24	3 12	3 18	3 24	2 12	2 8	
A,D	A,G,J			E,K	B	C	B	
N/A	3 6	2 8	3 6	4 12	3 12	2 6	2 4	
D,E	D			G	B	C	B	
N/A	4 32	4 64	3 24	4 48	3 48	2 24	2 16	
K	K			K	B	C	B	
N/A	N/A	N/A	3 18	N/A	3 36	2 18	2 12	
					B	C	B	
N/A	3 18	1 12	3 18	3 27	3 36	2 18	2 12	
A,D	H,J			A,K	B	C	B	
N/A	N/A	N/A	3 18	N/A	3 36	2 18	2 12	
					B	C	B	
N/A	N/A	N/A	3 18	N/A	3 36	2 18	2 12	
					B	C	B	
N/A	N/A	N/A	3 18	N/A	3 36	2 18	2 12	
					B	C	B	

BLOCK LEGEND

1-EQUIPMENT IS NON-FUNCTIONAL
2-PRIMARY AND/OR BACKUP SYSTEMS FAILED, LABOR INTENSIVE ALTERNATIVES REQUIRED
3-EQUIPMENT IS MARGINAL BUT CURRENTLY OPERABLE
4-EQUIPMENT IS IN GOOD WORKING CONDITION

PRIORITY PRODUCT

X x Y x Z = PRIORITY PRODUCT
X=SAFETY CLASS
Y=PRIORITY OF FARM
Z=EQUIPMENT CONDITION

LOWEST NUMBER-INDICATES THE HIGHEST PRIORITY OF WORK TO BE ADDRESSED
HIGHEST NUMBER-INDICATES THE LOWEST PRIORITY OF WORK TO BE ADDRESSED

CORRECTIVE ACTION GOALS

A-EQUIPMENT NEEDS TO BE REPLACED
B-EQUIPMENT NEEDS MAJOR UPGRADE
C-EQUIPMENT NEEDS GENERAL MAINTENANCE
D-EQUIPMENT OUTDATED
E-EQUIPMENT NEEDS TO BE STANDARDIZED
F-EQUIPMENT NEEDS MINOR REPAIR
G-EQUIPMENT FUNCTIONAL
H-EQUIPMENT NEEDS TO BE REMOVED
J-NEW EQUIPMENT NEEDS TO BE ADDED
K-IN STANDBY MODE-EQUIPMENT NOT OPERATING

PRIORITY OF FARMS

1-WATCH LIST TANKS
2-AGING WASTE TANKS
3-NON-WATCH LIST LEAKERS
4-ALL OTHERS

SAFETY CLASS

1-FAILURE COULD ADVERSELY AFFECT THE ENVIRONMENT OR HEALTH AND SAFETY OF THE PUBLIC
2-FAILURE COULD ADVERSELY AFFECT THE ENVIRONMENT OR HEALTH AND SAFETY OF ON-SITE WORKERS
3-ITEMS FAILURE COULD ADVERSELY AFFECT THE HEALTH AND SAFETY OF FACILITY WORKERS OR RESULT IN RELEASE OF RADIOACTIVE OR TOXIC MATERIAL TO THE ENVIRONMENT
4-ITEMS WHOSE FAILURE HAS NO SIGNIFICANT IMPORTANCE TO SAFETY, HEALTH OR ENVIRONMENTAL PROTECTION

BLOCK LEGEND

CURRENT EQUIPMENT CONDITION

- 1-EQUIPMENT IS NON-FUNCTIONAL
 2-PRIMARY AND/OR BACKUP SYSTEMS FAILED, LABOR INTENSIVE ALTERNATIVES REQUIRED
 3-EQUIPMENT IS MARGINAL BUT CURRENTLY OPERABLE
 4-EQUIPMENT IS IN GOOD WORKING CONDITION

PRIORITY PRODUCT

- X * Y * Z = PRIORITY PRODUCT
 X=SAFETY CLASS
 Y=PRIORITY OF FARM
 Z=EQUIPMENT CONDITION

LOWEST NUMBER-INDICATES THE HIGHEST PRIORITY OF WORK TO BE ADDRESSED
 HIGHEST NUMBER-INDICATES THE LOWEST PRIORITY OF WORK TO BE ADDRESSED

CORRECTIVE ACTION GOALS

- A-EQUIPMENT NEEDS TO BE REPLACED
 B-EQUIPMENT NEEDS MAJOR UPGRADE
 C-EQUIPMENT NEEDS GENERAL MAINTENANCE
 D-EQUIPMENT OUTDATED
 E-EQUIPMENT NEEDS TO BE STANDARDIZED
 F-EQUIPMENT NEEDS MINOR REPAIR
 G-EQUIPMENT FUNCTIONAL
 H-EQUIPMENT NEEDS TO BE REMOVED
 J-NEW EQUIPMENT NEEDS TO BE ADDED
 K-IN STANDBY MODE-EQUIPMENT NOT OPERATING

PRIORITY OF FARMS

- 1-WATCH LIST TANKS
 2-AGING WASTE TANKS
 3-NON-WATCH LIST LEAKERS
 4-ALL OTHERS

SAFETY CLASS

- 1-FAILURE COULD ADVERSELY AFFECT THE ENVIRONMENT OR HEALTH AND SAFETY OF THE PUBLIC
 2-FAILURE COULD ADVERSELY AFFECT THE ENVIRONMENT OR HEALTH AND SAFETY OF ON-SITE WORKERS
 3-ITEMS FAILURE COULD ADVERSELY AFFECT THE HEALTH AND SAFETY OF FACILITY WORKERS OR RESULT IN RELEASE OF RADIOACTIVE OR TOXIC MATERIAL TO THE ENVIRONMENT
 4-ITEMS WHOSE FAILURE HAS NO SIGNIFICANT IMPORTANCE TO SAFETY, HEALTH OR ENVIRONMENTAL PROTECTION

Fig. D.1.
Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
 Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
Fault tree for ventilation system failing to provide sufficient flow.

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 Fault tree for ventilation system failing to provide sufficient flow.

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Fault tree for ventilation system failing to provide sufficient flow.

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Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)

Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
 Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
Fault tree for ventilation system failing to provide sufficient flow.

Fig. D.1. (Cont.)
Fault tree for ventilation system failing to provide sufficient flow.

TABLE D-3
SYSTEM UNAVAILABILITY FOR RELEVANT SPLIT FRACTIONS

SPLIT FRACTION	BOUNDARY CONDITIONS FOR USE	UNAVAILABILITY
	<i>Ventilation continues to operate?</i>	
VOP1	Electric power available.	0.1
	<i>Continuous tank level indication?</i>	
LI1	Electric power is available and tank level is above limits.	0.1
	<i>continuous tank temperature indication?</i>	
TI1	Electric power is available, and an exothermic reaction or ventilation failure has occurred.	0.1
	<i>Continuous tank pressure indication?</i>	
PI1	Electric power is available, and an exothermic reaction or ventilation failure has occurred.	0.01
	<i>Tank leak detectors are operable?</i>	
LKD1	Leak detection failure with electric power available.	0.1
	<i>Area radiation monitors are operable?</i>	
ARM1	Arm failure with electric power available.	0.1

The results of this analysis showed the point estimate value to be 4.48E-3, with the major contributors displayed in Table D-4. A listing of the basic events and their respective point values are found in Table D-5.

3.0. INITIATING EVENT FREQUENCIES

This section explains how frequencies were derived for the initiating event groups identified in Sec. 4.3. Most of the initiating event group frequencies were calculated using data found in the HTF UOR, as described in Sec. D.1. In general, the frequencies of these initiating events are assumed to be constant over time and applicable to the Hanford waste storage tanks for present activities, future waste retrieval, and final stabilization. This assumption was not judged to be applicable to the PSB initiator (see Table 4-2). For PSB, a Bayesian-aging analysis was performed to estimate future leak rates from historical evidence.

The resulting probability distributions for the initiating event group frequencies are summarized in Tables D-6 and D-7.

TABLE D-4
CAUSE TABLE FOR VENTILATION SYSTEM UNAVAILABILITY (VENTSY)

No.	Cut Sets	Value	% Importance	% Cumulative	Alignment
1	TFB-5-1E	1.680E-03	37.5154	37.5154	NORMAL
2	TDC-1-1E	1.680E-03	37.5154	75.0309	NORMAL
3	SEASON * TVB-1-1P	3.145E-04	7.0230	82.0539	NORMAL
4	THA-2-14	1.680E-04	3.7515	85.8054	NORMAL
5	PWR2 * TGB-4-1F	1.350E-04	3.0146	88.8200	NORMAL
6	THOUSE2 * TOACAM1T	1.000E-04	2.2331	91.0531	NORMAL
7	TDFK1VTC	5.040E-05	1.1255	92.1786	NORMAL
8	TFAK1-4G * TVDSY-2S	5.010E-05	1.1188	93.2973	NORMAL
9	TFAK1-4G * TVDSY-1S	5.010E-05	1.1188	94.4161	NORMAL
10	TVD4501C	3.360E-05	.7503	95.1664	NORMAL
11	TVD450XD	3.020E-05	.6744	95.8408	NORMAL
12	SEASON * TSJ-1-13	2.856E-05	.6378	96.4786	NORMAL
13	SEASON * TDC-1-1P	2.856E-05	.6378	97.1163	NORMAL
14	SEASON * ST1	2.856E-05	.6378	97.7541	NORMAL
15	TFAK1-4G * TFAP-28G	2.505E-05	.5594	98.3135	NORMAL
16	TFAK1-4G * TFAP-28F	2.505E-05	.5594	98.9728	NORMAL
17	SEASON * ST2	8.160E-06	.1822	99.0551	NORMAL
18	SEASON * TVDUCV1C	5.712E-06	.1276	99.1826	NORMAL
19	TFAK1-4G * TOAP-28Q	5.010E-06	.1119	99.2945	NORMAL
20	TVD4501S	4.570E-06	.1021	99.3965	NORMAL
21	TCHCAM13* TVDSY-2S	1.920E-06	.0429	99.4394	NORMAL
22	TCHCAM12 * TVDSY-1S	1.920E-06	.0429	99.4823	NORMAL
23	SEASON * TOAT1-2Q * TOAUCV1U	1.700E-06	.0380	99.5203	NORMAL
24	TFC-3-1E	1.680E-06	.0375	99.5578	NORMAL
25	TFC-3-2L * THOUSE1 * TVDSY-2S	1.680E-06	.0375	99.5953	NORMAL
26	TFC-3-2L * THOUSE1 * TVDSY-1S	1.680E-06	.0375	99.6328	NORMAL
27	TFAK1-4G * TVDSY-2A	1.503E-06	.0336	99.6664	NORMAL
28	TFAK1-4G * TVDSY-1B	1.503E-06	.0336	99.6999	NORMAL
29	TCHCAM13 * TFAP-28F	9.600E-07	.214	99.7214	NORMAL
30	TCHCAM13 * TFAP-28G	9.600E-07	.214	99.7428	NORMAL

TABLE D-4 (CONT)

No.	Cut Sets	Value	% Importance	% Cumulative	Alignment
31	TFAP-28G * TFC-3-2L * THOUSE1	8.400E-07	.0188	99.7616	NORMAL
32	TFAP-28F * TFC-3-2L * THOUSE1	8.400E-07	.0188	99.7803	NORMAL
33	PWR3 * TVDSY-2S	7.200E-07	.0161	99.7964	NORMAL
34	PWR3 * TVDSY-1S	7.200E-07	.0161	99.8125	NORMAL
35	TRAORLYH * TVDSY-2S	6.720E-07	.0150	99.8275	NORMAL
36	TRAORLYH * TVDSY-1S	6.720E-07	.0150	99.8425	NORMAL
37	TRAKP11H * TVDSY-2S	6.720E-07	.0150	99.8575	NORMAL
38	TRAKP11H * TVDSY-1S	6.720E-07	.0150	99.8725	NORMAL
39	T1157K	6.400E-07	.0143	99.8868	NORMAL
40	PWR2 * TOATTRANQ	4.500E-07	.0100	99.8968	NORMAL
41	PWR3 * TFAP-28G	3.600E-07	.0080	99.9049	NORMAL
42	PWR3 * TFAP-28F	3.600E-07	.0080	99.9129	NORMAL
43	TFAP-28F * TRAORLYH	3.360E-07	.0075	99.9204	NORMAL
44	TFAP-28F * TRAKP11H	3.360E-07	.0075	99.9279	NORMAL
45	TVDSY-1C * TVDSY-2S	3.360E-07	.0075	99.9354	NORMAL
46	TVDSY-1C * TVDSY-1S	3.360E-07	.0075	99.9429	NORMAL
47	TFAP-28G * TRAORLYH	3.360E-07	.0075	99.9504	NORMAL
48	TFAP-28G * TRAKP11H	3.360E-07	.0075	99.9579	NORMAL
49	TCHCAM13 * TOAP-28Q	1.920E-07	.0043	99.9622	NORMAL
50	TFAP-28G * TVDSY-1C	1.680E-07	.0038	99.9660	NORMAL
51	TFAP-28F * TVDSY-1C	1.680E-07	.0038	99.9697	NORMAL
52	TFC-3-2L * THOUSE1 * TOAP-28Q	1.680E-07	.0038	99.9735	NORMAL
53	T1183A * TVDSY-2S	1.600E-07	.0036	99.9770	NORMAL
54	T1183A * TVDSY-1S	1.600E-07	.0036	99.9806	NORMAL
55	T1183A * TFAP-28G	8.000E-08	.0018	99.9824	NORMAL
56	T1183A * TFAP-28F	8.000E-08	.0018	99.9842	NORMAL
57	PWR3 * TOAP-28Q	7.200E-08	.0016	99.9858	NORMAL
58	TOAP-28Q * TRAORLYH	6.720E-08	.0015	99.9873	NORMAL
59	TOAP-28Q * TRAKP11H	6.720E-08	.0015	99.9888	NORMAL
60	TCHCAM13 * TVDSY-2A	5.760E-08	.0013	99.9901	NORMAL
61	TCHCAM12 * TVDSY-1B	5.760E-08	.0013	99.9914	NORMAL

TABLE D-4 (CONT)

No.	Cut Sets	Value	% Importance	% Cumulative	Alignment
62	TFC-3-2L * THOUSE1 * TVDSY-2A	5.040E-08	.0011	99.9925	NORMAL
63	TFC-3-2L * THOUSE1 * TVDSY-18	5.040E-08	.0011	99.9936	NORMAL
64	TOAP-28Q * TVDSY-1C	3.360E-08	.0008	99.9944	NORMAL
65	TFC-3-1L * TFC-3-2E	2.822E-08	.0006	99.9950	NORMAL
66	PWR3 * TVDSY-2A	2.160E-08	.0005	99.9955	NORMAL
67	PWR3 * TVDSY-1B	2.160E-08	.0005	99.9960	NORMAL
68	TRAORLYH * TVDSY-2A	2.016E-08	.0005	99.9964	NORMAL
69	TRAORLYH * TVDSY-1B	2.016E-08	.0005	99.9969	NORMAL
70	TRAKP11H * TVDSY-2A	2.016E-08	.0005	99.9973	NORMAL
71	TRAKP11H * TVDSY-1B	2.016E-08	.0005	99.9978	NORMAL
72	T1183A * TOAP-28Q	1.600E-08	.0004	99.9981	NORMAL
73	T1182A * TVDSY-1S	1.200E-08	.0003	99.9984	NORMAL
74	T1182A * TVDSY-2S	1.200E-08	.0003	99.9987	NORMAL
75	TVDSY-1C * TVDSY-2A	1.008E-08	.0002	99.9989	NORMAL
76	TVDSY-1B * TVDSY-1C	1.008E-08	.0002	99.9991	NORMAL
77	T1153B	9.600E-09	.0002	99.9993	NORMAL
78	T1157J	6.400E-09	.0001	99.9995	NORMAL
79	T1182A * TFAP-28G	6.000E-09	.0001	99.9996	NORMAL
80	T1182A * TFAP-28F	6.000E-09	.0001	99.9997	NORMAL
81	T118EA * TVDSY-2A	4.800E-09	.0001	99.9998	NORMAL
82	T1183A * TVDSY-1B	4.800E-09	.0001	100.0000	NORMAL
83	T1182A * TOAP-28Q	1.200E-09	.0000	100.0000	NORMAL
84	T1182A * TVDSY-2A	3.600E-10	.0000	100.0000	NORMAL
85	T1182A * TVDSY-1B	3.600E-10	.0000	100.0000	NORMAL
86	TATMOSPH * TVDSY-2S	6.400E-11	.0000	100.0000	NORMAL
87	TATMOSPH * TVDSY-1S	6.400E-11	.0000	100.0000	NORMAL
88	TATMOSPH * TFAP-28G	3.200E-11	.0000	100.0000	NORMAL
89	TATMOSPH * TFAP-28F	3.200E-11	.0000	100.0000	NORMAL
90	TATMOSPH * TOAP-28Q	6.400E-12	.0000	100.0000	NORMAL
91	TATMOSPH * TVDSY-2A	1.920E-12	.0000	100.0000	NORMAL
92	TATMOSPH * TVDSY-1B	1.920E-12	.0000	100.0000	NORMAL

TABLE D-5
BASIC EVENT REPORT FOR TOP EVENT VOP FAULT TREE

BASIC EVENT NAME	BASIC EVENT DESCRIPTION	FREQUENCY (POINT ESTIMATE)
PWR2	LOSS OF POWER TO SY TANK FARM	4.50E-04
PWR3	LOSS OF 120V POWER TO P-23 CAM CAUSES P-23 EXHAUST FAN TO BE SHUTDOWN	7.20E-05
SEASON	FRACTION OF YEAR WHEN HUMIDITY IS HIGH AND TEMPERATURE IS LOW	1.70E-01
ST1	STEAM LINE TO HEATER RUPTURES	1.68E-04
ST2	LOSS OF STEAM FROM POWER PLANT FACILITY	4.80E-05
T1153B	ELECTROSTATIC SPARKS CAUSED BY LIGHTNING STRIKE: FAILS VENTILATION AND IGNITES	9.60E-09
T1157J	BURNING GAS SPILLS INTO TANK: FAILS VENTILATION AND IGNITES, LEAKING H ₂	6.40E-09
T1157K	RANGE FIRE PRODUCES SPARKS THAT FAIL VENTILATION AND IGNITES, LEAKING H ₂	6.40E-07
T1182A	FAILURE OF PRESSURE SWITCH K1-PS-1-1 FAILS VENTILATION AND CREATES SPARKS	1.20E-06
T1183A	MECHANICAL SPARKS FROM CATASTROPHIC FAILURE OF K1-4-1 (P-23) FAN	1.60E-05
TATMOSPH	ATMOSPHERIC CONDITIONS THAT PRODUCE NEGATIVE PRESSURE (<-6 IN. W.G.)	6.40E-09
TCHCAM13	CAM CAM1 SPURIOUSLY ALARMS	1.92E-04
TDC-1-1E	DEENTRAINER K1-1-1 PLUGS	1.68E-03
TDC-1-1P	DEENTRAINER K1-1-1 FAILS AND ALLOWS EXCESSIVE WATER THROUGH	1.68E-04
TDFK1VTC	MANUAL DAMPER IN THE K1 VENTILATION SYSTEM BETWEEN HEPAS: FAILS TO REMAIN OPEN	5.04E-05
TFAK1-4G	K1-4-1 FAILS TO CONTINUE RUNNING (NONCATASTROPHIC)	5.01E-03
TFAP-28F	BACKUP EXHAUST FAN P-28 FAILS TO START	5.00E-03
TFAP-28G	P-28 FAILS TO CONTINUE RUNNING	5.00E-03
TFB-5-1E	NBS PREFILTER K1-5-1 PLUGS DUE TO PARTICULATES	1.68E-03
TFC-3-1E	HEPA FILTER K1-3-1 PLUGS DUE TO PARTICULATES	1.68E-06
TFC-3-1L	HEPA FILTER K1-3-1 LEAKS; RUPTURES OR FAILS DUE TO SEAL FAILURE	1.68E-02
TFC-3-2E	HEPA FILTER K1-3-2 PLUGS DUE TO PARTICULATES	1.68E-06
TFC-3-2L	HEPA FILTER K1-3-2 FAILS TO FILTER DUE TO LEAKS, RUPTURES, OR SEAL FAILURES	1.68E-02
TGB-4-1F	DIESEL GENERATOR FOR EXHAUST FANS P-23 AND P-28 FAILS TO START	3.00E-01

TABLE D-5 (CONT)

BASIC EVENT NAME	BASIC EVENT DESCRIPTION	FREQUENCY (POINT ESTIMATE)
THA-2-14	STEAM HEATER K1-2-1 LEAKS FROM THE TUBES	1.68E-04
THOUSE1	ENOUGH RADIOACTIVE MATERIAL RELEASED TO GIVE HIGH RADIATION SIGNAL	1.00E-02
THOUSE2	ENOUGH RADIOACTIVE MATERIAL RELEASED TO REGISTER HIGH ON MISCALIBRATION CAM	1.00E-01
TOACAM1T	HUMAN OPERATOR MISCALIBRATES CAM SETPOINT	1.00E-03
TOAP-28Q	HUMAN OPERATOR FAILS TO START BACKUP FAN P-28	1.00E-03
TOAT1-2Q	HUMAN OPERATOR FAILS TO PERFORM KNOWN TASK, NOTICE LOW TI-1-2 READING	1.00E-03
TOATRANQ	HUMAN OP FAILS TO PERFORM KNOWN TASK TO ACTIVATE BACKUP POWER SOURCE	1.00E-03
TOAUCV1U	OPERATOR FAILS TO RESET TO CLOSED POSITION FOLLOWING TEST OR MAINTENANCE OF UPSTREAM MANUAL	1.00E-02
TRAKP11H	RELAY KP-1-1 SPURIOUSLY CHANGES STATES SO FAN OPERATION CIRCUIT BREAKS	6.72E-05
TRAORLYH	OVERLOAD RELAY ORLY SPURIOUSLY CHANGES STATE SO FAN OPERATION CIRCUIT BREAKS	6.72E-05
TSJ-1-13	TEMPERATURE CONTROL SWITCH TC-1-1 FAILS SPURIOUSLY SO THAT IT CLOSSES	1.68E-04
TVB-1-1P	TEMP FLOW CONTROL (SELF- REGULATING) VALVE TCV-1-1 FAILS TO OPERATE	1.85E-03
TVD4501C	HAND OPERATED (MANUAL) VALVE 4501 FROM TANK 101-SY, FAILS TO REMAIN OPEN	3.36E-05
TVD4501S	MANUAL VALVE 4501 FROM TANK 101-SY ERRONEOUSLY LEFT CLOSED	4.57E-06
TVD450XD	HAND-OPERATED (MANUAL) VALVES 4501, 4503, AND 4502 FROM TANK 101-SY FAIL TO REMAN CLOSED	3.02E-05
TVDSY-1B	HAND OPERATED (MANUAL) VALVE MV-K1-SY-1 TO P-23 FAN N.O. FTCD	3.00E-04
TVDSY-1C	HAND OPERATED (MANUAL) VALVE MV-K1-SY-1 TO P-23 FAN FAILS TO REMAIN OPEN	3.36E-05
TVDSY-1S	HAND OPERATED (MANUAL) VALVE MV-K1-SY-1 TO P-23 FAN ERRO-NEOUSLY CLOSED	1.00E-02
TVDSY-2A	HAND OPERATED (MANUAL) VALVE MV-K1-SY-2 TO FAN P-28 FAILS TO OPERATE ON DEMAND	3.00E-04
TVDSY-2S	HAND OPERATED (MANUAL) VALVE MV-K1-SY-2 TO P-28 FAN ERRO-NEOUSLY CLOSED	1.00E-02
TVDUCV1C	HAND OPERATED (MANUAL) VALVE UPSTREAM OF TCV-1-1, FAILS TO REMAIN OPEN	3.36E-05

TABLE D-6
UOR EVENTS FOR CORRESPONDING INITIATING EVENTS

Initiating Event	Unusual Occurrence Report Event	Mean
RVB1	Duct Condensate Leakage	2.10E-02
	Failure to Restore	2.10E-02
	Loop Seal Pot Loss	6.90E-03
	Riser Leaks	8.70E-03
	Tank Riser Damage by a Vehicle	1.50E-03
FB1	Filter Blowthrough	7.60E-02
	Filter Frame Damage	2.10E-02
LOTV	Accidental Loop Seal Filling	2.20E-02
	Loss of Ventilation	4.10E-01
	Inadequate Ventilation Fan	8.70E-03
	Filter Plugging	9.00E-02
	Deentrainer Plugging	3.50E-02
LOSP	Total Area Outage	8.80E-02
	One-Side Outage	1.00E-01
	Individual Systems Outage	2.30E-01
WI3	Surface Water Intrusion	6.30E-03
	Raw Water Leak Intrusions	3.40E-03
	Intrusions from Interfacing Systems	9.50E-03

TABLE D-7
PROBABILITY DISTRIBUTIONS FOR INITIATING EVENT GROUP FREQUENCIES

Initiating Event	Description	Mean Frequency	5%	Median	95%
PSB	Primary Tank Shell Breach ^a	3.37E-03			
DB	Tank Dome Breach ^b	5.00E-04			
RVB1	Tank Riser or Ventilation Piping Breach	5.90E-02	2.36E-02	5.38E-02	1.08E-01
FB1	Tank Exhaust HEPA Filter Failure	9.75E-02	4.47E-02	9.20E-02	1.64E-01
BURP	Bound Flammable/Toxic Gas Release Event ^c	3.51E+00	2.64E+00	3.44E+00	4.74E+00
LOTV	Loss of Active Tank Ventilation	5.66E-01	4.32E-01	5.62E-01	7.16E-01
LOSP	Loss of Electric Power Supply to Tank Farm	4.18E-01	2.65E-01	4.06E-01	6.14E-01
WI3	Water Intrusion Event	1.93E-02	1.17E-02	1.86E-02	2.82E-02
WT	Waste Transfer Event	N/A			

^aAging analysis conducted.

^bFault-tree analysis conducted.

^cData used since March 1989.

N/A - not applicable to Tank 101-SY.

3.1. Leaks in SS Tanks

All early tanks were SS tanks. These were built in groups at different times since 1944, the latest being built around 1964. Almost every group of these SS tanks has developed leaks of various sizes, from a few hundred gallons to hundreds of thousands of gallons. Once a leak is detected in any tank, efforts are made to minimize the continuing leak over the future years by removing the drainable liquid out of the tank. The time of detection of these leaks is not very precise because of the sparsity of leak detectors around the tanks. If a leak occurs in the close proximity of a functioning detector, it will be detected early. If a large leak causes the level of supernatant liquid to decrease, it will be detected early, whereas small leaks may exist for long periods before they are detected.

When a leaking tank was discovered, all transfers to that tank were stopped as a first step toward stabilizing the tank. Since 1980, there have been no transfers to any of the SS tanks. To stabilize the tank, all the supernatant liquid is transferred out of the tank in a process that can take up to 3 yr to accomplish because the contents of the tank continue to separate into sludge and supernatant liquid. A stage is reached, labeled "Interim Stabilized," when the supernatant liquid is reduced to about 5000 gal. When this process of supernatant liquid reduction is complete, efforts are made to remove the interstitial liquid by boring into the sludge and pumping out the liquid that seeps into the bored space. This again is a long-term process. An interim-stabilized tank can contain up to 50,000 gal. of interstitial liquid. However, when an interim-stabilized tank develops a leak, the maximum possible instant leak is limited to 5000 gal., and then the tank will continue to leak at a low rate as the interstitial liquid continues to seep out.

The December 1991 Tank Farm Surveillance Report⁴ gives the data on the year these tanks were built, the year they began to leak, and the year they were interim stabilized. The data is reproduced in Table D-8. In cases where the year that a tank was interim stabilized could not be determined from the above report, it was assumed the stabilization occurred 3 yr after the tank was removed from service.

If the average failure rate over 45 tank-yr is compared to the average failure rate of tanks grouped in different ways, there are small variations in the leak-failure values. Failure rates for tanks as a function of age are shown in Table D-9. This table seems to indicate that the newer tanks have a slightly higher failure rate. The tanks were also evaluated by grouping according to series (100 series and 200 series tanks). From this comparison, it was found that the average failure rates are very close (Table D-10). The only real variation is that the 200 series tanks failed much

**TABLE D-8
HANFORD TANK FARM SINGLE-SHELL DATA**

No.	Tank I.D.	Supernatant Liquid kgal.	Interim Stabilized	Start Date (yr)	Year		Leak Data (yr)	Date Stabilized	Amount Leaked (gal.)	Leak Size
					Removed from Service					
1	A-101	0	IS	55	80			*		
2	A-102	4	IS	55	80			89		
3	A-103	4	IS	55	80	87			5500	L
4	A-104	0	IS	55	75	75			2500	S
5	A-105	0	IS	55	83	63			277,000	L
6	A-106	0	IS	55	80			82	*	
7	AX-101	0	IS	64	80					
8	AX-102	3	IS	64	80	88			3000	S
9	AX-103	0	IS	64	80			87		
10	AX-104	0	IS	64	78	77			8000	L
11	B-101	0	IS	44	74	74			8000	L
12	B-102	4	IS	44	78			85		
13	B-103	0	IS	44	77	78			8000	L
14	B-104	1	IS	44	72			85		
15	B-105	0	IS	44	72	78			8000	L
16	B-106	1	IS	44	77			85		
17	B-107	1	IS	44	69	80			8000	L
18	B-108	0	IS	44	77			85		
19	B-109	0	IS	44	77			85		
20	B-110	1	IS	44	71	81			10,000	L
21	B-111	1	IS	44	76	78			8000	L
22	B-112	3	IS	44	77	78			2000	S
23	B-201	1	IS	44	71	80			1200	S
24	B-202	0	IS	44	77			85		
25	B-203	1	IS	44	77	83			300	S

Source: Ref. 4.

IS: Interim Stabilized

—: Not Interim Stabilized

*: Not Available

S: Small Leak

L: Large Leak

TABLE D-8 (CONT)

No.	Tank I.D.	Supernatant Liquid kgal.	Interim Stabilized	Start Date (yr)	Year Removed from Service	Leak Data (yr)	Date Stabilized	Amount Leaked (gal.)	Leak Size
26	B-204	1	IS	44	77	84		400	S
27	BX-101	1	IS	47	72	72		8000	L
28	BX-102	0	IS	47	71	71		70,000	L
29	BX-103	4	IS	47	77		83		
30	BX-104	3	IS	47	80		89		
31	BX-105	5	IS	47	80		86		
32	BX-106	15	-	47	71		*		
33	BX-107	1	IS	47	77		90		
34	BX-108	0	IS	47	74	74		2500	S
35	BX-109	0	IS	47	74		90		
36	BX-110	1	IS	47	77	76		8000	L
37	BX-111	19	-	47	77	84		8000	L
38	BX-112	1	IS	47	77		90		
39	BY-101	0	IS	49	71		84		
40	BY-102	0	-	49	77		91		
41	BY-103	0	-	49	73	73		5000	S
42	BY-104	0	IS	49	77		85		
43	BY-105	0	-	49	74	84		8000	L
44	BY-106	0	-	49	77	84		8000	L
45	BY-107	0	IS	49	74	84		15,100	L
46	BY-108	0	IS	49	72	72		5000	S
47	BY-109	0	-	49	79		91		
48	BY-110	0	IS	49	79		85		
49	BY-111	0	IS	49	77		85		
50	BY-112	0	IS	49	76		85		
51	C-101	0	IS	44	70	80		20,000	L
52	C-102	3	-	44	76		82		
53	C-103	133	-	44	79		*		
54	C-104	0	IS	44	80		89		
55	C-105	0	-	44	79		85		
56	C-106	32	-	44	79		*		

TABLE D-8 (CONT)

No.	Tank I.D.	Supernatant Liquid kgal.	Interim Stabilized	Start Date (yr)	Year Removed from Service	Leak Data (yr)	Date Stabilized	Amount Leaked (gal.)	Leak Size
57	C-107	0	—	44	78		78		
58	C-108	0	IS	44	76		84		
59	C-109	4	IS	44	76		83		
60	C-110	5	—	44	76	84		2000	S
61	C-111	0	IS	44	76	68		5500	L
62	C-112	0	IS	44	76		90		
63	C-201	0	IS	44	77	87		550	S
64	C-202	0	IS	44	77	87		450	S
65	C-203	0	IS	44	77	84		400	S
66	C-204	0	IS	44	77	87		350	S
67	S-101	12	—	51	80		80		
68	S-102	0	—	51	80		*		
69	S-103	7	—	51	80		80		
70	S-104	1	IS	51	68	68		24,000	I
71	S-105	0	IS	51	74		88		
72	S-106	0	—	51	79		82		
73	S-107	6	—	51	80		80		
74	S-108	0	—	51	79		82		
75	S-109	0	—	51	79		75		
76	S-110	0	—	51	79		79		
77	S-111	10	—	51	75		*		
78	S-112	0	—	51	74		*		
79	SX-101	1	—	54	80		*		
80	SX-102	0	—	54	80		*		
81	SX-103	1	—	54	80		*		
82	SX-104	0	—	54	80	88		6000	L
83	SX-105	0	—	54	80		*		
84	SX-106	61	—	54	80		*		
85	SX-107	0	IS	54	64	64		5000	S
86	SX-108	0	IS	54	62	62		2400	S
87	SX-109	0	IS	54	65	65		5000	S

TABLE D-8 (CONT)

No.	Tank I.D.	Supernatant Liquid kgal.	Interim Stabilized	Start Date (yr)	Year		Leak Data (yr)	Date Stabilized	Amount Leaked (gal.)	Leak Size
					Removed from Service					
88	SX-110	0	IS	54	76		76		5500	L
89	SX-111	0	IS	54	64		74		2000	S
90	SX-112	0	IS	54	69		69		30,000	L
91	SX-113	0	IS	54	58		62		15,000	L
92	SX-114	0	IS	54	72		72		8000	L
93	SX-115	0	IS	54	65		65		50,000	L
94	T-101	30	-	44	78			*		
95	T-102	13	IS	44	78			84		
96	T-103	4	IS	44	74		74		1000	S
97	T-104	3	-	44	74			82		
98	T-105	0	IS	44	78			87		
99	T-106	2	IS	44	73		73		115,000	L
100	T-107	9	-	44	78		84		8000	L
101	T-108	0	-	44	74		74		1000	S
102	T-109	0	IS	44	74		74		1000	S
103	T-110	3	-	44	78			*		
104	T-111	2	-	44	74		80		1000	S
105	T-112	7	IS	44	77			82		
106	T-201	1	IS	44	76			78		
107	T-202	0	IS	44	76			81		
108	T-203	0	IS	44	76			78		
109	T-204	0	IS	44	76			81		
110	TX-101	3	IS	48	80			84		
111	TX-102	0	IS	48	77			84		
112	TX-103	0	IS	48	80			80		
113	TX-104	1	IS	48	77			84		
114	TX-105	0	IS	48	77		77		8000	L
115	TX-106	0	IS	48	77			77		
116	TX-107	1	IS	48	77		84		2500	S
117	TX-108	0	IS	48	77			83		
118	TX-109	0	IS	48	77			83		

TABLE D-8 (CONT)

No.	Tank I.D.	Supernatant Liquid kgal.	Interim Stabilized	Start Date (yr)	Year Removed from Service	Leak Data (yr)	Date Stabilized	Amount Leaked (gal.)	Leak Size
119	TX-110	0	IS	48	77	77		8000	L
120	TX-111	0	IS	48	77		77		
121	TX-112	0	IS	48	74		83		
122	TX-113	0	IS	48	71	74		8000	L
123	TX-114	0	IS	48	71	74		8000	L
124	TX-115	0	IS	48	77	77		8000	L
125	TX-116	0	IS	48	69	77		8000	L
126	TX-117	0	IS	48	69	77		8000	L
127	TX-118	0	IS	48	80		71		
128	TY-101	0	IS	52	73	73		1000	S
129	TY-102	0	IS	52	79		82		
130	TY-103	0	IS	52	73	73		3000	S
131	TY-104	3	IS	52	74	81		1400	S
132	TY-105	0	IS	52	60	60		35,000	L
133	TY-106	0	IS	52	59	59		20,000	L
134	U-101	3	IS	44	60	69		30,000	L
135	U-102	18	—	44	79		82		
136	U-103	13	—	44	78		*		
137	U-104	0	IS	44	51	61		55,000	L
138	U-105	37	—	44	78		*		
139	U-106	15	—	44	77		*		
140	U-107	31	—	44	80		*		
141	U-108	24	—	44	79		*		
142	U-109	19	—	44	78		*		
143	U-110	0	IS	44	75	75		8100	L
144	U-111	0	—	44	80		82		
145	U-112	4	IS	44	70	80		8500	L
146	U-201	1	IS	44	77		79		
147	U-202	1	IS	44	77		79		
148	U-203	1	IS	44	77		79		
149	U-204	1	IS	44	77		79		

TABLE D-9
SINGLE-SHELL TANKS GROUPED BY CONSTRUCTION TIME—FAILURE RATE

Tank Group	Number of Tanks Failed Due To Leaks	Exposure Time (Tank-Years)	Average Failure Rate (Events per Tank-Year)
Tanks constructed in 1944	27	2656	1.02E-02
Tanks constructed from 1947–1949	18	1559	1.15E-02
Tanks constructed from 1951–1952 and 1954–1955	19	1092	1.74E-02
Tanks constructed in 1964	2	91	2.20E-02
All Tanks	66	5398	1.22E-02

TABLE D-10
SINGLE-SHELL TANKS GROUPED BY TANK TYPE—FAILURE RATES

Tank Groups	Number of Tank Leaks	Exposure Time (Tank-Years)	Average Failure Rate (Events per Tank-Year)
100 Series	59	4700	1.2E-02
200 Series	7	698	1.00E-02
All Tanks	66	5398	1.22E-02

later in their life than the 100 series tanks, and the failure rate changed much more rapidly with time. These trends can be seen in Figs. D.2 through D.4.

Finally, the leak data was also examined as a function of the leak size: < 5000 gal. (small leaks) and > 5000 gal. (large leaks). The failure rate of one of these groups is about twice that of the other (Table D-11). Introducing the earlier variable of the tank type on this group, we see that the 200 series tanks also displayed a higher failure rate. This is also presented in Table D-11.

After examining the leak data closely, it was decided to model the failure as an aging process, with tank type and leak size being two distinct variables. To identify any single cause or some fixed causes that lead the tanks to develop leaks is difficult. The cause may be aging of the steel liner, accelerated by the contents of the tank, or inleakage of water from the ground through the concrete. The cause could

Fig. D.2.
Single-shell tanks—leaks.

Fig. D.3.
100 series single-shell tanks—leaks.

Fig. D.4.
200 series single-shell tanks—small leaks.

TABLE D-11
SINGLE-SHELL TANKS GROUPED BY LEAK SIZE—FAILURE RATES

Tanks Groups	Number of Tank Leaks	Tank Years	Average Failure Rate (Events per Tank-Year)
All Tanks, Large Leaks	40	4673	8.56E-03
All Tanks, Small Leaks	26	5325	4.88E-03
100 Series Tanks, Large Leaks	40	4107	9.74E-03
100 Series Tanks, Small Leaks	19	4627	4.12E-03
200 Series Tanks, Small Leaks	7	698	1.00E-02

also be cyclic thermal stresses caused by periodic addition of hot wastes that cause the steel liners to buckle and crack. The actual cause is most likely is a combination of the above and other factors. However the data is parsed, it is obvious that the failure rate has been increasing over the years. This increasing failure trend is illustrated by Figs. D.2 through D.4.

3.1.1. Methodology. The methodology used for the aging analysis was developed for the Electric Power Research Institute (EPRI) as the computer code DORIAN.⁶

In general, we seek to calculate the functional dependence of the tank leak frequency (ϕ) on t , where t represents the equipment age in either calendar years or operating years. From this point of view, the PSA specifies a mathematical function or algorithm, F , that relates the numerical value of the output variable ϕ to a series of elemental input variables, λ_j , representing tank failure mechanisms. This relationship is expressed as

$$\phi = F(\lambda_1, \lambda_2, \dots) ,$$

or simply

$$\phi = F(\lambda_j) .$$

The function F is referred to as the "risk model."

If age, t , is considered as an independent variable, it can affect ϕ only through its effect on either the parameters λ_j or the form of the function F itself. The effect of aging on risk can therefore be determined by computing the functions $\lambda_j(t)$ and F .

Computing $\lambda_j(t)$ and F requires the analyst to consider the following questions:

1. What is the effect of t on the nontime-dependent parameters λ_k that are already in the model?
2. What failure modes should be added to the model for ϕ to incorporate aging phenomena such as corrosion, fatigue, embrittlement, etc.?
3. What new parameters, λ_ζ , should be included in the function F to represent the frequency of release from these failure modes?
4. What is the time dependence of these new parameters?
5. What is the net effect on ϕ from these parameters?

Question 5 can be answered readily once the new $\lambda_j(t)$ parameters have been determined and inserted into the function F to obtain $\phi(t)$. Questions 2 and 3 require a thorough understanding of operations of the plant or system under consideration, as well as engineering judgment. Questions 1 through 4 are not routine; more effort is required to answer them. The approach used to answer questions 1 and 4 is as follows:

- **Data Analysis Approach.** Knowledge about the numerical values of the λ_j parameters is expressed in the form of probability curves. These curves are derived by Bayes' theorem, using generic industry data and engineering knowledge to establish prior distributions and updating these with the experience of the specific component at hand to derive a probability distribution for a failure rate that is assumed to be constant over time. However, given the whole history of a piece of equipment, the question, "Is there any evidence of equipment aging?" can be asked. If there is evidence of aging, this effect could be quantified by assessing the functions $\lambda_j(t)$. Because these functions cannot be assessed exactly, this question is asked in a probabilistic form, "What conclusions can be drawn about the functions $\lambda_j(t)$ based on the evidence that is available and with what degree of confidence?" Bayes' theorem is used to answer this question by postulating a function space [i.e., a family of possible functional forms for $\lambda_j(t)$] and

then by assessing a probability distribution over the various elements of this function space.

- **Bayesian Analysis of Time-Dependent Failure Rates.** Bayes' theorem is usually applied to continuous Poisson models having a constant failure rate parameter λ . In this study, component failure rates may be time dependent. This leads naturally to a consideration of time-dependent Poisson models. Such models are very powerful and can represent a wide variety of phenomena such as aging, wear-in, infant mortality, etc.

The basic equation describing the time-dependent Poisson model is

$$\frac{dP_0(t)}{dt} = -\lambda(t)P_0(t) , \quad (D.1)$$

where $P_0(t)$ is the probability that the component in question is still operable at time t , and $\lambda(t)dt$ is the conditional probability of failure during the infinitesimal interval $(t, t+dt)$, given that the component has not failed before time t .

From this equation, we obtain the probability of being operable at time t , $P_0(t)$, as

$$P_0(t) = e^{-\int_0^t \lambda(\tau) d\tau} . \quad (D.2)$$

The function $\lambda(t)$ is a measure of the reliability of our component over time. The following paragraphs discuss how this function is estimated from available evidence. Suppose, for example, that the item of equipment in question has been operated for T years, that k_t failures have been observed in year t for $t = 1, 2, 3, \dots, T$, and that the exposure time during year t is equal to e_t . The plant-specific evidence is therefore given by

$$E_1 = \{ \langle k_1, e_1 \rangle; \langle k_2, e_2 \rangle; \dots, \langle k_T, e_T \rangle \} , \quad (D.3)$$

and the prior evidence is

$$E_2 = \{ \text{everything else known about this kind of equipment} \} .$$

The variable $\lambda(t)$ is embedded in a function space where each element is defined by a combination of an initial failure rate, $\lambda(0)$, and a series of multipliers describing how the failure rate changes as a function of time, $A(t)$. Thus, the (i, j) th element of the function space at time t , given by $\lambda_{i,j}(t)$, will be equal to the product $\lambda_i(0)A_j(t)$. Furthermore, for convenience, assume that each aging model $A_j(t)$ is piecewise constant, taking on different values only every n years. Note that n can be set equal to 1 if the analyst wishes to specify aging multipliers for each year. Alternatively, larger values of n can be used to reduce the amount of effort involved in specifying the aging models.

The state of knowledge can be expressed as a probability distribution over this function space. In other words, the function $p(i, j | E_1, E_2)$, which is the probability that the true value of the function $\lambda(t)$ is equal to the product $\lambda_i(0)A_j(t)$, given the evidence E_1 and E_2 , is expressed by Bayes' theorem as

$$p(i, j | E_1 E_2) = \frac{p(i, j | E_2) p(E_1 | i, j, E_2)}{\sum_{i, j} p(i, j | E_2) p(E_1 | i, j, E_2)} \quad (D.5)$$

The prior distribution $p(i, j | E_2)$, which encodes all knowledge about the function $\lambda(t)$ excluding the evidence E_1 , can be specified by a consensus of expert opinion, based on a review of general engineering knowledge about aging phenomena. Assuming that the initial failure rates and the aging models are independent, the prior distribution will consist of a set of initial failure rates $\lambda_i(0)$, with their associated probabilities, p_i , and a set of piecewise constant aging models $A_j(t)$, with their associated probabilities q_j . Thus, the quantity $p(i, j | E_2)$ will be equal to $p_i q_j$.

The likelihood function, $p(E_1 | i, j, E_2)$, is the likelihood of observing the evidence E_1 if the time function $\lambda(t)$ is equal to the (i, j) th function in the function space. This is

$$p(E_1 | i, j, E_2) = \prod_{m=1}^M \frac{[\lambda_i(0)A_j(t)T_m]^{K_m} e^{-\lambda_i(0)A_j(t)T_m}}{K_m!} \quad (D.6)$$

where

$$K_m = \sum_{t=(m-1)n+1}^{m \times n} k_t = \text{the total number of events observed during the } m\text{th time step,}$$

$$T_m = \sum_{t=(m-1)n+1}^{m \times n} e_t = \text{the total observation or exposure time accrued during the } m\text{th time step, and}$$

M = the number of piecewise constant steps in the aging models.

Note that the product nM must be equal to T , which is the number of years for which data are available.

In the simplest case, where $n = 1$, for which the aging model is piecewise constant by year (rather than for multiple years) and $e_t = 1$ for all t (one year of observation time per calendar year), this reduces to

$$p(E_1|i, j, E_2) = \prod_{t=1}^T \frac{[\lambda_i(0)A_j(t)]^{k_t} e^{-\lambda_i(0)A_j(t)}}{k_t!} . \quad (D.7)$$

The best estimate for the failure rate of this equipment as a function of time is given by the expected value of the function $\lambda_i(0)A_j(t)$ over all possible combinations of i and j , taking into account their posterior probabilities $p(i, j | E_1, E_2)$. In other words, the expected mean failure rate is

$$\bar{\lambda}(t) = \sum_{i,j} \lambda_i(0)A_j(t)p(i, j | E_1, E_2) . \quad (D.8)$$

Uncertainty bands around this best estimate can be drawn from Eq. (D.5). Such uncertainties are displayed in graphical form as seen in Figs. D.5 through Fig. D.9, which show a family of curves for $\lambda(t)$ in continuous, rather than piecewise, constant form. By "cutting" this family of curves at any time t , we can then obtain a probability curve, $p(\lambda)$, for the actual failure rate at that time.

Equations (D.5) and (D.6) give the theoretical basis necessary for extending the Bayesian methodology to the case of time-dependent failure rates.

Fig. D.5.
100 series single-shell tanks—small leaks.

Fig. D.6.
100 series single-shell tanks—large leaks.

Fig. D.7.
200 series single-shell tanks—small leaks.

Fig. D.8.
Double-shell tanks, inner shell—small leaks.

Fig. D.9.
Double-shell tanks, inner shell—large leaks.

3.1.2. Tank Leak Model. For purposes of examining leak frequency, the SS tanks were treated as two distinct populations: 100 series and 200 series tanks. Other partitions are possible; e.g., based on the year the tanks were built or their conditions of service. However, the conditions the tanks were subject to during their lives is unknown and not traceable. Likewise, other breakdowns result in small population groups for which statistical inference becomes difficult.

Two failure modes are considered: small leaks (< 5000 gal.) and large leaks (> 5000 gal.). Once a tank has leaked, it is removed from the analysis tank population. No information about any additional leaks is obtained after the discovery of the initial leak. Therefore, for the small leak model, if a given tank develops a large leak in the n th year of its life, its contribution to the small leak data is 0 events in n years. The small leak model contains all single tanks in the population (133 for the 100 series and 16 for the 200 series tanks), whether or not they are interim stabilized. The stabilized tanks can contain up to 50,000 gal. of interstitial liquid, which can still seep out if there are any breaches in the tank.

For the large leak model, again, all tanks are initially in the model. Once a tank has developed a large leak or is stabilized, it is removed from the analysis population.

Looking at Table D-8, it is seen that all the 200 series tanks have less than 5000 gal. of supernatant liquid. These tanks, therefore, are only capable of small leaks in the future, and only the small leak model was developed.

The question of selecting suitable prior distributions for an analysis of tank aging requires an understanding of the different factors that affect the failure rate of the tanks. Passive components such as tanks are put in place at the beginning of their life and age (deteriorate) as a group. There is no piece-part replacement and there are no factors that tend to improve performance with age. Periodic inspections are the only current maintenance activities to monitor such degradation.

The process through which aging leads to failure can be thought of as a course of events composed of an initiating mechanism, along with modifying factors that act together to lead to failure. This viewpoint suggests that a certain degree of understanding of aging phenomena can be obtained if the initiating mechanism and the modifying factors can be identified. These identifications facilitate the expression of prior distributions for the aging process.

Some of the initiator mechanisms relevant to the tanks are identified as:

- corrosion,
- fatigue from thermal cycling,
- embrittlement of the liner,
- existing flaws,
- crack propagation, and
- impact.

Factors that might affect the aging process (by modifying the rate of degradation) are:

- design;
- operational conditions;
- environment; e.g., stress, temperature, pressure, radiation, chemical interactions;
- manufacturing process; and
- installation process.

An examination of each category of the initiator mechanisms reveals that all represent deterioration with time. All modifying factors can affect the rate of deterioration, either positively or negatively, but there are no factors such as refurbishment or part replacement that will make a sudden improvement in the failure rate.

Understanding the failure mechanisms acting on the tanks may affect the operation conditions, and a change in the mode of operation may bring about a favorable change in the rate of deterioration. As more experience is accumulated, the priors can be modified to represent a slower degradation rate.

For each model, a series of priors for multipliers were tested: linear and exponential models according to the methodology described earlier. Of all the different multiplier models, those with significant likelihood were retained for the final set of priors. The final set of priors consists of combinations of linear, exponential, and power series of multipliers, as were shown to be important in the trial runs. It was seen that the small leaks for 100 series tanks favored the linear models, whereas the large leaks for 100 series tended to favor the exponential model for multipliers. The 200 series tanks, on the other hand, seemed to tend toward the power series and exponential models.

3.1.3. Results. The data for the 100 series and 200 series tanks were used to update the priors. For the 100 series models, data for 40 yr up to the end of 1991 were used to develop a failure frequency as a function of age. For the 200 series, a tank

leak did not occur until the tanks were older than 35 yr. For this 200-series model for small leaks, data for 15 yr up to the end of 1991 were used. The posteriors are shown in Figs. D.5 through D.7.

3.1.4. Leaks in DS Tanks. To date, there are no recorded leaks in the DS tanks. Table D-8 shows the years that the DS tanks were built. These tanks are physically similar in size to the 100 series tanks. There are monitoring devices in between the two shells, which will detect leaks from inside the inner shell or from the ground through the outer shell. The detectors monitor the pressure of liquid and/or radiation.

The model developed for the leaks in DS tanks considers the failure of each shell independently. The prior for the failure rate of the inside shell is taken to be the failure rate of the SS tanks (100 and 200 series together), which is conservative. This judgment is based on the improved design and construction of the DS tanks, which included heat treatment to relieve stresses in welded joints. DS tank inner-shell failure was then predicted by updating the SS tank prior with the DS tank experience from Table D-12. The results of the inner-shell analysis for both small and large leaks is shown in Figs. D.8 and D.9.

The analysis of leaks in the outer shell of the DS tanks was also based on SS tank experience. Because there have been no leaks from the inner tanks in DS tanks and the tanks are not normally wetted on the outside, the integrity of the outer shells is not known. Therefore, the prior from SS tank experience was not updated

TABLE D-12
DOUBLE-SHELL TANK EXPERIENCE

Tank Farm I.D.	Number of Tanks	Year in Service	Total Tank-Years
SY	3	1976	48
AN	7	1981	77
AP	8	1986	48
A W	6	1980	72
AY	2	1970	44
AZ-101	1	1973	19
AZ-102	1	1977	15
Total	28		323

with DS tank experience. However, because the outer shells of the DS tanks are not wetted, potential aging mechanisms such as corrosion should not be as prevalent as in the inner shells. Thus, the leak rates from the SS tank experience were multiplied by 1/10 for applications to the DS tank outer shells.

3.1.5. Future Frequency of Leaks. It is believed that all tanks eventually will leak given a sufficient amount of time. Therefore, it is of interest to predict the possible future leak frequencies. Because the prediction is based mainly on past performance, large uncertainties exist in the predictions. The uncertainties increase with the increased time span of prediction. These increased uncertainties can be observed from the increased spreads of the 5th and 95th percentiles shown in Figs. D.5 through D.9.

The predicted mean, 5th percentile, and 95th percentile of the leak frequencies, have been included in Figs. D.5 through D.9. For each tank group, the possible leak frequencies for the next 10 yr have been predicted. These predictions assume that the future operation of the tank will be similar to past operation. To facilitate discussions of future leaks, the possible leak frequencies of the sixth year (1997) starting from 1992 are selected to represent the performance of the next 10 yr (Table D-13). For the outer shells of the DS tanks, the leak frequencies were applied to the average age of a DS tank in 1997 (18 yr). Characteristics of the leak frequencies are also included in Table D-13.

3.2. Tank Dome Breach (DB)

The tank DB initiator is a leak or crack in the dome structure owing to an external event, excluding aircraft crashes. Two failure modes are allowed for this initiator: breach and collapse. If the dome is breached but does not collapse, only airborne aerosol releases are possible. If, however, the dome should collapse, a significant pathway would be open to the environment, and soil or other material falling into the tank could cause the displacement of waste material above grade. A fault-tree analysis was used to calculate the initiating event frequency (see Fig. D.10). The causes mentioned in the fault tree for a tank dome breach are a dome failure owing to drilling or excavation contact, a pump or pit cover dropped in the pump pit, heavy equipment driven over the dome, or dome failure by flooding. The resultant initiating event mean frequency is $5.0\text{E-}4$. The most significant contributor to the initiator is the pump or pit cover dropping into the pump pit. The results of the fault-tree analysis are found in Table D-14. The basic event descriptions and their frequencies are found in Table D-15.

TABLE D-13
PREDICTED MEAN FREQUENCY OF LEAKS FOR THE YEAR 1997
(LEAK EVENTS/TANK YEAR)

Tanks	Mean	5th Percentile	Median	95th Percentile	Variance
SS Tanks, 100 Series, Large Leaks	5.80E-02	2.43E-02	5.36E-02	1.03E-01	7.32E-04
SS Tanks, 100 Series, Small Leaks	1.03E-02	6.15E-03	9.41E-03	1.70E-02	1.33E-05
SS Tanks, 200 Series, Small Leaks	1.74E-01	5.70E-02	1.40E-01	3.73E-01	1.08E-01
All SS Tanks, Large Leaks	5.53E-02	2.19E-02	5.11E-02	1.01E-01	6.78E-04
All SS Tanks, Small Leaks	1.71E-02	1.00E-02	1.53E-02	3.66E-02	6.1E-05
DS Tanks, Inner Shell, Large Leaks	1.03E-02	5.55E-03	9.68E-03	1.64E-02	1.17E-05
DS Tanks, Inner Shell, Small Leaks	4.77E-03	8.83E-03	3.67E-03	1.21E-02	1.42E-05
DS Tanks, Outer Shell, Large Leaks	1.15E-03	8.31E-04	1.15E-03	1.47E-03	3.43E-08
DS Tanks, Outer Shell, Small Leaks	5.84E-04	3.67E-04	5.92E-04	7.77E-04	1.72E-08

TABLE D-14
CAUSE TABLE FOR TOP EVENT DBIE AND SPLIT FRACTION DBIEF

No.	Cut Sets	Value	% Importance	% Cumulative	Alignment
1	PIT_DROP	3.00-04	60	60	Normal
2	DOME_FLOODED FAIL_FLOOD	1.5E-04	30	90	Normal
3	D_DRILL_FAIL_DRILL	5.0E-05	10	100	Normal

Fig. D.10.
Fault tree for dome breach initiating event dome breach initiating-event fault tree.

TABLE D-15
DOME BREACH BASIC EVENT DESCRIPTIONS AND FREQUENCIES

Basic Event Name	Description	Frequency
FAIL_DRILL	Contact fails dome	0.5
D_DRILL	Contact made	1.0E-03
PIT_DROP	Pump or pit cover dropped in pump pit	3.0E-04
EQUIP_OVRLD	Heavy equipment driven over dome	0
DOME_FLOODED	Raw water flooding over dome or extreme precipitation	3.0E-03
FAIL_FLOOD	Dome failed by water load	0.05

3.3. Tank Riser or Ventilation Piping Breach (RVB1)

The initiating event RVB1, which refers to a tank riser or ventilation piping breach, is a leak or crack in the ventilation ductwork on the DS Tank Farm ventilation system. Failure of risers or ventilation piping results in a direct release path to the environment for tank aerosols. The UOR database categories applied to RVB1 include duct condensate leakage, failure to restore, loop seal pot loss, riser leaks, or tank riser damaged by a vehicle. These individual UOR events were summed together to derive the initiating event frequency for a tank riser or ventilation piping breach (see Table D-6). This initiating event mean frequency is 5.9E-2/yr.

3.4. Tank Exhaust HEPA Filter Failure (FB1)

The initiating event FB1 refers to a tank exhaust HEPA filter failure. Failure of the exhaust HEPA filter will result in a direct release path to the environment for tank aerosols, as well as the release of the radionuclides trapped by the filter material. The causes for FB1 are plugging of ventilation lines and/or the events categorized in the UOR as a filter blowthrough or damage to the filter frame. These individual UOR events were summed together to derive the initiating event frequency for a tank exhaust HEPA filter failure (see Table D-6). The initiating event frequency mean for FB1 is 9.7E-2/yr.

3.5. Bound Flammable/Toxic Gas Release Event (BURP)

The BURP initiating event refers to a bound flammable/toxic gas release within Tank 101-SY. The number of gas release events in 101-SY since March 1984

have been recorded in Table D-16.⁷ The first three events until April 1985 were omitted from the analysis because the times between these events are uncharacteristically long. The average mean frequency per year of gas release events since August 1986 is calculated from this table data to be 3.98. The best assessment, however, for the present average mean frequency of burps is calculated using only the events from March 1989. This was judged to be appropriate because operations at that time were changed to halt air lancing in Tank 101-SY. The average mean frequency per year of burps since March 1989 is 3.51. A histogram of all the gas releases since March 1989 is shown on Fig. D.11. The median, 5th, and 95th percentiles for gas releases since March 1989 have been calculated as follows.

The median is found to be the middle observation of the gas release events, which is 3.44 burps/yr (see Table D-17). The 5th and 95th percentiles were calculated in the following manner. Because the i th order statistic is the $100P = [(i-0.5)/n]$ 100th percentile where P is the desired percentage and n is the number of gas releases, it follows that the $(100P)$ th percentile of the sample is the observation with rank $Pn + 0.5$.⁸ For the 5th percentile, the rank is approximately 1, and the corresponding frequency is 0.007 burp/day or 2.64 burp/yr. For the 95th percentile, the rank is approximately 13, and the corresponding frequency is 0.01 burps/day or 4.74 burps/yr.

3.6. Loss of Active Tank Ventilation (LOTV)

The initiating event LOTV refers to the plugging of ventilation lines and/or the failure of the DS tanks' exhaust fans. Potential consequences of such an event are the heatup of waste that could cause unwanted chemical reactions or the accumulation of flammable or toxic gases in the dome space. The causes for LOTV are categorized in the UOR as an accidental loop filling, a loss of ventilation fan, inadequate ventilation, a filter plugging, or a deentrainer plugging. These individual UOR events were summed together to derive the initiating event frequency for a loss of active tank ventilation. The initiating event mean frequency for LOTV is 0.566/yr.

3.7. Loss of Electric Power Supply to Tank Farm (LOSP)

The initiating event LOSP refers to a loss of electric power supply to the SY Tank Farm. This initiating event includes the loss of the 13.8-kV power supply to the tank farm and the loss of any transformers and distribution panels within the tank farm. The causes for LOSP are categorized in the UOR as total area outages,

TABLE D-16
GAS RELEASE EVENTS

Date	Waste Level Drop (in.)	Time Since Previous Event (Days)
March 1984	6	
July 1984	6.8	114
April 1985	6.1	280
August 1986	5.90	482
October 1986	5.80	80
January 1987	7.40	58
February 1987	5.30	45
June 1987	7.80	98
September 1987	10.10	97
November 1987	6.60	81
March 1988	8.40	110
May 1988	8.20	70
July 1988	7.40	62
August 1988	8.60	19
December 1988	6.50	128
March 1989	9.70	106
June 1989	6.60	77
September 1989	8.40	94
January 1990	7.70	109
April 1990	8.90	110
August 1990	5.10	108
October 1990	11.10	81
February 1991	5.00	110
May 1991	7.20	89
August 1991	6.00	103
December 1991	13.00	99
April 1992	7.20	138
September 1992	13.20	129

Source: Ref. 7.

Fig. D.11.
Histogram of gas releases for Tank 101-SY since March 1989.

TABLE D-17
GAS RELEASE EVENTS SINCE MARCH 1989, SORTED BY FREQUENCY

Date	Waste Level Drop (in.)	Time Since Previous Event (Days)	Rank
April 1992	7.20	138	1
September 1992	13.20	129	2
April 1990	8.90	110	3
February 1991	5.00	110	4
January 1990	7.70	109	5
August 1990	5.10	108	6
March 1989	9.70	106	7
August 1991	6.00	103	8
December 1991	13.00	99	9
September 1989	8.40	94	10
May 1991	7.20	89	11
October 1990	11.10	81	12
June 1989	6.60	77	13

one-side outages, or individual systems outages. These individual UOR events were summed together to calculate the initiating event mean frequency for LOSP of 0.418/yr.

3.8. Water Intrusion Event (WI3)

Water intrusion occurs when water from precipitation, raw water system spills, or other sources enters a waste tank. WI3 is defined as a DS tank water intrusion event. The UOR database categories applied to quantify WI3 are surface water intrusion, raw water leak intrusion, or intrusions from interfacing systems. These individual UOR events were summed together to derive the initiating event frequency for a water intrusion event (see Table D-6). The initiating event mean frequency is 1.93E-2/yr.

3.9. Water Transfer Event (WT)

Not applicable to Tank 101-SY.

REFERENCES

1. J. D. Anderson, "History of the 200 Area Tank Farms," Westinghouse Hanford Company report WHC-MR-032 (June 1990).
2. Westinghouse Hanford Company, "Tank Farms Misroutings 1977-1988," informal report based on a compilation of various Rockwell Hanford Operations and Atlantic Richfield Hanford Company occurrence reports (May 1991).
3. H. F. Martz and R. A. Waller, *Bayesian Reliability Analysis*, John Wiley & Sons, New York (1982)
4. Westinghouse Hanford Company, "Tank Farm Surveillance and Waste Status Summary Report for December 1991," prepared for the US Department of Energy, Office of Environmental Restoration and Waste Management, WHC-EP-0182-45 (December 1991).
5. T. B. Powers and S. D. Morales, "SY Tank Farm Ventilation; Isolation Option Risk Assessment Report," App. D, Westinghouse Hanford Company draft report (June 1992).
6. Pickard, Lowe and Garrick, Inc., "Development and Demonstration of Methods for Nuclear Power Plant Aging Risk Analysis," prepared for EG&G Idaho, Inc., Idaho National Engineering Laboratory report PLG-0743 (November 1989).
7. R. D. Crowe et al., "Technical Basis for Selection of Tank 101-SY Intrusion Window," Westinghouse Hanford Company report WHC-SD-WM-TI-458, Rev. 3 (July 1992).
8. R. V. Hogg and J. Ledolter, *Engineering Statistics*, University of Iowa, Macmillan Publishing Company, New York (1987).

APPENDIX E

PHENOMENOLOGICAL MODELS

The phenomenological models discussed in this appendix are conceptual models created by analysts to simulate the dynamics of various events that have occurred or could occur in the waste tanks to cause unplanned radiological exposure to tank contents. Understanding the mechanisms involved in these dynamic, potential-release events may assist in the development of preventive and mitigative measures.

This appendix examines various mechanical and chemical phenomenological events in various levels of detail with the goal of developing and updating the understanding of individual phenomenological issues by reviewing previous analyses and documentation, performing additional analyses when needed, and identifying and assessing the importance of various uncertainties.

1.0. TANK RESPONSE TO OVERPRESSURE EVENTS

This section examines details of the phenomenological models for mechanical tank failure caused by increased internal pressure. An evaluation of tank pressure capacity precedes discussion of the events that may cause this capacity to be exceeded.

1.1. Tank Pressure Capacity

A probabilistic characterization of the pressure capacity of the 101-SY waste storage tank has been performed by EQE Engineering Consultants. A copy of their complete report is included in this document as App. B. This section was extracted from App. B and summarizes the results of the EQE analysis.

To fit into the PSA context, a probabilistic description of the pressure capacity of the tank is required. Because pressure capacity is treated as a random variable, it is possible for more than one failure mode to significantly contribute to the risk, and each such failure mode must be evaluated. This section discusses how the pressure capacities are described in a probabilistic form.

For this investigation, stresses are not categorized as primary membrane, primary bending, etc., which are then compared with different allowables, depending on the load condition as is required in a code or design calculation. Rather, failure is

based on expected ultimate strengths and elongations using median material properties and associated variabilities.

1.1.1. Development of Failure Probabilities. The pressure capacities are evaluated for various failure modes dependent on several factors, including material properties, modeling assumptions, and postulated failure criteria. A major source of uncertainty in the failure criteria is the expected strain that results in failure. All welds are full penetration, and the probability of failure at membrane strains of either the primary tank or the secondary liner below yield is considered to be quite low. On the other hand, biaxial strains and gauge-length effects, as well as strain concentrations and bending, significantly reduce the expected membrane strain-at-failure when compared to elongation data developed from standard specimen ultimate tests. Because test data from vessel tests are extremely limited, especially for dynamic load conditions, considerable variability is introduced not only into the failure criteria but also into analytical modeling and other assumptions. Because many of the base parameters are random variables and the methods used to evaluate the capacities are subject to some uncertainty, the pressure capacity for any failure mode is also considered to be a random variable.

It is assumed that the pressure capacities have a lognormal distribution because this distribution has been shown to be a valid description of the variability in material strengths. In addition, for a random variable that can be expressed as the product and quotient of several random variables, the distribution of the dependent variable tends to be lognormal, regardless of the distributions of the independent base variables.

Variability in the pressure capacity of a closed vessel results from a number of sources, including material properties, pressure pulse shape and duration, and analytical modeling assumptions. Material properties and analytical modeling uncertainties were included in the current investigation. In contrast, the hydrogen-burn pressure pulse introduces no tank pressure-capacity variability as discussed below, and therefore, this analysis did not include pressure-pulse uncertainties.

Hydrogen-burn pressure pulses show rise times on the order of 0.3 s or longer, and virtually constant pressure magnitudes for several seconds. To develop any appreciable increase in dynamic yield strength over static strength of either reinforced concrete or steel, rise times of less than about 100 ms are required.¹ Also, the constant pressure period after the rise results in essentially a static condition for the tank (except that the overburden may be thrown in the air at high internal pressures).

Assuming that pressure capacity is the lognormal random variable denoted by P , the probability of failure occurring at a pressure less than a specific value p is expressed as:

$$P_f = \text{Prob}(P \leq p) = \Phi\left(\frac{\ln(p / \hat{P})}{\beta_c}\right), \quad (\text{E.1})$$

where

- P_f = probability that failure occurs at a pressure $P \leq p$,
- P = random pressure capacity,
- β_c = logarithmic standard deviation of P ,
- $\hat{P}$ = median pressure capacity, and
- $\Phi(\bullet)$ = cumulative distribution function for a standard normal random variable.

In Eq. (E.1), the pressure capacity for a given failure mode is, P described probabilistically as:

$$P = \hat{P} \cdot M \cdot S, \quad (\text{E.2})$$

where

- $\hat{P}$ = the median pressure capacity;
- M = a lognormally distributed random variable having a unit median and a logarithmic standard deviation, β_M , that represents the modeling uncertainty; and
- S = is another lognormally-distributed random variable having a unit median value and a logarithmic standard deviation, β_S , that represents the uncertainty in the material properties.

The median pressure capacity, $\hat{P}$, represents the internal pressure level for which there is a 50% probability of failure (leakage) for a given failure mode. Median values are evaluated from limit-state analyses for the different failure modes. The uncertainties, β_M and β_S , are associated with variability owing to a lack of knowledge related to differences between the analytical model and the real

structure. The overall uncertainty in the median capacity is obtained by taking the square root of the sum of the squares of β_M and β_S .

Modeling uncertainties are associated with the assumptions used to develop analytical models and their ability to properly represent the failure condition. The strength uncertainties are associated with variabilities related to the material resistance. Examples of the sources of such uncertainties include variability in concrete strength, steel yield strength, and stress-strain relationships.

1.1.2. Variability in Material Properties. Code values of material strengths typically are minimum values, whereas actual material properties and associated variabilities are required for the type of evaluation considered here. Reference 2 uses the following values for ASTM 516 Grade 65 as "typical" properties:

$$\begin{aligned}\sigma_y &= 51 \text{ ksi,} \\ \sigma_u &= 80 \text{ ksi, and} \\ \varepsilon &= 31\% ,\end{aligned}$$

where σ_y is yield stress, σ_u is ultimate stress, and ε is elongation.

Assuming that the elongation corresponds to a 2-in. gauge length, the above values may be considered as essentially median values. Based on test data for similar materials and assuming a lognormal distribution, the following median values and variabilities were used for ASTM 516 Grade 65 plate for the current evaluation:

$$\begin{aligned}\hat{\sigma}_y &= 51 \text{ ksi} & \beta &= 0.09 \\ \hat{\sigma}_u &= 80 \text{ ksi} & \beta &= 0.07 \\ \hat{\varepsilon} &= 31\% & \beta &= 0.24 ,\end{aligned}$$

where β is the lognormal standard deviation.

Based on information available in the literature,³ the following median strength values and variabilities were used for the ASTM 615-68 Grade 60 reinforcing bars:

$$\begin{aligned}\hat{\sigma}_y &= 71 \text{ ksi} & \beta &= 0.09 \\ \hat{\sigma}_u &= 110 \text{ ksi} & \beta &= 0.13 \\ \hat{\varepsilon} &= 12\% & \beta &= 0.14 .\end{aligned}$$

The tank concrete is also expected to exhibit strengths above its 4500-psi, 28-day design value. In addition, concrete can be expected to increase in strength with time after the 28-day test. Site-specific data on the concrete were not available at the time of this investigation, so based on comparison with tests from other 4500-psi design concrete, the median value of concrete compressive strength, f_c' , was estimated at 5640 psi with a β 0.11.

In addition to the variabilities in the yield stress, ultimate stress, and elongation, variability exists in the postyield stress-strain relationships, the crack spacing in the concrete and corresponding average strain in the reinforcing steel, and the failure strain in the primary tank and secondary liner. Because all credible failure modes of the tank involve some degree of inelastic deformation, these sources of variability must also be accounted for.

1.1.3. Modeling Variability. Uncertainties will exist in the estimated pressure capacities owing to differences between the analytical idealization of the structure and the real conditions. There are numerous possible sources of modeling uncertainties. Examples of the sources of modeling uncertainties include assumptions used to develop the internal force distributions, failure criteria, and the use of empirical formulae. Moreover, because these uncertainties are dependent on the particular failure model under consideration, they must be evaluated on a case-by-case basis. Bounding analytical assumptions, such as different boundary conditions, often can be used to establish an estimate of the modeling variability. However, in many instances, the evaluation of these uncertainties require very detailed analysis and/or extensive data, which may not be available. As a result, it was necessary to use subjective evaluation and engineering judgment to estimate these uncertainties. The evaluation of the modeling uncertainties associated with the estimated pressure capacities is included in the discussion of the specific failure modes in the next section.

1.1.4. Pressure Capacity. The expected static and hydrogen-burn pressure capacities were calculated for several modes of failure for the primary tank, secondary tank, and the dome where failure was defined as a breach of the pressure boundary.

An estimation of membrane capacities requires determining the median failure criteria, including median strains expected for failure, the stress-strain behavior of the reinforcing and plate steel, and the variabilities associated with these parameters. For this analysis, no credit was taken for the tensile strength of the concrete. A discussion of how these measures were determined follows.

First, the failure strain of the reinforcing steel was estimated by assuming uniform bond stress per unit length of the reinforcement and linear bar stress between points of maximum stress (at concrete crack locations) and minimum stress. Average reinforcing strain at bar fracture was estimated at about 4.5% based on an average crack spacing of 24 in., as determined in Ref. 4.

Estimating the expected failure strain of the primary and secondary liners is more complex. The ASME Code minimum uniaxial elongation is 19% in a 2-in. gauge specimen, with expected median uniaxial elongation of about 31%, as shown in Sec. E.1.1.2. Reference 5 notes that the potential for hydrogen embrittlement was considered, but was found to be an unlikely contributor to failure strain. However, a biaxial stress state, gauge length effects, and strain concentration effects will substantially decrease the failure strain when compared to uniaxial test data.

Another factor that can influence the failure strain is the effective gauge length. Part of the elongation reported for a 2-in. uniaxial test specimen results from necking. For longer specimens, the necking portion of the elongation remains essentially constant so that the total elongation for longer length specimens is less; i.e., the elongation for a uniaxial 8-in. test specimen is less than that for a 2-in. specimen. In addition, strain concentrations such as around the nozzles in the dome will further reduce the expected global strain at failure. Based on these considerations, a median failure strain of 9% with a lognormal standard deviation of 0.38 was assumed to correspond to failure for the primary and secondary cylinder portions of the tank, with a median failure strain of about 7.5% and a lognormal standard deviation of 0.40 for the dome.

A value of a 0.015-in. was assumed for the thickness reduction due to corrosion of the primary tank wall in Ref. 5. The same value was used for both the primary tank cylinder and the dome in the current investigation, possibly intruding some conservatism into the dome failure results. Failure in the primary tank cylinder is expected to occur in the nominal 3/8-in.-thick upper course. Based on the material properties discussed above, static yielding in this region is expected to occur at about 41 psig, with a lognormal standard deviation of 0.10. The strain in the cylinder required to close the 30-in. gap between the primary and secondary tank is 6.67%. The secondary tank has a median static yield capacity (independent of the primary tank) of about 63 psig. If the primary tank has not failed before the annular gap is closed, some strain hardening of the primary tank will occur, resulting in a median static pressure of about 110 psig at yield of the secondary tank and 6.7% strain in the primary tank. Note, however, that based on the variability in failure

strain in the primary tank, there is about a 24% probability of failure before the primary tank contacts the secondary tank wall. If the primary tank fails before the secondary tank reaches the 4.5% median strain corresponding to rebar failure, the median static failure pressure of the secondary tank is about 76 psig, with a lognormal standard deviation of 0.11. If the primary liner remains intact up to the median failure strain of the rebar, the median static capacity of the combined primary and secondary tanks is 130 psig. However, there is a 76% probability that rupture of the primary tank will have occurred before developing the median secondary tank rebar failure strain.

The dome failure capacity is determined only by the primary tank and reinforced concrete because the secondary tank liner is discontinued above the haunch. A dome median static yield pressure of about 42 psig and a median static failure pressure of about 51 psig, each with a lognormal standard deviation of 0.10, were calculated. Based on the static failure pressures discussed above, the dome is the portion of the tank most likely to fail as a result of increased internal static pressure.

Likewise, a dynamic pressure caused by a hydrogen burn will most likely cause the tank to fail as a result of dome failure. Assuming a pulse shape similar to that shown in Fig. E.1² with a rise time on the order of 0.3 s and essentially a constant pressure dwell for several additional seconds, the median dynamic failure pressure in the dome was estimated to be 46 psig, with a lognormal standard deviation of 0.27. This failure pressure includes consideration of the dynamic response characteristics of the tank, including the fact that, in view of the overburden discussed above, the dome is likely to be thrown into the air at pressures approaching failure. The soil that is thrown in the air is unlikely to cause failure when it impacts the dome unless internal tank pressure has resulted in tearing of the primary dome liner. However, above-ground components immediately above the tank will likely fail, and assuming failure of the dome owing to internal pressure, impact of the falling soil will likely result in collapse of the dome and soil into the tank with sloshing of liquids out of the tank, as well as airborne release.

1.2. Hydrogen Burn Probability

The tank pressure is most likely to be exceeded as a result of hydrogen burn. This section evaluates the likelihood that necessary conditions exist for a hydrogen burn to cause pressure-capacity exceedance by first considering the requirements necessary for a chemical reaction to result in a radionuclide release.

MAX OP BURP / VENT SYS INOP / RISER CLSD

CASE 10

FULL FRICTION

Fig. E.1.
Pressure-time relation.

1.2.1. Ignition Requirements for Deflagrations. This deflagration process involves combustion fronts that travel at subsonic speeds relative to the unburned gas. For such processes, the pressure is nearly uniform throughout the volume of interest, and the maximum pressure attained can be bounded by the adiabatic isochoric (constant volume) complete combustion (AICC) pressure. As noted in Ref. 6, if the combustion front is accelerated, a transition to detonation may occur. For detonations, peak local pressures can be as high as 35 times the precombustion pressure. The presence of obstacles has been shown to promote flame acceleration, whereas transverse venting tends to reduce flame speeds.

The initiation of combustion requires that the temperature of the reactant gases be raised above a "threshold temperature," thereby initiating reaction.⁷ As noted in Ref. 7, this temperature increase can be caused by a flame, spark, arc, hot gas, compression, shock waves, adiabatic heating, and the addition of pyrophoric or

hypergolic materials. The energy required to initiate combustion decreases as the hydrogen gas temperature increases until the self-ignition temperature is reached.

Assuming that a small volume of gases becomes sufficiently heated (i.e., by one of the mechanisms discussed above) to react, the reaction products will expand and be cooled by the surrounding layer of unburned products. The expansion process itself also removes energy from the burned gases, causing these gases to cool somewhat. If the temperature at the interface between the burned and unburned gases is greater than the minimum threshold temperature for flame propagation into the unburned layer, the reaction will be sustained. Conversely, if the interface temperature is lower than this minimum flame threshold temperature, the reaction will slow down and be "quenched" by the colder, unburned gas layer.

Reference 8 notes that the experimental data obtained for flame propagation for hydrogen concentrations in the range of 4 to 9% are "quite dependent on the nature of the ignition source as well as the experimental geometry." The ignition sources of primary concern are related to sparks caused by electrical arcs, moving machinery (such as the exhaust fan), and static electricity.

The presence of ignition sources does not necessarily guarantee ignition. Despite the presence of numerous ignition sources inside the Three Mile Island Unit 2 (TMI-2) containment, ignition apparently did not occur until the volumetric hydrogen concentration reached approximately 8.5% (back-calculated based on an observed 28-psi pressure rise). Such delays suggest the possibility of randomness in the ignition process; however, it could also reflect the uncertainty in the hydrogen concentration in proximity to the ignition source.

According to Ref. 9, stated flammability limits have little meaning at mixture temperatures in excess of approximately 1200°F. At these temperatures, the mixture becomes near-hypergolic (i.e., spontaneously reacting), essentially independent of steam concentrations. Typical spontaneous ignition temperatures for hydrogen-air-steam mixtures at ambient pressures are on the order of 983 K (1310°F) and occur at a hydrogen concentration of approximately 30% (stoichiometric). The self-ignition temperatures are well above those expected in Tank 241-SY-101.

The minimum energies required to ignite various hydrogen-air mixtures are shown in Fig. E.2¹⁰ and Fig. E.3.¹¹ Figure E.3 also shows the "quenching distance" as a function of hydrogen concentration. Quenching distance is defined⁷ as "the distance from the ignition source that the fire or light can be put out by cooling with a colder container wall, colder gas or liquid."

Fig. E.2.
Minimum ignition energy for hydrogen deflagrations (taken from Ref. 10).

As noted in Ref. 12, near-stoichiometric mixtures of hydrogen (approximately 30%) and air can be ignited with spark energy levels as low as 0.02 mJ. However, the ignition energies required to ignite hydrogen mixtures increase substantially as the mixture concentrations decrease or increase from the stoichiometric limit toward the flammability limits. As noted in Ref. 13, the energy required for ignition increases rapidly as the initial pressure is lowered. Conversely, the minimum spark energy decreases with increasing initial mixture temperatures. Measured ignition energy requirements for mixtures near the flammability limits appear to be very sensitive to the size of the vessel used in the experiment. One reported series of

Fig. E.3.
Minimum ignition energies and quenching distances for H₂-O₂-inert gas mixtures at atmospheric pressure (taken from Ref. 11)

experiments indicated that the required spark energy to ignite a 4.5% hydrogen mixture was in the range of 10 to 100 J, depending on whether the tests were conducted in a 240-ft³ vessel or a 10-ft³ vessel.

Figure E.4¹⁴ identifies the energy levels of various potential ignition sources. As a point of reference, based on the ignition energy requirements shown in Figs. E.2 and E.3, a match burning for only a fraction of a millisecond would generate sufficient energy to initiate a deflagration in a hydrogen-air mixture near the lower limit of flammability. Also, Ref. 15 suggests that electrostatic discharges associated

Fig. E.4.
Ignition source energies (taken from Ref. 14).

with humans can be on the order of 15 mJ, whereas Fig. E.2 shows that only 0.6 mJ is required for ignition at the lower flammability limit.

There is some concern that waste movement during "burps" will induce metal-to-metal contact and possible sparks. Reference 16 summarizes the results of tests performed at RPI relative to the ability to ignite mixtures of N₂O, H₂, N₂, and air with frictional or electrical sparks.* The experimentalists first tried to produce sparks by metal-to metal impact. However, such efforts failed to produce sparks and they "had to resort to a grinder" to produce sparks. The actual apparatus consisted of a silicon carbide grinding wheel attached to a motor and a piece of a round steel file that was positioned by a pneumatic piston so as to contact the grinding wheel. Both

*The estimated magnitudes of the energy deposited by electrical sparks was not provided the draft RPI report (Ref. 16).

conservative and best estimate BURP concentrations were examined and the released gas was assumed to be mixed with various amounts of air.

BURP gas—air mixtures (with both conservative and best estimate H₂ concentrations) appear to be susceptible to frictional spark ignition only when the BURP represents approximately 10 to 30% of the total mixture volume. Below BURP concentrations of 10% (corresponding to H₂ concentrations between 4.3 and 3.85%), the mixture appears to be too lean to be ignited by either frictional sparks or weak electrical sparks. Above BURP concentrations of 30% (corresponding to H₂ concentration between 16.3 and 14.7%), "there does not seem to be enough oxygen present to support combustion of the metal particles thrown off by the frictional ignition system." The RPI experimentalist judged that "N₂O does not seem to support metal particle combustion." The RPI report also notes that mixture with 30% or more of the best estimate BURP "are certainly more susceptible to other forms of ignition, such as electrical sparks..."

The RPI report indicates that friction induced sparks caused by the interaction of metallic and non-metallic sources inside the tank are unlikely and even if they were produced, they would be effective in igniting the gas mixture only in a limited range of concentrations. Unfortunately, however, this limited range is of the greatest interest in the tank PSA. Although the definition of "weak" was not provided, it does appear as though the presence of weak electrical sparks can ignite the mixtures of interest.

1.2.2. Ignition Requirements for Detonation. The peak pressures associated with detonations are well above the quasi-static pressures associated with deflagrations. However, the energies required to initiate detonations are many orders of magnitude above those required for deflagrations.

As noted in Ref. 8, detonation initiation within a range of hydrogen concentrations (in air) from 18 to 59 vol% (the approximate range of hydrogen detonability) requires an energetic ignition source, severe confinement, and/or a sufficiently large volume of gas mixture. Reference 8 concluded that "the energy levels required to directly initiate detonation are orders of magnitude greater than those necessary to initiate burning at the same hydrogen concentration" and that "a de facto transition to detonation is highly unlikely in reactor containment buildings particularly when there are high steam concentrations or hydrogen concentrations below about 18 volume percent." Minimum ignition energies of 4100 J have been reported⁸ for hydrogen-air mixtures. According to Ref. 8, this energy level is several orders of magnitude higher than would be produced from an electrical spark caused by

contact arcing or by electrostatic discharge and approximately eight orders of magnitude higher than the minimum ignition energy required to initiate deflagration.

Reference 17 addressed experiments performed at RPI to assess detonation cell widths (transverse wave spacing) and the propensity for deflagration to detonation transitions (DDT) for various mixtures of H_2 , N_2O , N_2 , and air. Both sets of tests were conducted in a detonation tube 5.35 m long and with a square cross-sectional flow area 8.3 cm x 8.3 cm. Ignition was induced near one end of the tube. For the determination of detonation cell widths, mixtures were ignited by an exploding wire. For the DDT tests, mixtures were ignited with a glow plug.

The detonation and DDT tests were performed for various mixtures of air and the gas released in the BURP. The BURP gas mixture, which was tested, contained the following gases by volume: 42.8% H_2 , 36.4% N_2O , and 20.8% N_2 . These gas concentrations correspond to the conservative estimate of the BURP gas mixture as it is released from the waste. The resulting maximum concentrations calculated for the dome space and ventilation system inlet were assumed to be 95th percentile values (of a lognormal distribution) in the PSA. Reference 18 (p. 3-14) notes that the hydrogen concentration in this mixture corresponds to the 2σ value (i.e., the 97.7th percentile of an assumed normal distribution) for the measurement uncertainty. The best estimate concentration of hydrogen in the gas released from the waste is 33.8%.

The BURP + air mixtures have been interpreted as follows. Let the total number of moles in the BURP gas be given by

$$\begin{aligned}N_{\text{Burp}} &= N_{\text{Hydrogen}} + N_{\text{Nitrous Oxide}} + N_{\text{Nitrogen}} \\N_{\text{Hydrogen}} &= 0.428 \times N_{\text{Burp}} \\N_{\text{Nitrous Oxide}} &= 0.364 \times N_{\text{Burp}} \\N_{\text{Nitrogen}} &= 0.208 \times N_{\text{Burp}}\end{aligned}$$

$$\text{But } H_2 \text{ Conc} = N_{\text{Hydrogen}} / (N_{\text{Burp}} + N_{\text{Air}}) = 0.428 \times N_{\text{Burp}} / (N_{\text{Burp}} + N_{\text{Air}}).$$

Assuming that BURP + 20% air implies that $N_{\text{Air}} / (N_{\text{Air}} + N_{\text{Burp}}) = 0.2$, then for X% air,

$$H_2 \text{ Concentration} = 0.428 \times (1.0 - X/100)$$

and the hydrogen concentrations corresponding to the various mixtures being considered area as follows:

	H ₂ Conc (%)
BURP + 0% Air	42.8
BURP + 20% Air	34.2
BURP + 40% Air	25.7
BURP + 60% Air	21.4
BURP + 80% Air	17.1

Based on the information given in Table E-3 and Fig. E.9 for the maximum predicted gas release of approximately 14,000 cu ft (1989–1995), the probability of the maximum hydrogen concentration exceeding 17% in the ventilation ducting (assuming the vent system to be operating) is less than 1.0×10^{-5} per year.

In general, a lower value for the detonation cell width indicates a greater sensitivity of the mixture to detonation initiation. For all other conditions being equal, the minimum value for cell width is predicted to occur at stoichiometric concentrations.

Reference 17 noted that "mixture with larger cell widths required larger amounts of energy discharged through the wire to obtain a detonation." Even though enhancements (a Schelkin Spiral) were used to promote detonation, a mixture of the BURP gas and 60% air (21.4% H₂ concentration) could not be detonated with the exploding wire system even with energy deposition as high as 185 J. As noted in Ref. 8, this ignition energy is at least an order of magnitude greater than would be produced by contact arching or by electrostatic discharge.

Thus, although it appears as though the H₂ - N₂O - Air mixtures tend to be more sensitive to detonation than previously believed, the combination of ignition energy required and predicted maximum hydrogen concentrations make it extremely unlikely that a direct detonation could be induced.

Under certain conditions, the flame front associated with a deflagration can accelerate to supersonic speeds, thus transitioning to conditions that are indicative of detonations. This process is known as deflagration to detonation transition (DDT). Although the geometry of the tank ventilation system appears to be conducive to such transitions, based on the data and discussion found in Ref. 6, it can be concluded that DDT has not been observed in experiments with less than 15 mol % hydrogen concentrations, regardless of geometry, the presence of obstacles in the flame path, or the degree of transverse venting.

The results of the DDT tests performed by RPI are summarized below.

	Clear Tube	Obstructed Tube
BURP + 0% Air	DDT	DDT
BURP + 20% Air	DDT	DDT
BURP + 40% Air	No DDT	DDT
BURP + 60% Air	No DDT	DDT
BURP + 80% Air	No DDT	Accel. Flame

As noted earlier, based on current HMS calculations, the estimated probability of achieving a peak H_2 concentration of 17.1% in the ventilation system is extremely small.

Reference 19 notes that a detonation wave develops when a combustion (deflagration) wave is allowed to travel in an explosive mixture which is within the limits of detonability in a long tube closed at the end where the combustion is initiated. Several reasons are cited for acceleration of the combustion wave.

1. The hot products (whose specific volume is much greater than that of the unburned mixture) expand and act as a hot-gas piston that accelerates the unburned gas mixture ahead of the combustion wave as well as the combustion wave itself.
2. The development of turbulence in the zone ahead of the combustion wave results in an increased burning velocity and, therefore, in acceleration of the combustion wave.

According to Ref. 19,

"...the compression waves produced ahead of the accelerating combustion wave coalesce in the unburned mixture and, if the tube is long enough, produce a shock wave. The distance between the accelerating combustion wave and the shock wave begins to decrease. If the shock wave is strong enough, it will compress the reacting mixture to such conditions that a rapid chemical reaction occurs and detonation wave forms. If the shock wave is not strong enough, it will not produce a detonation wave immediately. In such a case a further flame acceleration takes place; the flame catches up with the shock wave and, in this way, forms a detonation wave.

Experimental evidence indicates that a combustion wave that propagates in an explosive mixture from an open end of a tube (that is open also on the other end) does not accelerate to a detonation wave. It further indicates that a combustion wave which propagates from the

closed end of a tube accelerates continuously, whether the other end of the tube is open or closed. If the tube is long enough, a detonation wave will form. In a tube closed at both ends, the detonation wave forms in a shorter distance than a tube whose other end is open."

Thus, the RPI results for DDT must be applied to the SY-101 vent system geometry with some caution. If an ignition takes place in the ventilation system, burn back to the tank is assumed to occur at hydrogen concentrations considerably less than those required for DDT. A hydrogen concentration limit of approximately 11% is used in the current PSA model to determine if "burn back" from an ignition source is in the ventilation system to the tank dome space.

The current model predicts tank failure due to overpressure for burns at hydrogen concentrations considerably lower than those corresponding to mixtures which can transition to detonation. Thus, neither direct detonations nor DDT have been explicitly addressed in this PSA.

1.2.3. Ignition Sources and Likelihood of Ignition. Reference 20 discusses an assessment of the hydrogen ignition capability from in-tank and associated ex-tank electrical equipment and instrumentation for selected waste tanks. This assessment assumed that hydrogen was present in its most easily ignitable concentration; i.e., minimum ignition source energies are required.

Except for static electricity and the potential for sparks caused by metal-to-metal contact, there are no other ignition sources within the vapor or waste spaces of Tank 241-SY-101. The more likely source of ignition of the episodic hydrogen releases is from instrumentation installed to monitor these releases and from sources associated with the ventilation system.

The availability of an ignition source does not necessarily guarantee that ignition will occur. However, the uncertainty in ignition is more likely to be caused by uncertainties in the local conditions near potential ignition sources as opposed to any random uncertainties. In Vol. 5 of Ref. 21, the probability of ignition was assumed to be 1.0 if ac power were available (even if installed igniters were not operable) and the containment compartment were not inerted. The experts solicited to evaluate hydrogen ignition at the Sequoyah Nuclear Power Station believed that the main ignition source in the ice condenser region of the containment would be "due to static discharge caused by the opening and shutting of intermediate deck doors between the ice condenser and upper plenum." For this region, if the steam concen-

tration were less than 60%, the following probabilities of ignition were derived by aggregation of expert opinion:

Hydrogen Concentration (%)	Probability of Ignition
> 16	0.2
> 11, < 16	0.16
> 5.5, < 11	0.12

Thus, in the absence of electrical power sources for ignition, the experts believed that there was only approximately 1 chance in 10 that a hydrogen-air mixture near the lower flammability limit would ignite as the result of sparks caused by metal-to-metal contact.

The data on the hydrogen ignition capability of waste tank equipment from Ref. 20 were used in an effort to quantify the likelihood of burns in Tank SY-101 by the WHC in Ref. 22. In Ref. 22, the annual frequency of hydrogen burns in Tank 241-SY-101 was predicted to be 0.0162 with ventilation running and 0.0233 with ventilation off. Conditional frequencies for hydrogen burn ignition in the tank, burn in the ventilation system, and propagation of the burn from the ventilation system back to the tank were derived from this analysis. These conditional frequencies are shown in Table E-1. WHC estimates of hydrogen ignition in the tank and ventilation system are used in this evaluation. However, the values for propagation of a burn from the ventilation system to the tank for the case in which the ventilation system is operating were developed independently, as discussed in the next section.

TABLE E-1
HYDROGEN IGNITION DATA²²
(CONDITIONAL FREQUENCY PER RELEASE EPISODE)

Episode	Frequency
Hydrogen Ignition in Tank SY-101	0.00128
Hydrogen Ignition in SY Ventilation System	0.0066
Propagation from Vent System to Tank—Ventilation On	0.083
Propagation from Vent System to Tank—Ventilation Off	1.0

1.2.4. Likelihood of an Ignition in Ventilation System Propagating Back to Tank. Once a flammable gas is ignited, the flame begins to spread outward from the source of ignition. The movement of this flame is measured in terms of "burning velocity" or "flame speed." Burning velocity is defined⁷ as "the velocity of propagation of the flame with respect to the unburned gases." Flame speed is defined as "the movement of the flame front with respect to a stationary point of reference." Thus, if ignition occurs in a duct with flowing gas, the flame will not be able to propagate upstream from the source of ignition unless the flame speed exceeds the gas velocity.

Figure E.5²³ gives plots of both the laminar and turbulent burning velocities as a function of hydrogen concentration in mixtures of N_2O and air. According to Ref. 6, flame speeds are typically a factor of 6 (the ratio of the unburned to burned

Fig. E.5.
Calculated burning velocities for "turbulent" mixtures (chain-dashed curve) of 1:1 ratios of $H_2:N_2O$ in air compared to solid curve for quiescent mixtures (taken from Ref. 23).

gas densities) times the burning velocities. The flame speeds for various hydrogen concentrations are shown in Table E-2. As indicated by Fig. E.6, minimum velocities in the tank ventilation ducting when the fans are operating are expected to be greater than 2.8 m/s. Figure E.7 plots flame speed for various hydrogen concentrations and compares the normal flow velocity with flame speed. As indicated in Fig. E.7, propagation back to the tank is not expected for burns that occur at less than approximately 11% hydrogen concentration because the flame speed in the upstream direction is less than or equal to the minimum flow velocity (corresponding to fan-induced flow only) in the ducting adjacent to the tank.

Figures E.8a through E.8c depict the hydrogen concentrations (based on a best-estimate hydrogen concentration in the gas released from the waste of 33.8%) at various locations in the duct for various hydrogen releases from the waste, assuming that the ventilation system is in operation. Table E-3 summarizes the peak concentrations determined for these three cases, as well as estimated peak concentrations corresponding to a conservative estimate (42.8%) of the hydrogen concentration in the gas released from the waste. The values summarized in Table E-3 are plotted in Fig. E.9. As indicated in this figure, for any given gas release volume, the best-estimate hydrogen concentrations were assumed to represent the median of a lognormal distribution of hydrogen concentration, and the conservative values were assumed to represent the 95th percentile of those distributions. The resulting lognormal distributions for hydrogen concentrations for various gas release volumes are summarized in Table E-4.

Figure E.10 depicts a probabilistic algorithm (quantified with the STADIC program)²⁴ for determining the conditional frequency of propagation back to the tank based on the lognormal distributions developed for hydrogen concentration as a function of gas release volume and the cumulative probability for gas release volume, which is discussed in Sec. E.1.4. The resulting conditional frequency of a burn propagating back to the tank for the case with ventilation operating is 0.083. This value is somewhat higher than the value recommended in Table E-1. However, a value of 1.0 for propagation was used in this analysis for the "Ventilation Off" case.

1.3. Tank Pressure Loads from Hydrogen Burns

Both best and conservative estimates of the pressure loads resulting from postulated burns are detailed in this section. Best-estimate calculations²⁵ of the peak pressure following a postulated burn were performed for 5-, 10-, and 15-kg hydrogen

TABLE E-2
TURBULENT BURNING VELOCITIES AND FLAME SPEED

Hydrogen Concentration (%)	Turbulent Burning Velocity ¹⁹ (m/s)	Estimated Flame Speed ^a (m/s)
6	0.085	0.51
8	0.115	0.69
10	0.325	1.95
12	0.664	3.98
14	0.955	5.73

^aSix times burning velocity per.⁶

Fig. E.6.
Flow velocities in the tank ventilation system—ventilation operating.

Fig. E-7.
Flame speed for burns at various hydrogen concentrations.

5 kg Case

Fig. E.8a.

Hydrogen concentration in ventilation system for 5-kg hydrogen release (best-estimate H_2 concentration)—ventilation operating.

10 kg Case

Fig. E.8b.

Hydrogen concentration in ventilation system for 10-kg hydrogen release (best-estimate H_2 concentration)—ventilation operating.

Fig. E.8c.
Hydrogen concentration in ventilation system for 15-kg hydrogen release
(best-estimate H₂ concentration)—ventilation operating.

TABLE E-3
PEAK HYDROGEN CONCENTRATIONS IN VENTILATION
SYSTEM WITH VENTILATION OPERATING

Volume of Gas Released (ft ³)	Peak H ₂ Concentration Based on Best Estimate Concentration (%)	Peak H ₂ Concentration Based on Conservative Concentration (%)
6922	5.3	6.7
13,844	9.4	11.9
20,765	12.8	16.2

Fig. E.9.
Hydrogen concentration vs volume of gas released (data from Table E-3).

Fig. E.10.
STADIC algorithm for burn propagation.

TABLE E-4
LOGNORMAL DISTRIBUTIONS FOR HYDROGEN CONCENTRATION

Cumulative Probability	Hydrogen Concentrations (%) for Gas Volume (ft ³) of				
	6000	8000	10,000	12,000	14,000
0	2.89	3.25	3.73	4.60	5.38
0.01	3.62	4.29	5.00	6.04	7.00
0.05	3.92	4.74	5.54	6.66	7.68
0.1	4.09	4.99	5.85	7.01	8.07
0.2	4.31	5.32	6.25	7.46	8.57
0.3	4.47	5.56	6.56	7.80	8.94
0.4	4.61	5.79	6.83	8.10	9.28
0.5	4.75	6.00	7.10	8.40	9.60
0.6	4.89	6.22	7.38	8.71	9.94
0.7	5.05	6.47	7.68	9.05	10.31
0.8	5.24	6.77	8.06	9.46	10.76
0.9	5.51	7.21	8.62	10.07	11.42
0.95	5.75	7.60	9.10	10.60	12.00
0.99	6.23	8.39	10.09	11.68	13.17
1	7.80	11.07	13.51	15.35	17.12

releases. These mass releases correspond to total gas volume releases from the waste of 6922, 13,844, and 20,765 ft³ at dome vapor space conditions of 1.013 bar (14.7 psia) and 323 K (120°F). The predicted pressure rise for these three releases are shown in Table E-5. The predictions were made with the HMS-TRAC computer program, assuming the following:

- ventilation operable;
- gas released to the dome space from a planar area of the waste surface corresponding to the "inner half radius;"
- gas released to the dome space over approximately 200 s such that (in the absence of a burn) the moles of hydrogen in the dome space increase linearly with time over the first part of this period, remain constant over

TABLE E-5
BEST-ESTIMATE PRESSURE RISE

Hydrogen Released (kg)	Total Gas Released ^a (kg)	Total Gas Volume Released ^a (ft ³)	Pressure Rise due to Burn	
			bar	psi
5	170.5	6922	1.46	21.1
10	341.1	13,844	2.99	43.3
15	511.6	20,765	4.27	61.9

^aGas release quantities based on best-estimate molar concentrations.²⁵ Total volume of gas released computed at dome vapor space conditions of 1.013 bar (14.7 psia) and 323 K (120°F).²⁵

the second part of this period, and then "tail off" according to an exponential function;

- ignition occurs at the top of the tank, simulating a "burn back" from the ventilation exhaust system; and
- compressibility of the waste was conservatively ignored.

The three calculated pressure rises were used to produce the curve in Fig. E.11 that is labeled "best estimate." The curve in this figure, which is labeled "conservative," is based on calculations performed for App. P of Ref. 26. For any given volumetric release of gases, the best estimate calculations were assumed to represent the median of a lognormal distribution, and the conservative calculations were assumed to represent the 95th percentile of these distributions. A summary of the distributions for pressure rise for various volumetric releases is given in Table E-6. The next section discusses the frequency of tank failure caused by burn pressure rises.

1.4. Frequency of Tank Failure Resulting from Hydrogen Burns

The frequency of tank failure resulting from hydrogen burns is determined by a probabilistic model that combines the frequency and the magnitude of episodic hydrogen releases from the waste to the vapor space of the tank, the likelihood of ignition of this hydrogen, the overpressure resulting from ignition, and the ability of the tank to withstand this overpressure.

Fig. E.11.
Pressure rise from hydrogen burn.

TABLE E-6
LOGNORMAL DISTRIBUTIONS FOR PRESSURE RISE
DUE TO HYDROGEN COMBUSTION

Cumulative Probability	Load Distributions for Vgas (ft ³)					
	5000	7000	9000	11,000	13,000	15,000
0	7.26	10.23	13.13	15.70	18.70	22.95
0.01	10.39	14.62	18.72	22.53	26.70	32.08
0.05	11.80	16.60	21.23	25.60	30.29	36.11
0.1	12.62	17.75	22.69	27.39	32.37	38.45
0.2	13.69	19.26	24.60	29.75	35.13	41.51
0.3	14.52	20.42	26.07	31.56	37.23	43.84
0.4	15.27	21.47	27.40	33.20	39.13	45.94
0.5	16.00	22.50	28.70	34.80	41.00	48.00
0.6	16.77	23.58	30.06	36.48	42.95	50.15
0.7	17.63	24.79	31.59	38.37	45.15	52.55
0.8	18.69	26.28	33.48	40.71	47.86	55.51
0.9	20.29	28.52	36.31	44.21	51.92	59.93
0.95	21.70	30.50	38.80	47.30	55.50	63.80
0.99	24.63	34.62	43.99	53.75	62.96	71.83
1	35.25	49.51	62.72	77.13	89.91	100.39

1.4.1. Database. Table E-7 summarizes the significant episodic level drops that have occurred since January 1984 and the estimated gas release volumes associated with these events. Based on these data, the cumulative probability distribution for gas release shown in Fig. E.12 was derived. The observed level drops have also been depicted in Fig. E.13 in the form of a "scatter diagram." As indicated in Fig. E.13, there is a definite trend (as evidenced by linear, least squares fits to the observed data) in both the "average" level drop and for the upper-bound envelope for the drops.

In March 1989, the practice of "air lancing" in Tank 241-SY-101 was terminated. This change in operating practice changed the character and frequency of the episodic releases. Thus, assuming that neither the installation of additional equipment (such as the mixing pump) or instrumentation nor phenomenological

TABLE E-7
SIGNIFICANT EVENTS THAT HAVE OCCURRED IN TANK 241-SY-101

Date	Drop (in.)	Estimated Volume (ft ³) ^a
March 1984	6	4992
July 1984	6.8	5658
April 1985	6.1	5075
August 1986	5.9	4909
October 1986	5.8	4826
January 1987	7.4	6157
February 1987	5.3	4410
June 1987	7.8	6490
September 1987	10.1	8403
November 1987	6.6	5491
March 1988	8.4	6989
May 1988	8.2	6822
July 1988	7.4	6157
August 1988	8.6	7155
December 1988	6.5	5408
March 1989	9.7	8070
June 1989	6.6	5491
September 1989	8.4	6989
January 1990	7.7	6406
April 1990	8.9	7405
August 1990	5.1	4243
October 1990	11.1	9235
February 1991	5	4160
May 1991	7.2	5990
August 1991	6	4992
December 1991	13	10,816
April 1992	7.2	5990
September 1992	13.2	10,982

^aBased on 832 ft³ /in. of drop (memo from D. Sanzo, Los Alamos National Laboratory, to John Kindinger, August 6, 1991).

Fig. E.12.

Cumulative probability of gas released in Tank 101-SY, based upon all observed events since January 1984.

Fig. E.13.
Scatter diagram of observed drops in waste level during Tank 101-SY events.

changes in the waste has any impact on the trends, the frequency and magnitude of future significant episodic gas releases are based on actual data only for events that occurred after March 1989. Figure E.14 represents a scatter diagram, along with least squares fits for the average drop and the envelopes. Based on these least squares fits, predicted times and magnitudes of events for the next 3 yr were estimated. The predicted events are also shown in Fig. E.14. Table E-8 summarizes the actual events that have occurred since March 1989, as well as the predicted times and magnitudes of level drops and associated gas release volumes for the next 3 yr. Based on the events shown in Table E-8, a new cumulative probability distribution for the gas release volume was generated. This distribution is shown in Fig. E.15.*

A probabilistic characterization of the likelihood of ignition of the hydrogen-laden mixture of gases released to the vapor space of the tank is extremely different. As noted in Sec. E.1.2, mixtures of hydrogen are easily ignited, requiring only minimal sources of energy. On the other hand, although there are a number of potential ignition sources in the tank's ventilation system, there are limited ignition sources in the tank per se. The probability that an ignition occurring in the ventilation system can propagate back into the tank depends on the ventilation flow velocity and the burning velocity associated with the reacting gases.

The magnitude of the pressure rise associated with combustion events inside the tank has been deterministically estimated on both a best-estimate²⁵ and a conservative basis by using the HMS/TRAC computer program. The specific results of interest are shown in Fig. E.11. For each volume of gas released, the conservative and best-estimate values shown on Fig. E.11 are taken as the 95th and 50th percentiles of a lognormal distribution. Thus, uncertainties in both the volume of gas released and in the pressure rise associated with the combustion of a given volume of gas released from the waste are addressed.

1.4.2. Probabilistic Model. The quantification of the frequency of tank failure owing to combustion events is accomplished with the STADIC program²⁴ using the algorithm depicted in Fig. E.16. The STADIC program uses Monte Carlo sampling techniques to combine input probability distributions of various types to generate output distributions, according to a prescribed algorithm. Thus, as shown in Fig. E.16, the first step in the algorithm is to sample the cumulative probability

*Based on best-estimate hydrogen concentrations, events involving total gas releases less than approximately 5000 ft³ result in maximum hydrogen concentrations less than the lean flammability limit; i.e., 4%. Such events were ignored in the final gas release volume distribution used to calculate tank failure probability.

Fig. E.14.
Observed and predicted drops in waste level.

TABLE E-8
SIGNIFICANT EVENTS IN TANK 101-SY SINCE MARCH 1989
AND PREDICTED EVENTS FOR NEXT 3 YR (1993–1995)

Date	Drop (in.)	Estimated Volume (ft³)^a
March 1989	9.7	8070
June 1989	6.6	5491
September 1989	8.4	6989
January 1990	7.7	6406
April 1990	8.9	7405
August 1990	5.1	4243
October 1990	11.1	9235
February 1991	5.0	4160
May 1991	7.2	5990
August 1991	6.0	4992
December 1991	13.0	10,816
April 1992	7.2	5990
September 1992	13.2	10,982
December 1992	7.9	6588
March 1993	14.0	11,624
June 1993	8.5	7036
September 1993	14.5	12,072
December 1993	9.0	7484
March 1994	15.0	12,520
June 1994	9.5	7932
September 1994	15.6	12,968
December 1994	10.1	8,80
March 1995	16.1	13,416
June 1995	10.6	8828
September 1995	16.7	13,864
December 1995	11.1	9276

^aBased on 832 ft³/in. of drop (memo from D. Sanzo, Los Alamos National Laboratory, to John Kindinger, August 6, 1991).

Fig. E.15.
Cumulative probability distribution for volume of gas released (based on observed drops since March 1989 and extrapolated for next 3 yr).

Fig. E.16.
STADIC algorithm for Tank 101-SY failure.

distribution for the volume of gas released. The next step in the algorithm is to assess the probability of ignition. Assuming that the gas mixture ignites for the sampled volume, the pressure rise distribution corresponding to this volume is sampled (based on interpolation*). The probability distribution for tank strength is then sampled, and the peak tank pressure is compared to the sampled strength. If the pressure load exceeds the tank strength, the trial is assumed to result in tank failure. If the sampled strength exceeds the sampled load, the trial does not result in tank failure. This process is repeated thousands of times to provide statistically meaningful results for the conditional frequency of a tank failure given an episodic release of gas from the waste.

1.4.3 Results. The following three cases were analyzed the model described in the previous section:

1. Actuarial data for all significant waste-level drops/gas releases that have been observed since January 1984 (Table E-7); pressure rise distributions as discussed in previous section.
2. Actuarial data since March 1989 and estimated level drops/gas releases for the next 3 yr (Table E-8); pressure rise distributions as discussed in previous section.
3. Gas release of 13,100 ft³ [maximum allowable burp (MAB)]; pressure rise distributions as discussed in previous section.

The STADIC evaluation of these three cases is summarized in Table E-9. Case 2 is of particular interest and indicates that, for any burn, the conditional probability of tank failure is 0.12. If only actuarial data (Case 1) are used in this evaluation, the conditional probability of tank failure is reduced by an order of magnitude to 0.014.

2.0. FERROCYANIDE REACTIONS

A number of the Hanford tanks contain ferrocyanides, nitrates, and/or nitrite constituents. In the presence of nitrate and/or nitrite constituents, ferrocyanide salts can react and detonate under certain conditions, including dryness, proper chemical

*It is unlikely that the sampled volume will correspond exactly to one of the volumes for which there is a distribution. Thus, an interpolation between distributions for gas volumes above and below the sampled volume must be performed. When such interpolation is necessary, the pressure rise distributions for the two bounding volumes are assumed to be completely correlated.

TABLE E-9
RESULTS OF STADIC ANALYSES FOR TANK FAILURE FREQUENCY

Case	Conditional Frequency of Tank Failure
1	0.014
2	0.12
3	0.37

concentration and mixture, and elevated temperatures or a high-energy spark. However, these reactions are not expected to be important until temperatures reach approximately 285°C (545°F).

2.1. Background Information

Ferrocyanides were added to a number of tanks as part of a process to reduce radionuclide concentration in the freestanding liquid tank wastes to levels low enough to permit disposal of the liquid to the soil. This process involved the addition of ferrocyanide-containing compounds to the tanks to precipitate radioactive cesium out of the liquid.²⁷

Currently, 24 SS tanks are suspected to contain appreciable amounts of ferrocyanide precipitates [1000 g-moles (465 lb) or greater]. The estimated ferrocyanide content of these 24 tanks ranges from 1000 g-moles (465 lb) to approximately 200,000 g-moles (93,000 lb) in Tank 241-BY-104 (also referred to as Tank 104-BY).

A release of radionuclides is believed to have a low probability of occurrence, even from a localized "hot spot" as a result of a ferrocyanide reaction, because the maximum temperatures measured inside the tanks containing ferrocyanide at the Hanford Site are at or below 60°C (140°F), thus providing a significant margin of safety. Tank temperatures have also been declining (at a little less than 2°C/yr) as the tank fission products continue to decay. However, it should be noted that the cooling of the wastes with time is not solely the result of declining heat loads owing to radioactive decay.²⁸ The higher temperatures that occurred in the 1970s were caused by the additions of hot saturated solutions produced by in-tank solidification processes. These additions were terminated in 1975.

2.2. Issue Related Phenomenological Findings

A number of tests have been performed on tank samples, including differential scanning calorimetry (DSC), scanning thermogravimetry (STG), accelerating rate calorimetry (ARC), small-scale explosion testing, and various sensitivity tests for impact, electrical spark, friction, and temperature. These tests show that the oxidation mechanism for ferrocyanide is complex.²⁹ The minimum observed exothermic reaction temperature is 210°C (410°F). The minimum observed run-away temperature is 285°C (545°F). The current maximum temperature, 60°C measured inside the ferrocyanide tanks at the Hanford Site, are well below these limits.

Furthermore, heat removal from the tanks is facilitated by a number of existing heat sinks in the tanks. The presence of H₂O, NaNO₃, or NaAlO₂ provides heat sinks or mechanisms of heat removal. Three grams of H₂O, 14 g of NaNO₃, or 24 g of NaAlO₂/g of ferrocyanide (Na₂NiFe(CN)₆) would prevent propagation of the reaction.

Reaction propagation is a function of ferrocyanide concentration, as depicted in a three component diagram (Fig. E.17), which show areas where reaction may propagate and areas where reaction will not propagate owing to dilution. Pure dry reactants can support a propagating reaction. Vertical scans of the tanks studied show that ¹³⁷Cs is distributed over the entire sludge layer, with peak-to-mean ratio as high as three. Because a study of ¹³⁷Cs and ferrocyanide distributions showed that, at most, ferrocyanide would be concentrated no more than cesium, these vertical scans indicate that ferrocyanides are not concentrated in a thin band. Figure E.18 shows that the actual tank sludge compositions (of the ferrocyanide watch-list tanks) fall in the nonreactive area of the three-component diagram.

Any reactions that drive off water will cause compositions to move toward a more reactive component. Significant dryout could occur only by water evaporation into dry air flowing through the tank dome space. Steady-state analysis, along with the safe operating history, demonstrates that heat generated can be safely dissipated. However, the waste temperatures are required to be monitored to allow unexpected rises to be detected and mitigating actions to be taken, if required.

2.3. Applicability to Tank 241-SY-101

Tank 241-SY-101 does not contain appreciable amounts of ferrocyanide precipitates and has not been placed on the ferrocyanide watch list. Thus, exothermic reactions or explosions as a result of ferrocyanide reactions are not a concern for Tank 241-SY-101.

Note: Weight % Basis

NOTE: NO₂ PRODUCTION IS
ENDOTHERMIC

Westinghouse
Hamilton Company

39103114.1

Fig. E.17.

Ferrocyanide Tank 3 component diagram—reaction propagation vs concentration.

Note: Weight % Basis

Westinghouse
Hartford Company

39103114.2

Fig. E.18.
Ferrocyanide Tank 3 component diagram—actual tank sludge compositions.

3.0. ORGANIC-NITRATE REACTIONS

The presence of organic nitrates in the waste tanks is a potential concern because these compounds can support exothermic reactions. However, because the ignition temperature of these reactions can be as low as 180°C, these reactions are likely to occur before ferrocyanide reactions.

3.1. Background

Eight SS tanks may contain unacceptable concentrations of organic chemicals; e.g., more than 10 dry weight percent sodium acetate equivalent. The concentrations of organic materials in these SS tanks and their chemical identity are not known accurately at the present time.³⁰⁻³¹ However, very concentrated organic compounds could support an exothermic reaction at temperatures greater than 180°C (356°F).

For a scenario involving significant overheating of wastes to temperatures greater than 180°C (356°F), it can be postulated that a mixture of organic- nitrate/ nitrite solids might rapidly react, possibly overprocessing the tank and leading to releases of radioactive materials into the environment. Such an event is believed to have a very low probability of occurrence because the margin between minimum ignition temperature and measured tank temperatures is very large.

3.2. Issue Related Phenomenological Findings

Results obtained for Tank 241-SY-101 samples using DSC methods indicate that an exponential exothermic reaction rate is appropriate for reactions that could occur in this tank. This conclusion is based on the analysis discussed in the subsections that follow. Once organic nitrates achieve this reaction rate, the tank temperatures are expected to monotonically increase until a tank failure or a burn occurs.

The analysis discussed below also indicates that the ignition of this exothermic reaction can only occur after the endothermic process involving depletion (or evaporation) of bound and interstitial water. Therefore, as long as adequate moisture content is maintained in the tank wastes, ignition temperatures for these reactions are not expected to be attained.

3.2.1. Tank Heatup Analysis. The tank heatup analysis discussed here is applicable to both SS and DS tanks. The sources of heat available for tank heatup are as follows:

1. heat from radioactive decay, and
2. chemical reactions.

Heat can be removed from the tank by the following mechanisms:

1. conduction to the tank and ground,
2. evaporation of water,
3. convection to vented air space, and
4. radiation to the surroundings.

Before developing the overall tank heatup model, the elements of the model for the tank geometry shown in the above figure have to be developed. Sections E.3.2.2 through E.3.2.5 deal with various elements of the model.

3.2.2. Material Properties. The material properties assumed in this analysis are as follows:

$$\text{Density} = 1.7 \text{ g/cm}^3 .$$

Constituent	Weight Fraction
H ₂ O	40%
Na	20%
NO ₃	10–12%
NO ₂	10–13%
TOC	1.3%
¹³⁷ Cs	500 Ci/g
Heat Content	65–130 cal/g

The thermal conductivities of various materials (Ref. 32, pp. 3-214–3-221) are as follows:

Material	Thermal Conductivity (Btu/h/ft/°F)	
	Ref. 32	Ref. 33
H ₂ O	—	0.363
NaCl	—	0.33
Concrete	0.54	0.54
Soil	0.3	0.21–0.71
Sludge	1.0–3.0	—
Steel	25.9	25.9

3.2.3. Decay/Thermal Heat Load. The heat loads quoted for the tanks are in a range of less than 10,000 to 150,000 Btu/h. It is useful to convert these heat loads into heat loads per unit sludge mass (Btu/lbm/h). For example, Tank 106-C is quoted with a heat load of 150,000 Btu/h (Ref. 34, p. 16). The volume of the sludge in the tank is 197,000 gal., and the density of the tank sludge is 1.71 g/cm³. Thus, the heat generation rate per volume is 1.4×10^{-5} cal/cm³/s, and the corresponding heat generation rate per sludge mass is 8.2×10^{-6} cal/g/s.

3.2.4. Heat Load from Exothermic Chemical Reactions. The modeling of heat load from exothermic chemical reactions is discussed in this section. DSC test results were used to capture the nature of exothermic reactions and to model the exponential growth of exothermic heat generation once the ignition point was reached. Based on the DSC test results, it was assumed that the reaction is 1.0% complete at 200°C and 100% complete at 250°C. Thus, in accordance with the figure below,

$$Ae^{-\frac{B}{T}} = 0.01 \text{ @ } T = 200^\circ\text{C} , \text{and}$$

$$Ae^{-\frac{B}{T}} = 1.0 \text{ @ } T = 250^\circ\text{C} .$$

Solving for the constants A and B in these equations yields $A = 1.0 \times 10^8$ and $B = 4600$.

It is also known from the DSC experiments that the total heat generated is given by

$$\int_{204}^{416} Ae^{-\frac{B}{T}} dT = 0.128 . \quad (E.3)$$

The following information is from the DSC test results shown in Fig. E.19:

Total measured exothermic heat = 95.39 cal/g,
 Measured temperature change (416–204) = 212°C,
 DSC sample heating rate = 10°C per min, and
 Time corresponding to 212°C temperature rise = 1272 s.

$$\dot{Q}_C = 1.28 \times 10^7 e^{-\frac{4,600}{T}} \frac{\text{cal}}{\text{cm}^3 \text{s}} . \quad (E.4)$$

Fig. E.19.
 Differential scanning calorimetry of typical core segment.

Thus, the heat release rate can be calculated to be 0.075 cal/g/s, or in terms of per unit volume, 0.128 cal/cm³/s. Therefore,

$$Q_C = 0.128 A e^{-\frac{B}{T}} . \quad (E.5)$$

The following table shows the results of DSC/thermal gravimetric analysis (TGA) analysis of various samples. This table was prepared to determine a correlation between the ignition temperature predicted by the test and the sample size.

Sample/Analysis Method	Weight of Sample (mg)	Ignition Temperature (°C)	Radius of Sample (cm)
Jar 434 (TGA)	7.0	210	0.1
Jar 1058 (TGA)	5.7	258	0.093
Jar 664 (TGA)	8.8	207	0.107
Jar 434 (DSC)	6.4	206	0.096
Jar 1058 (DSC)	4.0	253	0.08256
Jar 664 (DSC)	9.2	205	0.1085

Although the range on the size of the sample selected is small, it is seen that as the sample radius increases, the ignition temperature decreases. This behavior indicates that the Thermal/Chemical Explosion Theory is likely to be applicable for predicting the behavior of this reaction. The Nature of Runaways, or the Thermal Explosion Theory, is explained briefly as follows:

The heat released during a runaway exothermic reaction is dependent on temperature. This temperature dependence is modeled as follows:

$$Q = Q_0^1 e^{E/RT} = Q_0 e^{\alpha(T-T_0)} . \quad (E.6)$$

In the above equation, E is the activation energy, R is the gas constant, and T is the temperature. If the only source of heat removal is conduction, the energy released can be equated to the heat removed by conduction.

Solving the steady-state, heat-transfer equation for conduction in a one-dimensional slab geometry, the following expression is obtained:

$$\frac{K}{\ell^2} \frac{d^2(T\alpha)}{d\left(\frac{x^2}{\ell^2}\right)} = -\alpha Q_0 e^{\alpha(T-T_0)} , \quad (E.7)$$

where

ℓ is the slab length,
 x is any position along the slab length, and
 α is thermal diffusivity.

Substituting the following nondimensional forms

$$\tau = \alpha(T - T_0), \quad \xi = \frac{x}{\ell},$$

and

$$\lambda = \frac{Q_0 \alpha \ell^2}{K}$$

yields the following expression:

$$\frac{d^2 \tau}{d\xi^2} + \lambda e^\tau = 0 . \quad (E.8)$$

Using the symmetry boundary condition

$$\frac{d\tau}{d\xi} = 0 @ \xi = 1 \geq \tau_0 = \alpha(T_{\max} - T_0) ,$$

the following expression is obtained:

$$e^{-\frac{1}{2}\tau_0} \cosh^{-1} \left(e^{\frac{1}{2}\tau_0} \right) = \sqrt{\frac{1}{2}\lambda} . \quad (E.9)$$

This result can be plotted to obtain critical values. If this analysis is performed for a cylindrical geometry, we obtain

$$\lambda_{CR} = 2.00$$

and

$$\tau_{0CR} = 1.36 .$$

A comparison of DSC experiments with the Thermal Explosion Theory can be performed as follows. As noted earlier, the following equation represents the heat released from a chemical reaction:

$$Q'_0 e\left(-\frac{E}{RT}\right) . \quad (E.10)$$

Using the Taylor series, this can be written as

$$Q'_0 e^{-\frac{E}{RT_0}} e^{\alpha(T-T_0)} ,$$

where

$$-\frac{E}{RT} = -\frac{E}{RT_0} = -\frac{E}{RT_0^2} (T - T_0) = -\frac{E}{RT_0} + \alpha(T - T_0) .$$

Combining the first two terms in the heat released equation,

$$Q = Q_0 e^{\alpha(T-T_0)} .$$

Solving for cylindrical geometry will yield

$$\lambda_{CR} = \frac{Q_0 \alpha \ell^2}{K} = 2.0 ,$$

where ℓ is cylinder length. This also can be expressed as

$$\lambda_{CR} = \frac{Q'_0 E \ell^2 e\left(-\frac{E}{RT}\right)}{RT_0^2 k} = 2.0 . \quad (E.11)$$

The following table uses the previous equation to predict values of Q_0 . In this prediction, E/R , one of the kinetics parameters, is assumed to be 4000. The purpose of this exercise is to see if the chemical explosion model is able to predict the second parameter Q_0 , as found in the earlier analysis.

Sample/Analysis Method	Ignition Temperature (°C)	Radius of Sample (cm)	Predicted Q_0 (with $E/R = 4600$)
Jar 434 (TGA)	210	0.1	4.46E+7
Jar 1058 (TGA)	258	0.093	1.08E+6
Jar 664 (TGA)	207	0.107	5.28E+7
Jar 434 (DSC)	206	0.096	7.27E+7
Jar 1058 (DSC)	253	0.08256	1.91E+6
Jar 664 (DSC)	204	0.1085	7.01E+7

The range of predicted Q_0 values implies that the chemical heat generation can be modeled by

$$\dot{Q}_C = 1.08 \times 10^6 e\left(-\frac{4,600}{T}\right) \leftrightarrow 7.27 \times 10^7 e\left(-\frac{4,600}{T}\right) \frac{\text{cal}}{\text{cm}^3 \text{s}} .$$

The chemical heat-generation rate obtained earlier (shown below) falls within this range:

$$\dot{Q}_C = 1.28 \times 10^7 e\left(-\frac{4,600}{T}\right) \frac{\text{cal}}{\text{cm}^3 \text{s}} . \quad (E.12)$$

This exercise implies that the chemical heat-generation rate obtained in this manner is acceptable.

3.2.5. Heat Removal by Evaporation. The dominant mode of heat removal from the sludge is through evaporation of the free and unbound water that is

present in the sludge. Evaporation of water provides a cooling effect to the sludge by removal of the latent heat of water.

An estimate of the heat removal rate by water evaporation can be evaluated by considering Tank 106-C, which is known to consume water. Water is periodically added to the tank to maintain proper temperature levels. Tank 106-C consumes 12,000 gal. of water per month. This consumption rate corresponds to $61,800 \text{ cm}^3/\text{s}$. The latent heat of evaporation of water is 9729 cal/g-mole or 540.5 cal/g . The total heat removed, given by $m\tau$ (m = mass and τ = latent heat), amounts to $334,029 \text{ cal/s}$. The sludge volume, V , in Tank 106-C is 197,000 gal., or $7.45 \times 10^8 \text{ cm}^3$. Thus, the heat removal rate given by $Q_{E(\text{total})}/V$ is $4.5 \times 10^{-4} \text{ cal/cm}^3\text{-s}$.

The evaporation rate as a function of the local temperature is of interest. It is clear that evaporation does not equate to boiling and does not occur only at 100°C . As indicated below, evaporation is a function of a number of different parameters.

Evaporation rate = f (dry bulb temperature, wet bulb temperature, humidity, air flow rate, surface area, etc.)

As a simplistic approximation, evaporation rate can be defined as

$$\text{Evaporation rate} = A \times (T_{\text{db}} - T_{\text{ref}}) ,$$

where

T_{db} = dry bulb temperature,

T_{ref} = reference temperatures, and

A = f (all other parameters).

The heat removal rate is therefore given by

$$\lambda \times A \times (T_{\text{db}} - T_{\text{ref}}) ,$$

which can also be written for a reference temperature of 20° , as

$$B \times (T_{\text{db}} - 20) ,$$

where B is substituted for the product $\lambda \times A$. The heat removal rate for Tank 106-C is given by

$$Q_E = 4.5 \times 10^{-4} \text{ cal/cm}^3\text{-s} .$$

B can be determined using this result, and therefore a generic heat removal rate can be established as

$$Q_E = 5.6 \times 10^{-6} (T_{db} - 20) \text{ cal/cm}^3\text{-s} .$$

3.2.6. One-Dimensional (Horizontal) Transient Tank Heatup Model. The heat balance equation is given by

Heat Accumulated = Heat Generated – Heat Removed, or mathematical format as:

$$\rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + Q_R + Q_C - Q_E , \quad (E.13)$$

where

- T = temperature,
- ρ = density,
- t = time,
- C_p = specific heat,
- x = distance,
- K = thermal conductivity,
- Q_R = decay heat,
- Q_C = heat of chemical reaction, and
- Q_E = evaporation heat.

One boundary condition for the one-dimensional model schematic shown below is given by

$$@ x = 0, \frac{\partial T}{\partial x} = 0 .$$

This boundary condition, in conjunction with internal heat generation, indicates that the temperature profile will go through a maximum temperature within the layer of interest. (It should be noted that this analysis would be more mathematically rigorous if a cylindrical geometry were used.)

The next boundary condition reflects the quasi-steady state at the concrete wall.

$$\frac{q}{A} = \frac{K_{\text{sludge}}}{\Delta X} (T_n - T_{n+1}) = \frac{K_{\text{conc}}}{\Delta X_{\text{conc}}} (T_{n+1} - T_B) ,$$

where

- T_B is the boundary temperature,
- T_n is the temperature at the n grid node point,
- T_{n+1} is the temperature at the $n+1$ grid node point,
- K_{sludge} is the sludge thermal conductivity,
- K_{conc} is the concrete thermal conductivity, and
- ΔX is the horizontal distance between two node points.

This boundary condition implies

$$T_{n+1} = \frac{CT_n + T_B}{(1 + C)} ,$$

where

$$C = \frac{K_{\text{sludge}}}{K_{\text{conc}}} \frac{\Delta X_{\text{conc}}}{\Delta X} .$$

Based on Secs. E.3.2.1 through E.3.2.5 and the model presented in this subsection, a computer model was developed in GWBASIC. This model was used to make a number of runs to predict the behavior of the tank under various conditions. The goal of these runs was to identify conditions under which tank heatup would increase and pose a threat to the tank integrity. A summary of the various runs is presented in Table E-10.

It can be seen from Table E-10 that, under most conditions, the tank would maintain safe temperature levels. However, under conditions of complete dryout (implied by a loss of heat removal by evaporation), the tank can slowly heat up and can enter runaway, exothermic reactions. Figures E.20 and E.21 depict the results of the computations corresponding to runs #19 and #20. These figures show temperature profiles for four consecutive years after complete dryout.

3.2.7. Results of the One-Dimensional Horizontal Transient Model. The significant findings of the one-dimensional, transient, horizontal heat-transfer analysis are discussed in this section.

Some configurations (complete dryout, which corresponds to runs #19 and #20) can lead to runaway/explosive situations after a long time (4 yr or more after dryout). First, the temperature rise measured in the sludge during this condition could be small (almost undetectable on a month-to-month basis). Second, this temperature increase occurs after residual water dryout. Thus, the temperature increase may not manifest until a complete or localized dryout has occurred. Finally, because the thermal conductivity of the sludge is poor, the tank center line temperature could be much higher than that measured near the wall. This fact may be significant because temperature measurements for most tanks are not performed at (or near) the center line.

It is possible that a number of tanks presently could be in the dryout phase, especially if lost water is not being replenished. This condition may not be known because not all tanks are being monitored for temperature rises. Additionally, the contents of some tanks are planned to be processed through evaporators to remove water. This process will deplete the water content of the sludge, making it more prone to dryouts and subsequent runaways.

3.2.8. One-Dimensional (Vertical), Steady-State Model. This section discusses the extension of the heatup analysis to evaluate the effects of conduction in the vertical direction. In the vertical direction, the tank contents are exposed to an air space that breathes into the atmosphere through a ventilation system. The tank

TABLE E-10
SUMMARY OF COMPUTER RUNS FOR HORIZONTAL MODEL

Run #	T _{in} °C	T _B °C	T _{ref} °C	Ksludge cal/ (s cm °C)	Q _R cal/ (g/s)	Q _{CO} cal/ (cm ³ /s)	Q _E cal/ (cm ³ /s)	Den g/cm ³	Max Temp °C	Run Time (Days)	Remark
1	40	20	40	0.0015	8.2E-6	1.28E+7	5.6E-6	1.71	42	125	SS
2	70	20	40	0.0015	x 10	1.28E+7	5.6E-6	1.71	65	125	SS
3	95	20	40	0.0015	x 10	1.28E+7	5.6E-6	1.71	65	125	SS
4	40	20	40	x 100	x 10	1.28E+7	5.6E-6	1.71	65	125	SS
5	40	20	40	0.0015	8.25E-6	1.28E+7	5.6E-6	1.71	42	125	SS
6	40	20	40	0.0015	x 1/10	1.28E+7	5.6E-6	1.71	40	125	SS
7	40	20	40	0.0015	x 100	1.28E+7	5.6E-6	1.71	**	4	Exp
8	40	20	40	0.0015	x 50	1.28E+7	5.6E-6	1.71	**	32	Exp
9	40	20	40	0.0015	x 30	1.28E+7	5.6E-6	1.71	115	125	SS
10	40	20	40	0.0015	x 20	1.28E+7	5.6E-6	1.71	90	125	SS
11	95	20	40	0.0015	x 20	1.28E+7	5.6E-6	1.71	90	125	SS
12	40	20	40	0.0015	x 10	1.28E+7	x 0.0	1.71	**	20	Exp
13	40	20	40	0.0015	x 10	1.28E+7	x 1/2	1.71	90	250	SS
14	95	20	40	0.0015	x 10	1.28E+7	x 1/2	1.71	90	250	SS
15	40	20	40	0.0015	x 10	1.28E+7	x 1/10	1.71	**	28	Exp
16	40	20	40	0.0015	8.2E-6	1.28E+7	x 1/10	1.71	64	125	SS
17	40	20	40	0.0015	8.2E-6	1.28E+7	x 0.0	1.71	**	177	Exp
18	40	20	40	0.0015	8.2E-6	1.28E+7	x 1/100	1.71	**	235	Exp
19	40	20	40	0.0015	x 1/10	1.28E+7	x 0.0	1.71	57	250	UK
20	95	20	40	0.0015	x 1/10	1.28E+7	x 0.0	1.71	113	250	UK

SS = Steady-state source term
Exp = Exponential source term

UK = Not certain if steady state reached
T_B = Tank boundary temperature

T_{in} = Initial temperature profile value
T_{ref} = Reference temperature

Fig. E.20.
Run No. 19 transient model results.

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Fig. E.21.
Run No. 20 transient model results.

sludge itself is nonuniform, with a convective sludge layer or supernatant and a nonconvective sludge layer. At the bottom, the tank sludge conducts heat to the ground through the tank shell and concrete.

In general, the one-dimensional, heat-transfer equation for this case can be written as:

$$T = \frac{-Q_R X^2}{2K} + C_1 X + C_2 ,$$

where X is vertical distance. The various elements of the tank can be depicted as shown in the following figure.

Analysis of the one-dimensional transient models of Sec. E.3.2.6 provides a number of insights into the heatup process that could be advantageously applied to the vertical conduction model. For example, transient heatup rates were very small. Thus, a steady-state analysis would suffice to predict if a stable steady state and safe state were possible.

Evaporation of water is the dominant heat removal mechanism, and as long as water is available for evaporation, temperatures are well within the safe zone. Therefore, only cases without water (dry cases) need to be evaluated to see if the heat transfer in the vertical direction is able to maintain safe levels for the dry cases.

Chemical reactions will be important only after a long transient heatup. Transient analysis in Sec. E.3.2.6 showed that runaway chemical-reaction-induced exothermic reactions are inevitable if the heatup is able to bring temperatures to 200°C. Thus, the present vertical tank heatup model evaluated for this analysis is a steady-state model that does not include evaporation and chemical reactions. Application of the general heat-transfer equations identified above to the various vertical layers results in the following temperature profiles:

$$\begin{aligned} T_{\text{CRUST}} &= C_1X + C_2, \\ T_{\text{SLUDGE}} &= \frac{-Q_R X^2}{2K} + C_3X + C_4, \\ T_{\text{CONC}} &= C_5X + C_6, \text{ and} \\ T_{\text{SOIL}} &= C_7X + C_8. \end{aligned}$$

The boundary conditions for the heatup model are given below.

$$\begin{aligned} T_{\text{CRUST}} @ (X = 0) &= T_{\text{AIR}}, \\ K_{\text{CRUST}} \frac{dT}{dX} &= K_{\text{SLUDGE}} \frac{dT}{dX} @ (X = X_{\text{CR}}), \\ T_{\text{CRUST}} &= T_{\text{SLUDGE}}, @ (X = X_{\text{CR}}), \\ K_{\text{SLUDGE}} \frac{dT}{dX} &= K_{\text{CONC}} \frac{dT}{dX}, @ (X = X_{\text{SL}}), \\ T_{\text{SLUDGE}} &= T_{\text{CONC}}, @ (X = X_{\text{SL}}), \\ K_{\text{CONC}} \frac{dT}{dX} &= K_{\text{SOIL}} \frac{dT}{dX}, @ (X = X_{\text{SO}}), \\ T_{\text{CONC}} &= T_{\text{SOIL}}, @ (X = X_{\text{SO}}), \text{ and} \\ T_{\text{SOIL}} &= T_{\infty}, @ (X = 2\sqrt{\alpha t}). \end{aligned}$$

Based on the model presented in this subsection, a computer model was developed in GWBASIC. This model was used to make a number of runs to predict the behavior of the tank under various conditions. The goal of these runs was to

identify conditions under which tank heatup would increase and pose a threat to the tank integrity. A summary of the various runs is presented in Table E-11.

Although water evaporation was not modeled, the presence of water was parametrically introduced into the model by artificially increasing the thermal conductivity of the sludge layer. The convection within the supernatant was also handled by increased conductivity.

The results from the steady-state analysis (shown in Figs. E.22 and E.23) indicate that as long as there is moisture in the sludge, the tank temperatures will be in the safe zone. If the sludge layer dries out and has the normal reduced thermal conductivity, the maximum temperatures are just below 200°C (see Fig. E.22). The safety level of this temperature profile is minimal because chemical reactions are expected to start just over 200°C. If the supernatant also loses moisture and stops convecting, the temperatures go beyond the safe margins.

The depth of the supernatant layer is found to be an important parameter. If the depth of the supernatant is dropped, as shown in Fig. E.23, the temperatures are within the marginally safe zone, even for the case of loss of moisture for both the supernatant and the sludge.

TABLE E-11
SUMMARY OF RUNS FOR STEADY-STATE MODEL

Run #	Tair °C	Tsoil °C	Kcr cal/s/cm/°C	ΔX_{cr} cm	Ksl cal/s/cm/°C	ΔX_{sl} cm	Kco cal/s/cm/°C	ΔX_{co} cm	Kso cal/s/cm/°C	ΔX_{so} cm	Max Temp. °C
1	30	20	0.0041	536	0.0041	508	0.0022	46	0.00124	200	383
2	30	20	0.0041	536	0.0041	508	0.0022	46	0.00124	50	259
3	30	20	0.0041	536	0.0041	508	0.0022	46	0.0124	200	224
4	30	20	0.0041	536	0.0041	508	0.022	46	0.0124	200	194
5	30	20	0.619	536	0.0041	508	0.0022	46	0.00124	200	182
6	30	20	6.19	536	0.0041	508	0.0022	46	0.00124	200	180
7	30	20	0.619	536	0.0124	508	0.0022	46	0.00124	200	96
8	30	20	0.0041	53.6	0.0041	50.8	0.0022	46	0.00124	200	36
9	30	20	0.0041	53.6	0.0041	508	0.0022	46	0.00124	200	206

Fig. E.22.
Effect of moisture in sludge/supernate layers.

Fig. E.23.
Effect of sludge/supernate bed depths for complete dryout cases.

Thus, the vertical steady-state model confirms the findings of the transient horizontal slab model. It further adds insight into the possibility of maintaining safe levels within the tank for dryout cases, provided that the supernatant remains convective or appropriate supernatant bed depth is maintained.

3.3. Applicability to Tank 241-SY-101

Tank 241-SY-101 does not contain appreciable amounts of organic nitrates and is not placed on the ferrocyanide watch list. However, exothermic organic-nitrate reactions are possible if complete dryout of the tank sludge occurs. Currently, Tank 241-SY-101 has sufficient amount of water content to preclude such exothermic reactions. If safe moisture levels are maintained in the tank, exothermic reactions (or explosions) involving organic nitrates do not appear to be a concern for Tank 241-SY-101.

4.0. CRITICALITY

Specific calculations were performed for Tank 241-SY-101 to determine if criticality (owing to concentration of plutonium in the bottom layers of the tank) is an issue of concern.

The criticality calculations were performed assuming an infinite configuration (zero leakage) of a plutonium-water solution as a function of plutonium concentration. The zero leakage assumption is conservative. All plutonium was assumed to be ^{239}Pu . The results of these calculations are shown in Fig. E.24, which plots k_{eff} (k_{∞} , in the case of an infinite configuration) as a function of the plutonium concentration normalized to the maximum measured value of 0.00165 g/gal. At the nominally measured plutonium concentration (concentration factor = 1), the k_{∞} was calculated to be 0.00012, an extremely small value. At 100 times the reference, the k_{∞} was still only 0.012. A concentration factor of 16,000 is required before the conservative, infinite configuration will become critical. It is believed that such concentrations cannot be achieved. Also, when the total plutonium inventory of 910 g and the presence of sludge are included in the analysis, criticality is not reached.

Based on these results, it can be concluded that Tank 241-SY-101 does not present a criticality hazard.

Fig. E.24.
Criticality analyses for Tank 101-SY.

5.0. WASTE FLAMMABILITY

5.1. Background

The presence of a dry crust with organic content raises the question of waste flammability. This question is especially important for a correct estimate of source terms for release scenarios. A sustained burn of the crust will volatilize or disperse a significant fraction of radionuclides.

5.2. Issue-Related Phenomenological Findings

DSC sampling and other sampling tests have shown that the exothermic combustion of the crust will be preceded by an endothermic phase. This endothermic phase is due to the evaporation of moisture (both free and bound moisture). A sample DSC curve is shown in Fig. E.25.

If the endothermic mechanisms exceed the exothermic heat generated on a per weight basis, then the net result will be endothermic, implying that a sustained combustion is not feasible. This is conservative in light of the fact that heat losses would also delete heat generated by exothermic reactions. On the other hand, if the exothermic heat generated exceeds the sum of endothermic mechanisms and heat losses, then a sustained burn is possible.

Using conservative estimates,

- exothermic heat of reaction = 95.39 cal/g,
- heat capacity = 1300 J/kg/K,
- ignition temperature = 500K, and
- latent heat of water = 540.5 cal/g,

and neglecting heat losses, a sustained combustion is not possible for less than 6.3% moisture content. However, if an external heat source is also available (in addition to the exothermic heat), then a burn is possible for a moisture content greater than 6.3%.

5.3. Analysis of Crust Sear from Hydrogen Burn in Tank 241-SY-101

The crust in Tank 241-SY-101 has a moisture content greater than 10%. Thus, a sustained burn is not expected. In addition, DSC calculations show that the endothermic heat of reaction exceeds the heat generated by exothermic combustion processes, thus ruling out sustained crust burn. In the event of a hydrogen burn following a burp, an external heat source would be available. Radiation heat from this burn will sear a thin layer of the exposed crust. The amount or mass of crust seared will depend on the temperature and duration of the hydrogen burn.

The heat balance equation for this searing is

$$\text{Sear Heat} = \text{Heat from Radiation} - \text{Heat Removed by Conduction in the Crust.}$$

Fig. E.25.
 Differential scanning calorimetry of typical core segment.

Heat of radiation received from the hydrogen burn is given by

$$\dot{q} = \sigma F_{G-C} \epsilon_G \tau_A \alpha_C (T_G^4 - T_C^4) ,$$

where

- $\dot{q}$ = heat flux,
- ϵ_G = emissivity of gas,
- τ_A = transmissivity of air,
- α_C = absorptivity of crust,
- T_G = temperature of gas,
- T_C = temperature of crust,
- σ = Stefan Boltzmann constant, and
- F_{G-C} = radiation shape factor from gas to crust.

Using conservative estimates, a 2-min hydrogen burn at 1500 K will sear more than 100 kg of crust. Assuming a 4000 ft³ release of hydrogen, this searing accounts for less than 1.5% of the potential energy that can be released by a complete H₂/N₂O combustion. The spreadsheet giving the details of this calculation is presented in Table E-12. The output distributions for the mass seared and the depth of searing are presented in Figs. E.26 and E.27. The input distributions for the analysis are presented in Figs. E.28 through E.37.

Using a more optimistic (or realistic) estimate, the temperature of the hydrogen will drop sharply as a function of time, as depicted in Fig. E.38, as a result of heat losses. This scenario is predicted to sear about 15 kg of crust. Assuming a 4000 ft³ release of hydrogen, this searing accounts for less than 0.2% of the potential energy that can be released by complete H₂/N₂O combustion. This decaying temperature profile calculation approximates a 1400 K temperature hydrogen burn for a duration of 5 s. The spreadsheet for this calculation is presented in Table E-13. The output distributions for the mass seared and the depth of searing are shown in Figs. E.39 and E.40. The input distributions for the analysis are shown in Figs. E.41 through E.48.

TABLE E-12
CONSERVATIVE CRUST BURN ESTIMATES

Crust Burn Analysis					
Properties		Dimensions		Assumptions	
Density (kg/m ³)	1400.4	tank diameter (m)	22.86	hydrogen burn time (min)	1.9
Heat Capacity (J/kg/K)	1300	crust height (m)	0.5	burn temp. (K)	1500.5
Thermal Conductivity (W/m/K)	0.2	crust width (m)	0.5	emmisivity of gases	0.4
Ignition Temp. (K)	500	free cylinder height (m)	2	transmitivity of air	1
Burn Completion Temp. (K)	700	crust diagonal (m)	0.7	emmisivity of crust	0.8
Moisture Content (wt %)	10	constants/calculations			
Initial Crust Temp. (°C)	30	Stefan Boltemann Constant (kcal/m ² /h/K ⁴)	4.9E-08		
Latent Heat of Water (cal/g)	540.5	area exposed crust (m ²)	50.7		
		radiation area (m ²)	1.4E+03		
Tank 101-SY Sample DSC		shape factor	0.035		
Endothermic Heat (cal/g)	127.5				
Exothermic Heat (cal/g)	-82.9				
Net Heat	44.6				
Results					
Radition Heat Flux to the Crust (kcal/m ² /h)	2834.7	heat flux conducted out of crust (kcal/m ² /h)	137.4	net heat flux input to the crust (kcal/m ² /h)	2697.3
Mass of Crust Seared (kg)	102.0				
Depth of Crust Searing (mm)	1.4				

Forecast: mass of crust seared (kg)

Statistics:	<u>Display Range</u>	<u>Entire Range</u>
Trials	3020	3070
Mean	115.81	120.88
Median	104.51	(unavailable)
Standard Deviation	65.46	77.48
Variance	4,285.48	6,002.62

Percentiles for Entire Range (kg):

<u>Percentile</u>	<u>mass of crust seared (kg)</u>
0%	0.00
5%	31.49
25%	67.21
50%	105.41
75%	154.83
95%	263.35
100%	1,136.75

End of Forecast

Fig. E.26.
Mass of crust seared (kg).

Forecast: depth of crust searing (mm)

Statistics:	<u>Display Range</u>	<u>Entire Range</u>
Trials	3036	3070
Mean	1.53	1.57
Median	1.43	(unavailable)
Standard Deviation	0.69	0.80
Variance	0.47	0.64

Percentiles for Entire Range (mm):

<u>Percentile</u>	<u>depth of crust searing (mm)</u>
0%	0.00
5%	0.61
25%	1.04
50%	1.44
75%	1.94
95%	2.99
100%	16.92

End of Forecast

Fig. E.27.
Depth of crust searing (mm).

Normal distribution with parameters:

Mean	1,400.00
Standard Dev.	50.00

Selected range is from -Infinity to +Infinity

Mean value in simulation was 1,400.38

Fig. E.28.

Conservative assumption: density (kg/m³).

Uniform distribution with parameters:

Minimum	115.25
Maximum	140.00

Selected range is from 115.25 to 140.00

Mean value in simulation was 127.53

Fig. E.29.

Conservative assumption: endothermic heat (cal/g).

Normal distribution with parameters:

Mean	0.50
Standard Dev.	0.17

Selected range is from -Infinity to +Infinity
Mean value in simulation was 0.50

Fig. E.30.
Conservative assumption: crust height (m).

Normal distribution with parameters:

Mean	0.50
Standard Dev.	0.17

Selected range is from -Infinity to +Infinity
Mean value in simulation was 0.50

Fig. E.31.
Conservative assumption: crust width (m).

Normal distribution with parameters:

Mean	0.80
Standard Dev.	0.08

Selected range is from 0.50 to 1.00

Mean value in simulation was 0.80

Fig. E.32.

Conservative assumption: emissivity of crust.

Normal distribution with parameters:

Mean	0.40
Standard Dev.	0.09

Selected range is from 0.10 to 0.60

Mean value in simulation was 0.40

Fig. E.33.

Conservative assumption: emissivity of gases.

Lognormal distribution with parameters:

Mean	2.00
Standard Dev.	0.90

Selected range is from 0.00 to 5.00

Mean value in simulation was 1.95

Fig. E.34.

Conservative assumption: hydrogen burn time (min).

Normal distribution with parameters:

Mean	1,500.00
Standard Dev.	35.00

Selected range is from 1,400.60 to 1,600.10

Mean value in simulation was 1,500.46

Fig. E.35.

Conservative assumption: burn temperature (K).

Uniform distribution with parameters:

Minimum	-95.39
Maximum	-70.00

Selected range is from -95.39 to -70.00

Mean value in simulation was -82.88

Fig. E.36.

Conservative assumption: exothermic heat (cal/g).

Lognormal distribution with parameters:

Mean	0.20
Standard Dev.	0.10

Selected range is from 0.00 to +Infinity

Mean value in simulation was 0.20

Fig. E.37.

Conservative assumption: thermal conductivity (W/m/K).

Fig. E.38.
Predicted temperature histories.

TABLE E-13
OPTIMISTIC (REALISTIC) CRUST BURN ESTIMATES

Crust Burn Analysis										
Time-Dependent Temperature Profile-Based Calculation										
Properties	Dimensions			Assumptions						
Density (kg/m ³)	1400.6	tank dia (m)	22.9	hydrogen burn time (s)	4.5	temp. (°C)	temp. (K)	time (s)	duration (s)	mass seared (kg)
Heat capacity (J/kg/K)	1300.0	crust height (m)	0.5	burn temp. (K)	1403.8	1200.0	1473.0	1.0	1.0	3.7
Thermal conductivity (W/m/K)	0.4	crust width (m)	0.2	emmisivity of gases	0.4	1100.0	1373.0	2.5	1.5	3.9
Ignition temp. (K)	500.0	free cylinder ht (m)	2.0	transmitivity of air	1.0	1000.0	1273.0	4.0	1.5	2.6
Burn completion temp. (K)	700.0	crust diagonal (m)	0.5	emmisivity of crust	0.8	900.0	1173.0	6.0	2.0	2.0
Moisture content (wt%)	10.0	constants/ calculations		volume of H ₂ burned (ft ³)	4000.0	800.0	1073.0	8.0	2.0	1.0
Initial crust temp. (°C)	30.0	Stefan Boltzmann constant (kcal/m ² /h/K ⁴)	4.9E-08	mass of H ₂ (kg)	10.7	700.0	973.0	11.0	3.0	0.2
Latent heat of water (cal/gm)	540.5	area exposed crust (m ²)	119.6	moles of H ₂ burned (gm-moles)	4432.0	600.0	873.0	16.0	5.0	0.0
		radiation area (m ²)	1410.1	heat of H ₂ -N ₂ O reaction (kcal/gm-moles)	77.4	500.0	773.0	22.0	6.0	0.0
101-SY sample DSC		shape factor	0.0	total heat released (kcal)	342903.8				22.0	13.4
Endothermic heat (cal/gm)	127.6									
Exothermic heat (cal/gm)	-82.7									
Net heat	45.0									
Results										
Radiation heat flux to the crust (kcal/m ² /h)	4950.0	heat flux conducted out of crust (kcal/m ² /h)	985.4	net heat flux input to the crust (kcal/m ² /h)	3964.6					
Mass of crust seared (kg)	13.4			radiation heat to crust (kcal)	732.4					
				fraction of H ₂ burn radiation heat to crust	0.0					
Depth of crust searing (mm)	0.0									

TABLE E-13 (CONT)

The DCH release category represents scenarios where a catastrophic tank failure due to BURP burn results in dome collapse leaving the tank open to environment.				
The key issues here are: (1) amount of material entrained by wind gusts during the exposure period, (2) amount of seared material released to atmosphere, and (3) amount of material entrained in the filters released to atmosphere.				
Parameter	Units	Value	Comment	
Amount stored in deentrainer and HEPA filters	kg of crust material	6.01	Reference 3	
Stored fraction released to atmosphere	None	0.90	Assumption	
Stored amount released to atmosphere	kg of crust material	5.41	Calculation	
Amount seared during BURP burn	kg of crust material	13.44	Assumption for realistic burn with temperature decay	
Burnt fraction released to atmosphere	None	0.80	Assumption	
Seared amount released to atmosphere	kg of crust material	10.76	Calculation	
Period the tank is exposed to wind following DCH	days	1.86	Assumption	
Exposure to wind gusts over 20 mph	sec/day	7.96	Assumption	
Radioactivity entrainment rate for winds over 20 mph	gm/sec	19.78	HMS analysis	
Amount entrained by wind gusts	kg of crust material	17.58	Calculation	
Amount released for DCH scenario	kg of crust material	33.75	Result	

Forecast: mass of crust seared for temp decay (Kg)

Statistics for Display Range:	Value
Trials	1986
Mean	13.44
Median (approx.)	12.29
Mode (approx.)	13.00
Standard Deviation	7.96
Variance	63.31

Percentiles for Display Range:

Percentile	Value (approx.)
0%	0.00
5%	2.60
25%	7.76
50%	12.29
75%	17.70
95%	28.29
100%	50.00

Fig. E.39.
Mass of crust seared for temperature decay.

Forecast: depth of crust searing (mm)

Statistics for Display Range:

	<u>Value</u>
Trials	1334
Mean	0.06
Median (approx.)	0.05
Mode (approx.)	0.04
Standard Deviation	0.04
Variance	0.00

Percentiles for Display Range:

<u>Percentile</u>	<u>mm (approx.)</u>
0%	0.00
5%	0.01
25%	0.03
50%	0.05
75%	0.08
95%	0.15
100%	0.25

Fig. E.40.
Depth of crust searing for temperature decay.

Normal distribution with parameters:

Mean	1,400.00
Standard Dev.	50.00

Selected range is from -Infinity to +Infinity

Mean value in simulation was 1,398.96

Fig. E.41.

Realistic assumption: density (kg/m³).

Uniform distribution with parameters:

Minimum	115.25
Maximum	140.00

Selected range is from 115.25 to 140.00

Mean value in simulation was 127.54

Fig. E.42.

Realistic assumption: endothermic heat (cal/g).

Assumption: crust height (m)

Normal distribution with parameters:

Mean 0.50

Standard Dev. 0.17

Selected range is from -Infinity to +Infinity

Mean value in simulation was 0.50

Fig. E.43.

Realistic assumption: crust height (m).

Assumption: crust width (m)

Normal distribution with parameters:

Mean 0.14

Standard Dev. 0.05

Selected range is from -Infinity to +Infinity

Mean value in simulation was 0.14

Fig. E.44.

Realistic assumption: crust width (m).

Normal distribution with parameters:

Mean	0.80
Standard Dev.	0.08

Selected range is from 0.50 to 1.00

Mean value in simulation was 0.80

Fig. E.45.

Realistic assumption: emmisivity of crust.

Normal distribution with parameters:

Mean	0.40
Standard Dev.	0.09

Selected range is from 0.10 to 0.60

Mean value in simulation was 0.39

Fig. E.46.

Realistic assumption: emmisivity of gases.

Uniform distribution with parameters:

Minimum	-95.39
Maximum	-70.00

Selected range is from -95.39 to -70.00

Mean value in simulation was -82.54

Fig. E.47.

Realistic assumption: exothermic heat (cal/g).

Normal distribution with parameters:

Mean	0.43
Standard Dev.	0.08

Selected range is from -Infinity to +Infinity

Mean value in simulation was 0.43

Fig. E.48.

Realistic assumption: thermal conductivity (W/m/K).

REFERENCES

1. G. F. Kinney and K. J. Graham, *Explosive Shocks in Air*, 2nd Edition, Springer Verlag, New York (1985).
2. "Structural Consequences of a Hydrogen Burn," Preliminary Draft, APP P-1 (June 1992).
3. S. A. Mirza and J. G. MacGregor, "Variability of Mechanical Properties of Reinforcing Bars," *Journal of the Structural Division*, ST5, ASCE (May 1979).
4. P. Park and T. Paulay, *Reinforced Concrete Structures*, John Wiley & Sons, New York (1975).
5. G. L. Fox et al., "Response of Tank 241-SY-101 to a Postulated Hydrogen Burn," Westinghouse Hanford Company report WHC-SD-WM-TI-426, Rev. 0 (May 1990).
6. M. P. Sherman et al., "FLAME Facility: The Effect of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale," prepared for US Nuclear Regulatory Commission, NUREG/CR-5275 (April 1989).
7. D. R. Stull, *Fundamentals of Fire and Explosion*, AIChE Monograph Series, Vol. 73, No. 10 (1977).
8. Industry Degraded Core Rule Making Program (IDCOR), "Hydrogen Combustion in Reactor Containment Buildings," EPRI-Electric Power Research Institute Technical Report 12.3 (September 1983).
9. D. C. Williams et al., "Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behavior; Analysis and Calculations with the CONTAIN Code," prepared for US Nuclear Regulatory Commission, NUREG/CR-4896 (May 1987).
10. A. Camp et al., "Light Water Reactor Hydrogen Manual," prepared for US Nuclear Regulatory Commission, NUREG/CR-2726 (August 1983).
11. B. Lewis and G. von Elbe, *Combustion, Flames and Explosions of Gases*, Academic Press Inc., New York, Third Edition (1987).
12. M. Hertzberg, "Flammability Limits and Pressure Development in H₂-Air Mixtures," Pittsburg Research Center Report No. 4305, presented at the Workshop on the Impact of Hydrogen on Water Reactor Safety, Albuquerque, New Mexico, January 25-28, 1981.

13. D. Liu et al., "Some Results of WNRE Experiments in Hydrogen Combustion," prepared for US Nuclear Regulatory Commission, NUREG/CR-2017 (September 1981).
14. Fauske & Associates, "Technical Support for the Hydrogen Control Requirement for the EPRI Advanced Light Water Requirements Document," prepared for US Department of Energy, DOE/ID-10290 (1990).
15. R. W. Johnson, "Ignition of Flammable Vapors by Human Electrostatic Discharges," *Loss Prevention*, Vol. 14, pp. 29-34 (1981).
16. J. C. Krok and J. E. Shepherd, "Electrical and Frictional Spark Ignition of N_2O - H_2 - N_2 - Air Mixtures," draft report prepared for Los Alamos National Laboratory by the Department of Mechanical Engineering, Rensselaer Polytechnic Institute (June 8, 1993).
17. R. Akbar and J. E. Shepherd, "Detonations in N_2O - H_2 - Air Mixtures," prepared for Los Alamos National Laboratory by the Department of Mechanical Engineering, Rensselaer Polytechnic Institute (June 18, 1993).
18. D. E. Simpson et al., "Flammable Gas Safety Issue Review Tank 241-SY-101," draft report prepared by Westinghouse Hanford Company for the U.S. Department of Energy, WHC-EP-0578 (September 1992).
19. J. A. Owczarek, *Fundamentals of Gas Dynamics*, International Textbook Company, Scranton, Pennsylvania (1964).
20. C. C. Scaief, "Hydrogen Ignition Capability of Tank Farm Instrumentation and Electrical Equipment," Westinghouse Hanford Company report WHC-SD-WM-ES-176, Rev. 0 (September 1992).
21. J. J. Gregory et al., "Evaluation of Severe Accident Risks: Sequoyah, Unit 1," NUREG/CR-4551, Vol. 5, Rev. 1, Part 2 (December 1990).
22. Powers, T. B., and S. D. Morales, "SY Tank Farm Ventilation Isolation Option Risk Assessment Report," Westinghouse Hanford Company draft report (June 1992).
23. K. L. Cashdolla et al., "Laboratory Flammability Studies of Mixtures of Hydrogen, Nitrous Oxide, and Air," prepared by Pittsburgh Research Center, Bureau of Mines, for Westinghouse Hanford Company report WHC-SD-WM-ES-219 (September 1992).
24. D. J. Wakefield and K. N. Fleming, "STADIC Computer Code User Manual," PLG, Inc., Proprietary, PLG-0689, Rev. O/PC (October 1990).

25. J. Travis, "Best Estimate Calculations," internal Los Alamos National Laboratory note to Don MacFarlane, August 30, 1992.
26. Los Alamos National Laboratory, "A Safety Assessment for Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-101-SY: Hanford Site, Richland, Washington," prepared for the US Department of Energy, Rev. 4 (September 2, 1992).
27. A. K. Postma, et al., "Current Understanding of the Safety of Storing High-Level Waste containing Ferrocyanide at the Hanford Site," Westinghouse Hanford Company report WHC-EP-0531 (Predecisional), prepared for US Department of Energy, Office of Environmental Restoration and Management (November 1991).
28. "Progress in Evaluating the Hazard of Ferrocyanide Waste Storage Tanks," Westinghouse Hanford Company report WHC-SA-1369-FP, prepared for US Department of Energy.
29. "Hanford Site Waste Tank Safety Program," presented to High Level Radioactive Waste Safety Program by Westinghouse Hanford Company/Pacific Northwest Laboratory, March 26-27, 1991.
30. Westinghouse Hanford Company, "High-Priority Hanford Site Radioactive Waste Storage Tank Issues: An Overview," WHC-SA-1539-FP, prepared for US Department of Energy, Office of Environmental Restoration and Waste Management (April 1992).
31. Westinghouse Hanford Company, "Summary of Singe-Shell Tank Waste Stability," WHC-EP-0347, prepared for US Department of Energy, Office of Environmental Restoration and Waste Management (May 1992).
32. E. D. Waters, G. K. Allen, and D. E. Place, "Analysis of Tank Bump Potential during In-Tank Washing Operations Proposed for the 241-AZ-Tanks," Westinghouse Hanford Company report WHC-SD-WM-ER-114, prepared for US Department of Energy, Richland Operations (June 1991).
33. R. H. Perry and C. H. Chilton, *Chemical Engineers Handbook*, 5th Edition, McGraw Hill, New York (1973).
34. B. M. Hamlon, "Tank Farm Surveillance and Waste Status Summary Report for December 1991," Westinghouse Hanford Company report WHC-EP-0182-45, prepared for the US Department of Energy, Office of Environmental Restoration and Waste Management (March 1992).

APPENDIX F

HUMAN RELIABILITY ANALYSIS

The risk from Tank 101-SY is dominated by the scenario that involves a bound hydrogen gas release and ignition. During normal operations, human actions do not significantly affect the frequency of gas release. Human actions may affect the probability of gas ignition following a gas release, however, both directly through causing an ignition source to occur or indirectly through failure to detect and correct an incipient failure that leads to a continuous ignition source. Direct human causes of ignition are unlikely during normal tank operations because of the nature of the operator surveillance and tight administrative control, including the "window" control currently in place on Tank 101-SY. The most significant source of direct human-caused ignition would be a second gas release unexpectedly following a smaller-than-normal initial gas release. The likelihood of such an event, however, is principally a phenomenological question. Currently this possibility is not quantified in the analysis. If a second release is shown to be important, a conservative assumption would be to estimate the fraction of window time and operations time that could lead to sparking and estimate the probability of the release occurring during this at-risk time. If significant mitigation operations are carried out on Tank 101-SY, there will be more opportunities for operator actions leading to sparking and even inducing gas releases.

Human factors also enter into the risk analysis through emergency response and to a much lesser extent through accident mitigation. There are few operator actions that significantly affect the course of the dominant Tank 101-SY accidents. Therefore, human reliability analysis has not played a major role in determining accident sequence frequency. No credit currently is taken for emergency response in the analysis, so no significant human factors analysis of emergency response was performed.

1.0. IDENTIFICATION OF IMPORTANT HUMAN ACTIONS

Human actions pervasively affect any engineered system. Human interaction with the system begins with design and continues through decommissioning. Human actions can initiate events, enable an accident precursor to develop into an accident-initiating event, arrest an accident progression, exacerbate or ameliorate accident conditions, and mitigate or enhance the consequences of an accident.

Because of the potential importance of human actions, we considered all aspects of the system in identifying human actions that could affect the HTF risk through development of a Master Logic Diagram (MLD). All observations were based on normal tank farm operations. When special operations are performed (such as Tank 101-SY mitigation tests), human factors may impact risk much more substantially than currently because the consequences of human error will be much higher. This is because of the increased likelihood of human error causing a tank breach or inducing a burp-gas release, while at the same time providing a spark source. However, such operations are outside the scope of this study.

2.0. HTF OBSERVATIONS

Human reliability does not directly impact Tank 101-SY onsite and offsite population risk in a significant manner; however, it does affect the amount of local contamination and personnel exposure experienced at the HTF. For this reason, we have included observations on human factors at the HTF collected during our visits and reading. This information may be valuable from the collateral viewpoint of safe operations and minimizing local contamination.

The observations in this section are based on two visits to the site in early 1992, interviews with numerous operators and managers, and an extensive review of the HTF Unusual Occurrence Reports (UORs) and related documents. We noted seven main areas of human factors concern at the site. These are discussed in detail below.

2.1. Safety Culture

The HTF does not have the ingrained safety culture that marks such notably safe technical endeavors as nuclear weapons production and handling, well-run nuclear power plants, and the commercial airline industry. Our impression was that many HTF operators had regarded the tanks as benign in the past, though this was not the universal viewpoint, and it seemed to be changing. The impetus for developing a safety culture must come from management, and such changes seemed to be occurring, although it will take several years to develop a mature safety attitude.

A few instances of deliberate recording of readings not actually taken has occurred in the past, according to the UORs. In addition, there have been several instances where out-of-specification readings were not investigated, sometimes for

long periods of time. Such incidents occur in the best of facilities, but their incidence seems higher at the HTF than at most facilities we have studied in the past.

2.2. Operator Selection, Training, and Experience Levels

We were very impressed with the selected operators interviewed at HTF. They were knowledgeable, and most demonstrated an appreciation of the importance of human action in determining system safety. However, we were informed that many of the operators were not as highly trained and motivated as the ones we interviewed. The HTF is addressing their personnel shortcomings through an improved selection process and through vastly improved training. The training documents that currently are being produced at HTF are excellent in our view, and their training program is becoming much more formalized and comprehensive. It will again take several years for the full impact of improvements in this area to be translated into increased safety at the HTF.

One glaring weakness in training was in emergency response. At the time of our visits, only one emergency response exercise had been carried out. This drill, which simulated a major contaminated aerosol release to the atmosphere, went poorly, with a worst-case error having been committed during personnel evacuation. All personnel were correctly ordered indoors but then were evacuated during the maximum passage of the contamination cloud. The HTF management is well aware of this shortcoming and seems to be trying to address emergency response through better procedures and further training.

Operator average experience level is likely to decline at the HTF over the next several years due to older operators retiring and to a reduced tempo of operations as many tanks are stabilized and isolated. Thus, transfer errors may actually be relatively more likely in the future because operator familiarity with the transfer system will suffer from lack of hands-on experience.

2.3. Procedures

Historically, written procedures at the HTF have been poor. In the past, no written procedures existed for many evolutions, and those that did exist were poorly maintained, and some contained known errors. Their use was spotty, probably as a result of both the lack of an HTF safety culture and the inadequacy of the procedure itself. New procedures are being written for many operations and maintenance.

2.4. Communications

Operational communications at HTF have been historically weak. Numerous UORs have resulted from a failure to communicate when equipment was taken out of service. Communications between the CASS operators and field operators have been informal and sometimes *ad hoc*. This has fostered a culture of assumption: each operator assumes the other operators involved in an evolution know what is going on; thus, they do not bother to insure that there is a formal transfer of information. Thus, CASS alarms are often cleared at CASS, and the field operator is never informed. In addition, shift-to-shift turnover communications appears to have been weak. Alarms sometimes are cleared and disabled for days until the original cause of the alarms is forgotten or never investigated.

2.5. Administrative Control

Numerous instances of a breakdown in administrative control are represented in the UOR database. Additional incidents were supplied by the operators and managers. Some of these incidents have potentially serious consequences. For example, failure to notify personnel through the proper channels has resulted in irradiation of construction workers during waste transfers. Failure to follow maintenance procedures and lack of a good tagging system has caused near-miss incidents with the ventilation systems that could have resulted in serious injury to maintenance personnel. Failure of supervisors to adequately check valve and jumper lineups has resulted in several mistransfers. Failure to restore lineups and changes in existing lineups have resulted in mistransfers and accidental discharge of liquids to cribs. The impression is that administrative controls are improving under the general increase of safety awareness that is occurring at the HTF, but it will take some time for this to trickle down to markedly increased safety of operations.

2.6. Equipment Physical Condition

The condition of equipment at the HTF significantly impacts the operator performance. Years of inadequate funding and attention have taken their toll on the equipment. Many instruments are inoperable, so the operators are sometimes "flying blind." Many valves are frozen or severely corroded and are operated by long reach-rods. This, coupled with poor design, makes valve position determination almost impossible. Several misroutings have been directly traced to this cause.

Some nozzles have been mis-marked in the past, setting the operator up for mis-transfers. This may be a problem of the past, but there is no way to guarantee that such is the case currently. Some important pieces of equipment, such as exhausters, are near the end of their useful life, and some remain inoperable for extended periods.

2.7. Contamination Levels

Extensive contamination of the area around many tanks requires the use of breathing apparatus and anticontamination suits for access. This greatly increases the difficulty of all operations and vastly increases the likelihood of errors of both omission and commission. An uncomfortable, burdened operator is much more likely to take shortcuts and violate safe practices than an unburdened operator. In addition, being in a radiation field increases the tendency to hurry so that personal exposure is minimized.

3.0. HUMAN ERROR ESTIMATES

The primary HRA factor needed to quantify the fault trees presented in Chap. 4.0 was an estimate of the Operator Failure to Prevent Tank Overflow (OP1 in Table 4-5). See Fig. F.1.

OP1: Failure to prevent tank overflow given level indicator/alarm is operable

Assume that this is not a diagnostic problem, there is a lot of time available (hours) , therefore it is a matter of whether the operators respond to the indications that are available (note problems in past with response) and whether the leak to the tank can be stopped.

A: CASS operator takes action in response to annunciator and indication of high tank level (action is to notify LOCAL operator)

THERP annunciator response model, Table 20-23, item #1 in Ref. 1, probability that operator fails to initiate action in response to alarm. $P(F)_1 = 1 \text{ E-}4$ EF = 10.

Use upper bound to account for past operational history and poor performance, thus, $HEP = 1 \text{ E-}4 \times 10 = 1 \text{ E-}3$.

$$\begin{aligned}\text{Failure (F)} &= ab + aBd + Ac + ACd \\ &= 1.3 \text{ E-2 per demand (EF = 10)}\end{aligned}$$

Summary of Event Probabilities

A/a	0.999/0.001	C/c	0.997/0.003
B/b	0.7/0.3	D/d	0.99/0.01

Fig. F.1. Event tree for operator failure to prevent overflow.*

B: LOCAL operator (242-A) responds to annunciators/indicator given 'a' (CASS fails to notify LOCAL)

Normal procedure is for LOCAL to respond at the request of the CASS staff, therefore, model the LOCAL as a checker, not the primary responder. Based on discussions with Hanford personnel, the level is not annunciated at the LOCAL station, only indicated.

Table 20-22, item #1 in Ref. 1, checking routine tasks, modify with a PSF of X3 due to past experiences and history, HEP = $0.1 \times 3 = 0.3$.

*Note: For the purposes of this HRA the events denoted with a capital letter [e.g. 'A'] are a success while the lower case letter [e.g. 'a'] denote failures.

- C: LOCAL operator follows oral instructions to check for abnormal tank conditions**
Table 20-8, item #6, footnote ++ in Ref. 1, indicates that the probability for failure to initiate the task when oral instructions are general = 0.001.

EF = 3, using upper bound the overall HEP = 3 E-3.

D: LOCAL operator terminates water intrusion event

This value is more related to the ability to isolate or stop the water intrusion and may be more affected by the configuration of the system which might prevent the operator from terminating the event. It is assumed that if the intrusion can be stopped by closing a valve, etc., that it will be with almost certainty. There may be some accident sequences where it is not physically possible to terminate the event. Assuming that the LOCAL operator will terminate the intrusion with a highly likely probability a value of 1 E-2 is taken for the HEP.

REFERENCES

1. A. D. Swain and H. E. Guttman, "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications," Sandia National Laboratories document NUREG/CR-1278 (August 1983).

APPENDIX G

DESCRIPTION OF WASTE MATERIALS

Since 1942, liquid and solid wastes from various processes used to separate plutonium from uranium and the fission products in spent metallic uranium fuel have accumulated at the Hanford Site. A significant portion of these wastes were pumped to large underground storage tanks that consist of a single steel inner shell surrounded by a concrete outer shell. In the early 1970s, a decision was made to transfer all liquid waste from these SS tanks to newer storage tanks that have double steel shells. Before transferring the wastes to the DS tanks, the wastes were concentrated using crystallizer-evaporators.

Although the contents of the 177 (149 SS and 28 DS) Hanford Site waste tanks can be estimated, contents from only a few of the tanks have been sampled and analyzed. Furthermore, generating an exact description of the chemical components of the 177 tanks is difficult for a number of reasons. First, over the years slurries from different processes were deposited and mixed in these tanks. Also, tank volumes were often reduced by separating the settled solids from the slurries from the pumpable liquid by a "cascading" process. At the end of the cascading process, vast volumes of "free liquid" judged to contain minimum amounts of toxic contents were pumped into the ground in areas called cribs. Since 1944, a total of about 440 billion gal. of liquid containing at total of about 680,000 Ci of radioactivity was disposed of in this manner.

Therefore, even if the exact composition of the individual tanks were known at the time of their initial deposition, the present contents of these tanks are mostly uncertain as a result of the post-fill operations (mixing, cascading, and draining). This uncertainty is further accentuated because about 300 different chemicals were added in sizable quantities to these tanks over the years to speed up the settling process. For an overview of the characteristics of all 177 tanks in the various tank farms, see Table G-1.

1.0. GENERAL NATURE OF THE WASTES

Four separate chemical processing operations were the generation source of radioactive waste streams deposited into the underground storage tanks at the Hanford Site.¹ These processes were:

**TABLE G-1
WASTE TANKS SUMMARY DATA**

Tank No.	Farm, Completed Date	Capacity and Type (gal.)	Type Waste	Watch List	Total Amt Leaked, Date (K gal.)	Current Liquid (Kgal.) Pump/Total	Current Solids (Kgal.) Slg. Scake	Current Total (Kgal.)	Radioactivity (Ci, ⁹⁰ Sr, ¹³⁷ Cs, TRU), 1980	Status (SS) or Use (DS)	Heat Rate (Btu/h)	Temp. (°F)	Farm Support Systems Priority
101	A, 1955	1 M, SS	DSSF	HYDG	S	391/413	3,950	953	4.0E+03	/PI		155	164
102		1 M, SS	DSSF		S	0/6	15, 22	41	1.2E+07	IS/PI			
103		1 M, SS	DSSF		5.5 K, 1987	0/17	366, 0	370	2.0E+06	IS/II			
104		1 M, SS	NCPLX	HIHT	2.5 K, 1975	0/0	28, 0	28	5.0E+03	IS/II	50,000	188	
105		1 M, SS	NCPLX	HIHT	277 K, 1963	0/4	19, 0	19	1.0E+06	IS/II	50,000	133	
106		1 M, SS	CP		S	0/7	125, 0	125	3.0E+03	IS/II			
101	AN, 1981	1.16 M, DS	DN		S	548/548	0, 0	548		DRCVR			202
102		1.16 M, DS	CC		S	1006/1009	89, 0	1095		CWHT			
103		1.16 M, DS	DSS	HYDG	S	15/15	937 (DSS)	952		CWHT, N		112	
104		1.16 M, DS	DSSF	HYDG	S	801/823	264, 0	1062		CWHT, N		116	
105		1.16 M, DS	DSSF	HYDG	S	1131/1131	0, 0	1131		CWHT, N		106	
106		1.16 M, DS	CP		S	1001/1001	17, 0	1018		CWHT			
107		1.16 M, DS	CC		S	944/953	134, 0	1078		CWHT			
101	AP, 1986	1.16 M, DS	DN		S	1063/1063	0, 0	1063		DRCVR			933
102		1.16 M, DS	DN		S	133/133	0, 0	133		GRTFD			
103		1.16 M, DS	DN		S	1135/1135	0, 0	1135		DRCVR			
104		1.16 M, DS	DN		S	21/21	0, 0	21		GRTFD			
105		1.16 M, DS	DSSF		S	826/826	0, 0	826		CWHT			
106		1.16 M, DS	DN		S	1134/1134	0, 0	1134		DRCVR			
107		1.16 M, DS	DN		S	1128/1128	0, 0	1128		DRCVR			
108		1.16 M, DS	DN		S	175/175	0, 0	175		DRCVR			
101	AW, 1980	1.16 M, DS	DSSF		S	1040/1042	84, 0	1124		CWHT			637
102		1.16 M, DS	DN		S	1026/1026	1, 0	1027		EVFD			
103		1.16 M, DS	DN/PD		S	300/322	363, 0	648	6.0E-03	DRCVR			
104		1.16 M, DS	DN		S	864/886	179, 111	1127		DRCVR			
105		1.16 M, DS	DN/PD		S	613/635	297, 0	903		DRCVR			
106		1.16 M, DS	DN		S	264/286	198, 85	529	7.0E+05	SRCVR			
101	AX, 1964	1 M, SS	DSSF	HYDG	S	298/320	3, 745	748	1.2E-03	/PI		141	171
102		1 M, SS	CC		3 K, 1988	3/17	7, 29	39	1.0E-02	IS/II			
103		1 M, SS	CC	HYDG	S	3/36	2, 110	112	2.0E+04	IS/II		118	
104		1 M, SS	NCPLX		8 K, 1977	0/0	7, 0	7	2.1E+07	IS/II			
101	AY, 1970	1 M, DS	DC		S	814/816	83, 0	896	1.2E +06	DRCVR			433
102		1 M, DS	DN		S	905/905	32, 0	937	2.0E+05	DRCVR			
101	AZ, 1977	1 M, DS	AGNG		S	947/947	35, 0	982	8.0E+05	CWHT			417
102		1 M, DS	AGNG		S	863/866	91, 0	954	1.0E+04	DRCVR			

TABLE G-1 (CONT.)

Tank No.	Farm, Completed Date	Capacity and Type (gal.)	Type Waste	Watch List	Total Amt Leaked, Date (K gal.)	Current Liquid (Kgal.) Pump/Total	Current Solids (Kgal.) Slg. Scake	Current Total (Kgal.)	Radioactivity (Ci, ⁹⁰ Sr, ¹³⁷ Cs, TRU), 1980	Status (SS) or Use (DS)	Heat Rate (Btu/h)	Temp. (°F)	Farm Support Systems Priority
201	B, 1944	55 K, SS	NCPLX		1.2 K, 1980	0/4	28, 0	113		IS/II			173
202		55 K, SS	NCPLX		S	0/3	27, 0	32	3.0E+02	IS/II			
203		55 K, SS	NCPLX		0.3 K, 1983	0/6	50, 0	59	3.0E+01	IS/II			
204		55 K, SS	NCPLX		0.4 K, 1984	0/6	49, 0	371	8.0E+03	IS/II			
101		530 K, SS	NCPLX		8 K, 1974	0/6	113, 0	306	2.0E+05	IS/II			
102		530 K, SS	NCPLX		S	0/4	18, 10	117	2.6E+04	IS/II			
103		530 K, SS	NCPLX	ORSLT	8 K, 1978	0/0	59, 0	165	3.1E+05	IS/II		68	
104		530 K, SS	NCPLX		S	25/47	301, 69	94	1.6E+04	IS/II			
105		530 K, SS	NCPLX		8 K, 1978	0/23	40, 266	127	9.1E+04	IS/II			
106		530 K, SS	NCPLX		S	0/7	116, 0	246	2.1E+03	IS/II			
107		530 K, SS	NCPLX		8 K, 1980	0/13	164, 0	237	7.5E+04	IS/II			
108		530 K, SS	NCPLX		S	0/4	94, 0	33	2.5E+05	IS/II			
109		530 K, SS	NCPLX		S	0/8	127, 0	29	2.7E+05	IS/II			
110		530 K, SS	NCPLX		10 K, 1981	17/23	245, 0	27	2.2E+03	IS/II			
111		530 K, SS	NCPLX		8 K, 1978	0/22	236, 0	51	2.0E+00	IS/II			
112		530 K, SS	NCPLX		2 K, 1978	0/3	30, 0	50	7.1E+05	IS/II			
101	BX, 1947	530 K, SS	NCPLX		8 K, 1972	0/1	42, 0	43	3.0E+05	IS/II			179
102		530 K, SS	NCPLX	FECN, 3K	70 K, 1971	0/4	96, 0	96	6.0E+05	IS/II	< 10,000	71	
103		530 K, SS	NCPLX		S	0/4	62, 0	66	6.4E+03	IS/II			
104		530 K, SS	NCPLX		S	27/33	96, 0	99	5.1E+05	IS/II			
105		530 K, SS	NCPLX		S	4/11	43, 3	51	4.0E+04	IS/II			
106		530 K, SS	NCPLX	FECN, 1K	S	15/15	31, 0	46	5.1E+05	/PI	< 10,000	69	
107		530 K, SS	NCPLX		S	23/30	344, 0	345	2.3E+05	IS/PI			
108		530 K, SS	NCPLX		2.5 K, 1974	0/1	26, 0	26	3.8E+04	IS/II			
109		530 K, SS	NCPLX		S	8/13	193, 0	193	3.0E+05	IS/PI			
110		530 K, SS	NCPLX	FECN, 1K	8 K, 1976	0/21	189, 9	199	1.0E+06	IS/PI	< 10,000	68	
111		530 K, SS	NCPLX	FECN, 1K	8K, 1984	47/69	68, 143	230	1.0E+06	/PI	< 10,000	73	
112		530 K, SS	NCPLX		S	2/8	164, 0	165	1.3E+04	IS/PI			
101	BY, 1949	758 K, SS	NCPLX	FECN, 1K	S	0/5	109, 178	387	1.6E+06	IS/II	8,200	74	183
102		758 K, SS	NCPLX		S	61/83	0, 341	341	4.0E+05	/PI			
103		758 K, SS	NCPLX	FECN, 1K	5 K, 1973	86/108	5, 395	400	2.0E+05	/PI	8,600	81	
104		758 K, SS	NCPLX	FECN, 200 K	S	0/18	40, 366	406	1.8E+06	IS/II	17,000	130	
105		758 K, SS	NCPLX	FECN, 100 K	8 K, 1984	172/194	44, 459	503	1.1E+06	/PI	37,700	114	
106		758 K, SS	NCPLX	FECN, 30K	8 K, 1984	213/235	95, 547	642	1.3E+06	/PI	12,200	131	
107		758 K, SS	NCPLX	FECN, 80K	15 K, 1984	0/25	60, 206	266	8.0E+05	IS/II	14,500	83	
108		758 K, SS	NCPLX	FECN, 70K	5 K, 1972	0/9	154, 74	228	6.0E+05	IS/II	23,000	101	
109		758 K, SS	NCPLX		S	89/111	83, 340	423	2.0E+05	/PI			

TABLE G-1 (CONT.)

Tank No.	Farm, Completed Date	Capacity and Type (gal.)	Type Waste	Watch List	Total Amt Leaked, Date (Kgal.)	Current Liquid (Kgal.) Pump/Total	Current Solids (Kgal.) Slg. Scape	Current Total (Kgal.)	Radioactivity (Ci, ⁹⁰ Sr, ¹³⁷ Cs, TRU), 1980	Status (SS) or Use (DS)	Heat Rate (Btu/h)	Temp. (°F)	Farm Support Systems Priority
110		758 K, SS	NCPLX	FECN, 90K	S	0/9	103, 295	398	1.2E+06	IS/II	25,200	124	
111		758 K, SS	NCPLX	FECN, 3K	S	0/0	21, 438	459	1.2E+06	IS/II	34,200	92	
112		758 K, SS	NCPLX	FECN, 3K	S	0/8	5, 286	291	5.2E+05	IS/II	< 10,000	85	
201	C, 1944	55 K, SS	NCPLX		0.6 K, 1988	0/0	2, 0	2	3.0E+04	IS/II			182
202		55 K, SS	EMPTY		0.5 K, 1988	0/0	1, 0	1	3.0E+03	IS/II			
203		55 K, SS	NCPLX		0.4 K, 1984	0/0	5, 0	5		IS/II			
204		55 K, SS	NCPLX		0.4 K, 1988	0/0	3, 0	3		IS/II			
101		530 K, SS	NCPLX		20 K, 1980	0/3	88, 0	88	3.0E+05	IS/II			
102		530 K, SS	NCPLX		S	42/48	424, 0	427	4.0E+06	/PI			
103		530 K, SS	NCPLX	ORSLT	S	133/133	62, 0	195	1.2E+05	/PI			
104		530 K, SS	CC		S	5/11	295, 0	295	1.0E+06	IS/II			
105		530 K, SS	NCPLX	HIHT	S	5/11	150, 0-	150	8.6E+06	/PI	42,000	99	
106		530 K, SS	NCPLX	HIHT	S	42/48	197, 0	229	5.0E+06	/PI	150,000	165	
107		530 K, SS	NCPLX		S	28/34	337, 0	337	4.2E+05	/PI			
108		530 K, SS	NCPLX	FECN, 20K	S	0/0	66, 0	66	1.6E+05	IS/II	< 10,000	78	
109		530 K, SS	NCPLX	FECN, 50K	S	0/4	62, 0	66	1.0E+04	IS/II	< 10,000	81	
110		530 K, SS	NCPLX		2 K, 1984	15/21	196, 0	201	6.0E+04	/PI			
111		530 K, SS	NCPLX	FECN, 30K	S	0/0	57, 0	57	1.1E+05	IS/II	< 10,000	78	
112		530 K, SS	NCPLX	FECN, 70K	S	26/32	104, 0	104	1.1E+05	IS/PI	< 10,000	85	
101	S, 1951	758 K, SS	NCPLX		S	74/96	244, 171	427	2.2E+06	/PI			164
102		758 K, SS	DSSF	HYDG, ORSLT	S	208/230	4, 595	549	2.0E+05	/PI		109	
103		758 K, SS	DSSF		S	80/102	10, 221	248	2.0E+01	/PI			
104		758 K, SS	NCLPX		24 K, 1968	23/29	293, 0	294	1.2E+06	IS/II			
105		758 K, SS	NCPLX		S	13/35	2, 454	456	3.0E+05	IS/II			
106		758 K, SS	NCPLX		S	93/115	32, 511	543	4.4E+04	/PI			
107		758 K, SS	NCPLX		S	29/51	293, 69	368	2.0E+06	/PI			
108		758 K, SS	NCPLX		S	81/103	4, 600	604	3.0E+06	/PI			
109		758 K, SS	NCPLX		S	102/124	13, 555	568	1.6E+06	/PI			
110		758 K, SS	NCPLX		S	38/60	131, 561	692	1.3E+06	/PI			
111		758 K, SS	NCPLX	HYDGN	S	180/202	139, 447	596	8.0E+06	/PI		93	
112		758 K, SS	NCPLX	HYDGN	S	122/144	6, 131	637	1.1E+06	/PI		90	
101	SX, 1954	1 M, SS	DC	HYDGN	S	124/146	112, 343	456	1.0E+02	/PI		140	155
102		1 M, SS	DSSF	HYDGN	S	161/183	117, 426	543	5.0E+05	/PI		155	
103		1 M, SS	NCLPX	HYDGN	S	223/243	115, 536	652	4.0E+05	/PI		180	
104		1 M, SS	DSSF	HYDGN	6 K, 1988	116/138	136, 478	614	1.0E+06	/PI		174	
105		1 M, SS	DSSF	HYDGN	S	239/261	73, 610	683	9.0E+05	/PI		186	

TABLE G-1 (CONT.)

Tank No.	Farm, Completed Date	Capacity and Type (gal.)	Type Waste	Watch List	Total Amt Leaked, Date (Kgal.)	Current Liquid (Kgal.) Pump/Total	Current Solids (Kgal.) Slg. Scale	Current Total (Kgal.)	Radioactivity (Ci, ⁹⁰ Sr, ¹³⁷ Cs, TRU), 1980	Status (SS) or Use (DS)	Heat Rate (Btu/h)	Temp. (°F)	Farm Support Systems Priority
106		1 M, SS	NCPLX	HYDGN, ORSLT	S	233/255	12,465	538	5.0E+06	/PI		107	
107		1 M, SS	NCPLX	HIHT	5 K, 1964	0/5	104,0	104	5.0E+06	IS/II	42,000	171	
108		1 M, SS	NCPLX	HIHT	2.4 K, 1962	0/6	115,0	115	4.0E+06	IS/II	45,000	191	
109		1 M, SS	NCPLX	HYDGN, HIHT	5 K, 1965	0/10	250,0	250	3.7E+06	IS/II	50,000	151	
110		1 M, SS	NCPLX	HIHT	5.5 K, 1976	0/0	62,0	62	7.0E+06	IS/II	42,000	178	
111		1 M, SS	NCPLX	HIHT	2 K, 1974	0/7	125,0	125	5.0E+06	IS/II	44,000	192	
112		1 M, SS	NCPLX	HIHT	30 K, 1969	0/3	92,0	92	2.0E+06	IS/II	43,000	161	
113		1 M, SS	NCPLX		15 K, 1962	0/0	26,0	26	1.3E+06	IS/II			
114		1 M, SS	NCPLX	HIHT	8 K, 1972	0/14	181,0	181	5.0E+06	IS/II	58,000	188	
115		1 M, SS	NCPLX		50 K, 1965	0/0	12,0	12	1.0E+06	IS/II			
101	SY, 1976	1.16 M, DS	CC	HYDGN	S	231/237	561(DSS), 0, 560	1121	2.8E+06	CWHT, N		131	177
102		1.16 M, DS	DN/PT		S	570/570	71,0	641	4.0E+06	DRCVR			
103		1.16 M, DS	CC	HYDGN	S	172/172	573(DSS), 0, 4	749	5.0E+06	CWHT, N		115	
201	T, 1944	55 K, SS	NCPLX		S	0/4	28,0	29		IS/II			150
202		55 K, SS	NCPLX		S	0/2	21,0	21		IS/II			
203		55 K, SS	NCPLX		S	0/4	35,0	35	4.0E+00	IS/II			
204		55 K, SS	NCPLX		S	0/4	38,0	38	5.0E-01	IS/II			
101		530 K, SS	NCPLX	FECN, 10K	S	30/35	103,0	133	3.2E+06	/PI	< 10,000	73	
102		530 K, SS	NCPLX		S	13/13	19,0	32	1.2E+05	IS/II			
103		530 K, SS	NCPLX		1 K, 1974	0/4	23,0	27	7.9E+04	IS/II			
104		530 K, SS	NCPLX		S	44/50	442,0	445	1.1E+05	/PI			
105		530 K, SS	NCPLX		S	17/23	98,0	98	5.4E+05	IS/II			
106		530 K, SS	NCPLX		115 K, 1973	0/2	19,0	21	2.2E+06	IS/II			
107		530 K, SS	NCPLX	FECN, 5K	8 K, 1974	16/22	171,0	180	2.1E+06	/PI	< 10,000	74	
108		530 K, SS	NCPLX		1 K, 1974	0/0	44,0	44	1.0E+04	IS/II			
109		530 K, SS	NCPLX		1 K, 1974	0/0	58,0	58	6.5E+03	IS/II			
110		530 K, SS	NCPLX	HYDGN	S	36/42	375,0	379	3.2E+04	/PI		69	
111		530 K, SS	NCPLX		1 K, 1984	45/51	456,0	458	1.0E+04	/PI			
112		530 K, SS	NCPLX		S	7/7	60,0	67	6.4E+02	IS/II			
101	TX, 1948	758 K, SS	NCPLX		S	0/5	84,0	87	7.2E+05	IS/II			172
102		758 K, SS	NCPLX		S	0/22	0,113	113	2.9E+06	IS/II			
103		758 K, SS	NCPLX		S	0/15	157,0	157	1.0E+05	IS/II			
104		758 K, SS	NCPLX	ORSLT	S	0/15	0,64	65	6.9E+05	IS/II			
105		758 K, SS	NCPLX		8 K, 1977	0/20	0,609	609	2.8E+06	IS/II		99	
106		758 K, SS	NCPLX		S	0/10	0,453	453	1.4E+06	IS/II			
107		758 K, SS	NCPLX		2.5 K, 1984	0/2	0,35	36	1.1E+06	IS/II			

TABLE G-1 (CONT.)

Tank No.	Farm, Completed Date	Capacity and Type (gal.)	Type Waste	Watch List	Total Amt Leaked, Date (K gal.)	Current Liquid Pump/Total (Kgal.)	Current Solids (Kgal.)	Current Total (Kgal.)	Radioactivity (Ci, ⁹⁰ Sr, ¹³⁷ Cs, TRU), 1980	Status (SS) or Use (DS)	Heat Rate (Btu/h)	Temp. (°F)	Farm Support Systems Priority
108		758 K, SS	NCPLX		S	0/0	0,134	134	7.0E+05	IS/II			
109		758 K, SS	NCPLX		S	0/10	0,384	384	4.0E+05	IS/II			
110		758 K, SS	NCLPX		8 K, 1977	0/15	0,462	462	1.0E+06	IS/II			
111		758 K, SS	NCPLX		S	0/9	0,370	370	2.5E+06	IS/II			
112		758 K, SS	NCPLX		S	0/24	0,649	649	2.7E+06	IS/II			
113		758 K, SS	NCPLX		8 K, 1974	0/16	0,607	607	2.1E+06	IS/II			
114		758 K, SS	NCPLX		8 K, 1974	0/15	0,535	535	3.0E+05	IS/II			
115		758 K, SS	NCPLX		8 K, 1977	0/19	0,640	640	2.3E+06	IS/II			
116		758 K, SS	NCPLX		8 K, 1977	0,23	0,631	631	5.6E+05	IS/II			
117		758 K, SS	NCPLX		8 K, 1977	0/8	0,626	626	3.5E+04	IS/II			
118		758 K, SS	NCPLX	FECN, 3K, ORSLT	S	0/27	0,347	347	1.4E+05	IS/II	4,900	74	
101	TY, 1952	758 K, SS	NCPLX	FECN, 30K	1 K, 1973	0/0	118, 0	118	5.1E+05	IS/II	< 10,000	68	162
102		758 K, SS	NCPLX		S	0/14	0,64	64	2.0E+05	IS/II			
103		758 K, SS	NCPLX	FECN, 30K	3 K, 1973	0/5	162, 0	162	8.0E+04	IS/II	< 10,000	70	
104		758 K, SS	NCPLX	FECN, 20K	1.4 K, 1981	0/15	43, 0	46	3.0E+03	IS/II	< 10,000	71	
105		758 K, SS	NCPLX		35 K, 1960	0/0	231, 0	231	1.8E+05	IS/II			
106		758 K, SS	NCPLX		20 K, 1959	0/0	17, 0	17	2.3E+03	IS/II			
201	U, 1944	55 K, SS	NCLPX		S	0/1	4, 0	5	3.0E+04	IS/II			174
202		55 K, SS	NCPLX		S	0/1	4, 0	5	3.0E+04	IS/II			
203		55 K, SS	NCPLX		S	0/1	2, 0	3	3.0E+04	IS/II			
204		55 K, SS	NCPLX		S	0/1	2, 0	3	9.0E+03	IS/II			
101		530 K, SS	NCPLX		30 K, 1959	0/3	22, 0	25	1.4E+06	IS/II			
102		530 K, SS	NCPLX		S	122/144	43, 313	374	6.0E+05	/PI			
103		530 K, SS	NCPLX	HYDGN	S	167/189	32, 423	468	1.0E+05	/PI			
104		530 K, SS	NCPLX		55 K, 1961	0/7	122, 0	122	4.0E+05	IS/II			
105		530 K, SS	NCPLX	HYDGN	S	157/179	32, 349	418	2.3E+04	/PI			
106		530 K, SS	NCPLX	ORSLT	S	61/83	26, 185	226	6.6E-02	/PI		85	
107		530 K, SS	DSSF	ORSLT	S	156/178	15, 360	406	1.0E+05	/PI		81	
108		530 K, SS	NCPLX	HYDGN	S	174/196	29, 415	468	2.0E+05	/PI			
109		530 K, SS	NCPLX	HYDGN	S	160/182	48, 396	463	2.0E+05	/PI			
110		530 K, SS	NCPLX		8 K, 1975	9/15	186, 0	186	9.0E+05	IS/PI			
111		530 K, SS	DSSF		S	100/122	26, 303	329	6.0E+05	/PI			
112		530 K, SS	NCPLX		8.5 K, 1980	0/4	45, 0	49	3.1E+05	IS/II			

TABLE G-1 (CONT.)

Abbreviations

DSSF = DS slurry feed

NCPLX = noncomplexed waste

CP = concentrated phosphate waste

DN = dilute noncomplexed waste

CC = complexant concentrate waste

DSS = DS slurry

PD = neutralized cladding removal waste

DC = dilute complexed waste

AGNG = aging waste (neutralized current acid waste)

PT = plutonium finishing plant TRU solids

HIHT = high heat load tank, > 40,000 Btu/h

HYDG = tank with potential for flammable gas accumulation, above LFL

ORSLT = tank with organic salt concentration > 10 wgt % TOC

FECN = tank containing > 1000 gm mol of ferrocyanide

S = sound tank, no history of leaks

CWHT = concentrated waste holding tank

DRCVR = dilute receiver tank

EVFD = evaporate feed tank

GRTFD = grout feed tank

SRCVR = slurry receiver tank

N = DS tank not currently involved in transfers

IS = interim stabilized, contains < 50K gal. of drainable liq. and < 5K gal. of supernatant liquid

PI = partially interim isolated

II = interim isolated

- the bismuth phosphate (BiPO_4) process,
- the tributyl phosphate (TBP) process,
- the REDOX process, and
- the PUREX process.

Three of these were chemical separations programs for recovering of plutonium from irradiated reactor fuels. The fourth process (TBP) was recovered uranium metal waste generated by the BiPO_4 process. For all process the aqueous wastes were made alkaline before being stored in the underground tanks. These chemical processes generated a number of waste streams that were stored in the underground storage tanks. A summary listing of these waste streams is as follows.

- Alkaline coating removal waste stream, containing small amounts of fission products, combined with first-cycle decontamination waste.
- Metal waste stream from the extraction unit.
- By-product cake solution and waste solution from the first decontamination waste cycle (1C), containing about 10% of the original fission activity and 1% of the plutonium.
- Second decontamination-cycle waste, containing less than 0.1% of the fission activity and about 1% of the plutonium.
- Waste generated as a result of decladding aluminum-clad fuels in a boiling solution of sodium nitrate by adding 50% caustic.
- Coating solution (generated when zircaloy-clad fuels were declad in a boiling ammonium nitrate-ammonium fluoride mixture) neutralized with 50% caustic.
- Organic wash waste (OWW).
- Neutralized PUREX Plant acid waste.
- Waste from two thorium campaigns.

The present state of the waste stored in tanks at the Hanford Site is categorized in Fig. G.1. In the solid waste category, sludge refers to the hydrous metal oxides, such as iron and manganese, that precipitated as a result of neutralization of acid wastes; salt cake refers to salts resulting from the evaporation of water from the wastes, such as sodium hydroxide, nitrate, and aluminate, and DS slurry refers to waste that was evaporated almost to its sodium aluminate saturation boundary, or 6.5M hydroxide.

Fig. G.1.
Categorization of present Hanford Site tank wastes.

In the liquid waste category, supernatant refers to the free liquid above the solids in the waste storage tanks; and drainable interstitial liquid (DIL) refers to the interstitial liquid that is not held in place by capillary forces and will therefore migrate or move by gravity.

2.0. CHEMICAL/PHYSICAL PROPERTIES OF THE TANK CONTENTS

As mentioned earlier, the exact chemical nature of individual tanks is largely unknown. Only a few tanks have been sampled and their samples analyzed. A listing of chemical and physical properties of some tanks (which have been sampled) are listed in Tables G-2 and G-3.²

3.0. TANK CONTENTS AND INVENTORIES

The total volumes of general waste types and their storage as of April 1992 are listed in Table G-4.³ The various volumes of liquid and solid waste in SS tanks and DS tanks are summarized in Fig. G.2.

TABLE G-2
CHEMICAL PROPERTIES

Chemical	101-SY (CC and DS Slurry)	110-B (BiPO ₄)
Aluminum (g/L)	6.9E+01	1.6E+00
Calcium (g/L)	1.2E+00	1.2E+00
Chromium (g/L)	7.6E+00	1.1E+00
Iron (g/L)	2.6E+00	2.6E+01
Potassium (g/L)	5.1E+00	5.1E-01
Manganese (g/L)	6.3E-01	1.4E-01
Sodium (g/L)	3.8E+02	1.3E+02
Silicon (g/L)	1.3E+00	1.3E+01
Zirconium (g/L)	3.6E-02	1.3E-01
Carbonate (g/L)	3.5E+01	—
Fluoride (g/L)	—	2.6E+00
Nitrite (g/L)	1.2E+02	1.4E+01
Phosphate (g/L)	5.7E+00	3.4E+01
Nitrate (g/L)	2.4E+02	2.5E+02
Sulfate (g/L)	5.6E+00	1.5E+01
Hydroxide (g/L)	3.0E+01	—
Pu 239 +240 (μCi/L)	9.5E+01	1.5E+02
Am 241 (μCi/L)	7.7E+02	1.0E+02
Cs 137 (μCi/L)	6.8E+05	1.9E+04
Sr 90 (μCi/L)	—	1.2E+05

Source: Ref. 2.

TABLE G-3
PHYSICAL PROPERTIES

Physical Property	101-AZ 102-AZ (NCAW)	103-AW 105-AW (NCRW)	102-SY (PFP)	102-AN (CC)	103-SY (CC & DSS)	110-B (BiPO ₄)
Shear strength (dynes/cm ²)	26,000	48,000	39,000	2900	32,000	—
Sludge density (g/ml)	1.3–1.6	1.4–1.8	1.2–1.5	1.3–1.5	1.5–1.9	1.3–1.4
Mean particle diameter (microns) (based on number density)	1.2	1.0	0.9	0.9	—	1.2
Penetration resistance (psi)	2.5	5	11	—	—	<2
Miller number	8	23	—	—	—	—

Source: Ref. 2.

**TABLE G-4
MONTHLY SUMMARY**

		TANK STATUS					
		April 1992					
		200	200				
		EAST AREA	WEST AREA	TOTAL			
IN SERVICE		25	3	28 ^a			
OUT OF SERVICE		66	83	149			
SOUND		59	52	111			
ASSUMED LEAKER		32	34	66			
INTERIM STABILIZED ^b		51	54	105			
ISOLATED							
PARTIAL ITERIM		21	30	51			
INTERIM		45	53	98			
		WASTE VOLUMES (K gal.)					
		200	200		SST	DST	
		EAST AREA	WEST AREA	TOTAL	TANKS	TANKS	TOTAL
SUPERNATANT							
AGING	Aging waste	1764	0	1764	0	1764	1764
CC	Complexant concentrate waste	1945	191	2136	3	2133	2136
CP	Concentrated phosphate waste	997	0	997	0	997	997
DC	Dilute complexed waste	853	1	854	1	853	854
DN	Dilute noncomplexed waste	8698	0	8698	0	8698	8698
DN/PD	Dilute noncomplex/PUREX TRU solids	886	0	886	0	886	886
DN/PT	Dilute noncomplex/PFP TRU solids	0	606	606	0	606	606
DSSF	Double-shell slurry feed	3816	48	3864	56	3808	3864
NCPLX	Noncomplexed waste	234	310	544	544	0	544
TOTAL SUPERNATANT		19,193	1156	20,349	604	19,745	20,349
SOLIDS							
	Double-shell slurry	937	1103	2040	0	2040	2040
	Sludge	8202	6215	14417	12466	1951	14417
	Saltcake	6577	17654	24231	23471	760	24231
TOTAL SOLIDS		15,716	24,972	40,688	35,937	4751	40,688
TOTAL WASTE		34,909	26,128	61,037	36,541	24,322	61,037
AVAILABLE SPACE IN TANKS		5899	885	6784	0	6784	6784
DRAINABLE INTERSTITIAL		2252	4505	6757	6319	438	6757
DRAINABLE LIQUID REMAINING		21,440	5661	27,101	6918	20,183	27,101

^aIncludes five DS tanks on hydrogen watch list not currently in service, 103-AN, 104-AN, 105-AN, 101-SY, and 103-SY.

^bIncludes tanks that do not meet current established supernatant and interstitial liquid stabilization criteria, B-104, B-107, B-110, B-111, BX-110, T-102, T-112, and U-110.

Note: x/- 1 Kgal. differences are the results of computer rounding.

Source: Ref. 3.

Fig. G.2.
Single- and double-shell tank liquid and solid waste volumes.

The breakup of the liquid and solid wastes into their various constituents is depicted by Figs. G.3 and G.4.

As can be seen in Table G-4 and the above figures, the solid waste (except double-shell slurry) is predominantly stored in SS tanks (35,937 kgal., 88%) while the supernatant is predominantly stored in DS tanks (19,745 kgal., 97%). The drainable interstitial liquid, which is stored along with the solid wastes, is predominantly stored in SS tanks (6,319 kgal., 94%).

4.0. WATCH LIST SAFETY ISSUES

Fifty-three tanks (48 SS tanks and 5 DS tanks) out of the total 177 tanks are currently placed on watch lists because of increased safety concerns relating to the following four safety issues:^{4,5}

Fig. G.3.
Solid waste tank constituents.

Fig. G.4.
Liquid waste tank constituents.

- hydrogen or flammable gas generation,
- high heat generation,
- potential organic-nitrate reactions, and
- potential explosion mixtures of ferrocyanide.

These four safety concerns are listed as priority 1 issues and/or situations, which satisfy most of the necessary conditions that could lead to onsite or offsite radiation exposure through an uncontrolled release of radioactive waste. Tank details and descriptions of tank contents for those tanks on watch lists are provided in Table G-1.

The safety-issue watch list includes tanks that are of concern because of the nature of their content. A breakup of these 55 tanks into the four safety issues categories is depicted in Fig. G.5. Some tanks are watched for more than one safety issue and are placed on more than one watch list.

4.1. Hydrogen Generation

Five DS tanks and 18 SS tanks have been identified as having a significant potential for flammable gas accumulation, entrapment below the crust layer, and periodic gas releases. The simultaneous presence of a flammable gas mixture and an ignition source poses the potential for a deflagration, which could lead to an increased risk of the release of radioactive waste. However, operational restrictions have been imposed for the 23 waste tanks to reduce the potential for sparks and ignition sources. In contrast, an unfiltered release of radioactivity into the environment caused by overpressurizing the ventilation system during a periodic gas venting poses lower potential risk. Tank 101-SY, has released concentrations of hydrogen that for a short period of time exceeded the amount necessary to support combustion⁶ during several venting periods. During these releases, overpressurizations have occurred but they have not resulted in any offsite release. The venting of gases is expected to recur periodically until some form of remediation is taken. Two of the 23 hydrogen watch list tanks are reported to leak to the ground.

4.2. Heat Generation

Eleven SS tanks are currently on the high heat load watch list. The predominant heat load for these tanks is from ¹³⁷Cs (half-life of 30 yr) and ⁹⁰Sr (half-life of 28.1 yr). In some of these tanks, periodic water addition is required to maintain

Fig. G.5.
The number of tanks on priority 1 watch lists.

evaporative cooling and thus to prevent overheating. The majority of these high heat load tanks (9 out of 11) are reported to leak.

The following is a brief description of one tank on this high-heat watch list:

Tank 241C-106 (referred to as tank 106-C) is a 2.0 million-ℓ (530,000 gal.) capacity SS tank. The tank has been used for high-level radioactive waste storage since mid-1967 and currently is approximately half full. In the late 1960s, during the implementation of a program to recover heat-generating strontium and cesium from high-level radioactive waste in some of the SS tanks, heat-generating sludge was inadvertently transferred to Tank 106-C. Since mid-1971, water has been added periodically to Tank 106-C to keep the sludge wet and to promote heat removal by evaporative cooling to the vapor space. The cooling water is in addition to the other drainable liquids in the tank. If Tank 106-C should leak, the addition of cooling water could increase the amount of leakage to the ground. However, if cooling water additions to the

tank are stopped, the sludge will heat to temperatures greater than established limits and may cause tank structural damage, possibly leading to dome collapse and an unacceptable radioactive release into the environment. A Tri-Party Agreement milestone has been established to remove all of the drainable liquid (which would eliminate the use of cooling water) and interim isolate Tank 106-C by September 1996. Tank 106-C is currently not a declared leaker.

4.3. Organic-Nitrate Reactions

Eight SS tanks may contain unacceptable concentrations of organic chemicals; e.g., more than 10 dry weight percent sodium acetate equivalent. The accurate concentrations of organic materials in the listed SS tanks and their chemical identity are not known at present. However, very concentrated organic materials could support an exothermic reaction at temperatures greater than 180°C (356°F).

Under a scenario involving significant overheating of tank waste to greater than 180°C (356°F), it may be possible for a mixture of organic-nitrate/ nitrite solids to react rapidly, possibly damaging the tank and causing a release of radioactive materials into the environment. This scenario is believed to have a very low probability of occurrence because the margin between minimum ignition temperature and measured tank temperatures is very large. Two of the eight tanks are reported to leak.

4.4. Ferrocyanide Reactions

Twenty-four SS tanks may contain appreciable amounts of ferrocyanide precipitates [1000 g-moles (465 lb) or greater]. Estimated ferrocyanide content of the 24 tanks ranges from 1000 g-moles (465 lb) to approximately 200,000 g-moles (93,000 lb) in Tank 241-BY-104 (referred to as Tank 104-BY). During the early 1950s, a process was developed to reduce radionuclide concentration in the freestanding liquid tank wastes to levels low enough to permit disposal of the liquid to the soil and therefore quickly adding waste storage volume. This process involved the addition of ferrocyanide compounds to the tanks to precipitate radioactive cesium out of the liquid. Ferrocyanide salts in the presence of nitrate and/or nitrite constituents, which these tanks contain, can react and detonate under certain conditions, such as being dry, having the proper chemical concentration and mixture, and having elevated temperatures or a high-energy spark. Reactions can occur at temperatures as low as 285°C (545°F). Organic materials (which some of these tanks also very probably

contain) can produce an exothermic reaction in the temperature range of 180 to 200°C (360 to 430°F).

A recently completed study sponsored by the General Accounting Office (GAO) postulated dose consequences that were two orders of magnitude greater than stated in the 1987 EIS for a severe accident (Ref. 7). Such a release is believed to have a low probability of occurring even from a localized "hot-spot" because the maximum temperatures measured inside the ferrocyanide tanks at the Hanford Site are at or below 60°C (140°F), thus providing a significant margin of safety. Tank temperatures have also been declining at a little less than 2°C per year as the tank fission products continue to decay. Thirteen of these 24 tanks are reported to leak.

REFERENCES

1. J. D. Anderson, "A History of the 200 Area Tank Farms," Westinghouse Hanford Company report WHC-MR-0132 (June 1990).
2. L. Sasaki, "General Chemical and Physical Properties of Tank Wastes," Red Team Phenomenology Sub-Panel Review, Westinghouse Hanford Company (April 14, 1992).
3. Westinghouse Hanford Company, "Tank Farm Surveillance and Waste Status Summary Report for April 1992," WHC-EP-0182-49, prepared for the US Department of Energy, Office of Environmental Restoration and Waste Management.
4. Westinghouse Hanford Company, "High-Priority Hanford Site Radioactive Waste Storage Tank Issues: An Overview," WHC-SA-1539-FP, prepared for the US Department of Energy, Office of Environmental Restoration and Waste Management (April 1992).
5. Westinghouse Hanford Company, "Summary of Single-Shell Tank Waste Stability," WHC-EP-0347, prepared for the US Department of Energy, Office of Environmental Restoration and Waste Management (May 1992).
6. Westinghouse Hanford Company, "Evaluation of the Generation and Release of Flammable Gases in Tank 241-SY-101," WHC-EP-0517, prepared for the US Department of Energy, Office of Environmental Restoration and Waste Management (November 1991).
7. A. K. Postma et al., "Current Understanding of the Safety of Storing High-Level Waste Containing Ferrocyanide at the Hanford Site," WHC-EP-0531 (Predecisional), prepared for the US Department of Energy, Office of Environmental Restoration and Management (November 1991).

APPENDIX H

SCOPE OF THE HANFORD TANK FARMS PSA

1.0. OVERVIEW

The appendix details the scope of the risks evaluated in the HTF PSA that are defined by:

1. the time span of the events included in the PSA,
2. the time span of the consequences included in the PSA, and
3. the consequence measures used as risk indices.

The HTF PSA differs from standard PSAs for several reasons. For example, in many PSAs there is no time difference between occurrence of the events and the consequences. However, at Hanford, radionuclides and hazardous chemicals released into the soil may remain there for hundreds or thousands of years before re-emerging to produce unwanted consequences.

Also, PSAs typically use estimates of the frequency of severe accidents and/or health effects resulting from accidents to measure risk. At Hanford, the cost effectiveness of proposed storage and remediation schemes also will be a significant factor in the overall risk management of the site.

2.0. TIME SPAN OF EVENTS INCLUDED IN THE PSA

The life cycle of the Hanford Tank Farms can be described in terms of the four eras or operational phases that are discussed below. Each era presents different potential health and economic risks. It is recognized that the boundaries between these eras cannot be neatly delineated at any one point in time. These eras will necessarily overlap and will be of differing durations for different tanks. Regardless, these eras provide a useful basis for describing the scope of this and future risk-assessment activities.

2.1. Production Era

This era is the period of plutonium production that began in 1943 and continued for approximately 50 yr, until the present time. Tank processes that occurred during this era include the direct loading of wastes from separation and purification

processing, as well as in-farm processing and evaporation of wastes. Atmospheric and ground releases of radionuclides and hazardous chemicals occurred in this era. Acute health effects from these releases, if known, are already realized and are not considered further in this analysis. Delayed consequences from hazardous materials still in the soil beneath the site are still possible.

2.2. Interim Storage Era

This era is the period of time between the interim stabilization of wastes in nonwatch list tanks and the final waste stabilization for long-term, in-place storage or the removal of the wastes for processing. Risks from the activities required to stabilize watch list tanks and to maintain and characterize all tanks are included in this era. Additions of new waste from sitewide clean-up activities will continue through this era, which is expected to last between 10 and 20 yr.

2.3. Remediation Era

This is the period during which tank wastes are prepared for final, long-term storage. Activities performed during this era, which is expected to last 20 to 30 yr, may range from minimal action to removal of all tank wastes for processing and disposal.

2.4. Long-Term Storage Era

Even the most ambitious proposals for remediation of the HTF include long-term storage of at least low-level wastes on site. Long-term storage should begin within 30 to 50 yr from the present and extend indefinitely.

3.0. THE TIME SPAN OF THE CONSEQUENCES INCLUDED IN THE PSA

Radionuclides and hazardous chemicals released into the soil at Hanford may remain there for hundreds or thousands of years before possibly reemerging to produce unwanted consequences. Factors influencing the timing of the consequence realization include the time, magnitude, and location of the initial release, as well as future restrictions on public access to the Hanford Site.

Figure H.1, a map of the Hanford Nuclear Reservation as it exists today, shows the location of the 200 Area within the reservation. Radionuclide or hazardous chemical releases from the 200 Area must travel about 2.5 mi (3.9 km) to reach Highway 240, the nearest point of public access, and at least 8 mi (13.8 km) to

Fig. H.1.
Land use features at the Hanford Site.

cross the nearest site boundary. Within these boundaries, hazardous compounds released into the soil may either bind with minerals and become immobile or they may decay and dilute before reaching the site boundary so that their potential health risks are negligible. If the site boundaries are moved in the future so that the general public is allowed closer access, potential health effects from future or past releases could be increased. This is especially true if water wells are dug on site, thus creating a new, more direct, exposure path. For these reasons, future changes in site-usage restrictions could impact the magnitude of future consequences predicted from past or future groundwater contamination.

4.0. CONSEQUENCE MEASURES INCLUDED IN THE PSA

4.1. Health Effects Risk

Potential health effects resulting from exposure to radionuclides and hazardous chemicals are included in the HTF PSA. As described in Chap. 6, radionuclide exposure is measured in person-rem and converted to health effects through the use of generally accepted models. Hazardous chemical exposure is measured by the estimated peak concentration of the chemical in the environment and generally is not converted into potential health effects. Potential health risks from atmospheric releases are also calculated for onsite workers, as well as for the offsite population. The sources of risk included in the HTF PSA include exposure from accidental releases and their clean-up. Normal occupational exposure is limited by regulations and is assumed to present negligible health risk. Delayed doses from subterranean liquid releases also are calculated but are reported separately because of the time difference between release and consequence onset and because any consequences will be realized by different individuals.

4.2. Economic Risk

Decisions on alternative strategies for storage and remediation of the HTF should consider economic costs, as well as possible health effects. The measure of economic risk is, of course, dollars, and procedures for incorporating time-value effects in decision making are well known. The systematic inclusion of uncertainty in economic analysis is, however, much less prevalent. When viewed from the decision-making perspective, the sources of economic risk include uncertainty about

the cost of planned activities, as well as the costs associated with accident remediation. For the HTF PSA, the following categories of economic risk have been identified for evaluation.

Expected Costs for Storage and Remediation Activities

This category includes the estimated costs of normal storage and planned remediation activities. Decision alternatives may consider trade offs between one-time remediation costs and long-term maintenance costs.

Added Costs from Technological Failure of Planned Remediation Activities

New technologies inherently present the risk of technological failure. Because major technological uncertainties exist about the characteristics of the HTF wastes, uncertainties exist about stabilizing them *in situ*, removing them from the tanks, concentrating their radionuclides, and vitrifying to repository specifications. Setbacks and failures in these and other tasks represent significant economic risks.

Onsite Clean-Up Costs for Accidents

This category includes costs for the collection and disposal of contaminated soil, the repair of damaged tanks, and the interdiction and treatment of contaminated ground water.

Offsite Collateral Damage from Accidents

Included in this category are the economic costs from contaminated fisheries, the forced outage of commercial power plants located on the site, and offsite damage to the local environment, such as those costs resulting from lost farm production.

DOE Programmatic Damage from Accidents

This category includes any added costs to DOE for remediation and restoration activities at Hanford and other facilities that result from an accident at Hanford. This is analogous to the Three Mile Island (TMI) action plan requirements that were imposed on all commercial reactors after the TMI accident. An example might be that an accident at Tank 101-SY would force DOE to retrieve all SS tank wastes, rather than leave some in place.

5.0. INTEGRATED PSA SCOPE DESCRIPTION

The timing of potential HTF events and consequence discussed above can be joined to define the time span of coverage of the PSA. Because of the potential delay between the time that hazardous materials are released into the soil and the time at which they may produce health consequences, a two-dimensional concept of time is needed to describe the scope of coverage of the PSA. Figure H.2 provides a graphical representation of this concept. The risk-producing occurrence event time represented by the life cycle eras of the HTF are presented along the top axis from left to right. The vertical axis depicts the time at which consequences from a release are realized. For acute health effects from atmospheric releases, there is no delay between the time of release and time of consequence. However, for releases into the soil, there is a potential delay between the time of release until the time the material migrates offsite or the site boundaries are changed, allowing public access to already contaminated areas. As seen in Fig. H.2, these two axes define, nine hypothetical regions for which potential risks can be evaluated. These regions are discussed below.

Region 1 represents the completed production era for which acute consequences have already been realized. Regions 2 and 3 represent the potential future consequences from releases that occurred during the production era. These potential future consequences are arbitrarily divided into time spans with and without continued restriction of public site access. Regions 4, 6, and 8 represent the potential future consequences from events occurring during the interim storage, remediation, and long-term storage eras while site use restriction is continued. Regions 5, 7, and 9 represent the potential consequences from events occurring in these eras after the expiration of site use restrictions.

The HTF PSA effort is divided into three phases. The first phase addresses health and economic risks for time scope region 4 (interim storage) from Tank 101-SY. This report documents the results of phase 1. Phase 2 will expand the evaluation for region 4 to all 177 storage tanks and Phase 3 will address regions 6 (remediation) and 8 (long term storage).

Time-scope regions 3, 5, 7, and 9 are not included in this analysis because potential risks in the very long term are believed to be dominated by releases that have already occurred in the production era. These releases include approximately 200 million gal. of supernatant liquids skimmed from the tanks and deposited in cribs¹ plus between 600,000 and 900,000 gal. from tank leaks.² Any additional leaks

Fig. H.2.
Hanford Tank Farm life cycle and scope of the PRA.

occurring during the interim storage or remediation eras will add only incrementally to the radionuclide inventory already in the subterranean environment at Hanford. Preliminary analyses of the potential risk from subterranean contamination indicate the following points:

- The leaked fluids are primarily composed of ^{137}Cs and ^{90}Sr plus much smaller quantities of longer-lived isotopes. Cesium and strontium both have half-lives of about 30 yr and therefore will be substantially decayed away within about 300 yr.
- Estimates of the time it would take for these radionuclides to migrate beyond the current site boundaries range from 300 to 1800 yr. Thus, cesium and strontium may never migrate beyond the current site boundaries in significant quantities.
- Risks over the very long term will be dominated by unknowns related to the possible propagation of long-lived isotopes (released during the production era) through the subterranean environment and by assumptions made concerning the very long-term access of the public to the site. No decisions currently available to DOE management will influence the outcome of these questions.

Within the time-scope regions of interest identified above, the important consequence measures can be specified for each region to define the total scope of the PSA. Figure H.3 presents a matrix describing the total scope of the PSA.

REFERENCES

1. J. D. Anderson, "A History of the 200 Area Tank Farms," Westinghouse Hanford Company report WHC-MR-0132, Table 6 (June 1990).
2. "Tank Farm Surveillance and Waste Status Summary Report for July 1992," Westinghouse Hanford Company report WHC-EP-0182-52, Appendix H (July 1992).

HTF LIFE CYCLE ERA	CONSEQUENCE MEASURES								
	HEALTH RISKS				ECONOMIC RISKS				
	Worker Accident Exposure	Worker Clean-Up Exposure	Off Site Population Exposure	Delayed Exposure to Leaks	Expected Operating Costs	Technological Failure	Accident On Site Clean-Up Costs	Accident Off Site Collateral Damage	Accident DOE Programmatic Damage
Interim Storage [4]	1,2	2	1,2	1,2			2	2	2
Remediation [6]	3	3	3	3	3	3	3	3	3
Long Term Storage [8]	n/a	n/a	n/a	3	3	3	n/a	n/a	n/a

- 1) PRA Phase 1, Tank 101-SY Only
- 2) PRA Phase 2, All Tanks
- 3) PRA Phase 3, All Tanks

Fig. H.3.
Integrated PRA scope definition matrix.

APPENDIX I

CHEMICAL HAZARD RISK

1.0. INTRODUCTION

Potential risks from exposure to hazardous chemicals contained in tank 101-SY were also evaluated as part of this study. Hazardous chemical contamination of the Hanford site ground water and the Columbia River was comprehensively examined in the 1986 Hanford Environmental Impact Statement (Ref. 1, App. U). This study evaluated the impacts of potential leakage from all Hanford single shell tanks (SST) and found that hazardous chemical concentrations in the Columbia River remained well below EPA drinking water standards for all remediation scenarios under all site conditions. The EIS also showed that ground water within the current site boundaries would, over time, show hazardous chemical concentrations well above EPA standards with no tank remediation.

Because large leaks from double shell tanks were not explicitly evaluated in the EIS, a scoping analysis of the potential for contamination of the Columbia River was performed for tank 101-SY. This analysis, presented below, confirms that leaks from tank 101-SY represent no threat to the Columbia River. Since site boundaries were assumed to remain as they are now for this evaluation, as discussed in App. H, no further analysis of hazardous chemical risk was performed and no health impacts from hazardous chemical releases are included in the results reported here.

2.0. CHEMICAL HAZARDS ANALYSIS FOR TANK 101-SY

2.1. Identification of Toxic Chemicals

Tables I-1 and I-2 list the various chemicals present in the tank (Ref. 2). Table I-1 provides the chemical analysis of liquid phase samples from tank 101-SY, while Table I-2 provides the chemical analysis of the bulk and centrifuged solids samples. The exact chemical formulation of the compounds present in the tank cannot be determined from this chemical analysis. However, as the contamination in the Columbia river water would be determined by the individual concentrations of the soluble ionic form of the chemical compounds present, the chemical analysis results do provide initial concentration levels of these ionic species.

TABLE I-1
CHEMICAL ANALYSIS OF COMPOSITE SAMPLE LIQUID PHASE
(WEIGHT PERCENT EXCEPT CYANIDE)

Analysis	Composite Number			
	1	2	3	4
NO ₃ ⁻	16.1	15.0 ^c	11.9	12.2
NO ₂ ⁻	13.7	13.0 ^c	9.9	8.7
Cl ⁻	0.89	1.02 ^c	0.92	0.70
F ⁻	—	—	0.07	0.04
PO ₄ ³⁻	0.53	0.56 ^c	0.91	0.91 ^a
SO ₄ ²⁻	0.13	0.05 ^c	0.08	0.28
TIC	0.26	0.66 ^c	1.60 ^c	1.60 ^a
TOC	0.94	0.94 ^a	1.14	0.94
NH ₃ / NH ₄ ⁺	0.01	0.01	0.02	—
OH ⁻	2.82	2.82 ^a	3.08	1.98
CN ⁻ (ppm)	90.0	91.0	90.0	394.0
Na	19.3	17.7	21.1	17.9
Al	3.07	2.75	3.38	2.96
Cr	0.006	0.005	0.013	0.022
Fe	—	0.003	0.006	—
Ca	0.046	0.058	0.052	0.119
K	0.361	0.312	0.380	0.338
Mo	0.011	0.009	0.012	0.009
Ni	0.004	0.003	0.010	0.006
Zn	0.009	0.005	0.009	0.022
H ₂ O (b)	36.53	35.73	36.13	36.13
Mass Bal	101.4	96.4	103.5	96.6
Ion Bal	0.89	0.85	0.87	0.82

^aValue not determined; assumed to be same as composite from same layer (in order to calculate mass and charge balance).

^bValue not determined; assumed average of segment samples for convective layer (assumed nonconvective liquid equal to convective layer liquid average).

^cOne or more duplicate sample results discarded.

TABLE I-2
CHEMICAL ANALYSIS OF COMPOSITE BULK SAMPLES AND
CENTRIFUGED SOLIDS (WEIGHT PERCENT EXCEPT CYANIDE)

Analysis	Centrifuged Solids		Bulk Samples		
	#1	#2	#3	#4	#5
NO ₃ ⁻	8.7 ^c	8.7 ^c	10.5	10.4	12.8
NO ₂ ⁻	11.1	13.9	10.5	8.3	8.5
Cl ⁻	0.73	0.68	0.76	0.93	0.65 ^e
F ⁻	0.03	—	—	—	0.17 ^e
PO ₄ ³⁻	0.50	0.44	0.81	0.90	1.08 ^e
SO ₄ ²⁻	0.20	0.24	0.67	0.71	0.89 ^e
TIC	1.02	1.18	0.99	1.15	1.38
TOC (b)	1.70	1.89	1.97	1.93	1.96
NH ₃ / NH ₄ ⁺	0.19 ^e	0.26 ^e	0.31	0.37	<0.09
OH ⁻	2.12 ^e	1.58	2.52	2.42	1.69
CN ⁻ (ppm)	152.0 ^d	117.0 ^d	389.0	409.0	469.0
Na	22.0	22.5	20.3	22.3	20.1
Al	2.52	2.71	3.57	3.7	3.86
Cr	0.20	0.22	0.58	0.71 ^e	0.76
Fe	0.015	0.029	0.054	0.061	0.116
Ca	0.128	0.127	0.066	0.044 ^e	0.054
K	0.267	0.508	0.310	0.301	0.241
Mo	—	—	0.009	0.009	—
Ni	0.011	—	0.039	0.026 ^e	0.027
Zn	0.005	—	0.007	0.007	0.005
H ₂ O (a)	35.03	35.03	34.04	32.52	33.65
Mass Bal	97.0	101.7	100.2	99.5	101.9
Ion Bal	1.13	1.07	0.93	1.04	0.89

^aWt. % H₂O for Composites 1 and 2 taken from segment data in Table 7-7b; for Composites 3 and 4 taken from segment averages (see App. B); Composite 5 determined directly.

^bTOC values for Composites 1 and 5 determined directly; other values taken from segment averages (Table 7-9).

^cAverage of values from corresponding segments.

^dBulk sample, not centrifuged solids.

^eOne or more duplicate sample results discarded.

2.2. Scoping Evaluation of Maximum Concentration Levels in Columbia River

Bounding and pessimistic assumptions were made to perform a scoping evaluation of the concentration levels possible in the Columbia River. These assumptions were:

1. All of the 101-SY tank contents are released to the ground.
2. The retention factors for the vadose zone/aquifer are zero for all chemicals. This means that the vadose zone or the aquifer do not retain or absorb the released chemicals. Thus, the entire contents of the tank 101-SY would eventually be released to the Columbia river.
3. The release of these tank contents occurs over a period of one year. This does not imply the time of the release, but only the rate of release. The tank contents are released to the river at rate such that the tank contents are diluted with a river water volume equal to a years river flow. (This assumption is pessimistic; an analogous release for radiological evaluation was found to be over 200-yr period.)
4. No filtration of the river water is assumed prior to human consumption. A filtration or water treatment (with activated carbon) is likely to further reduce contaminant levels in drinking water.

Tables I-3 and I-4 show the calculation of various parameters. These include 101-SY tank volume, fraction of tank contents released, river flow rate and duration of release are used in the analysis. Concentration levels for select toxic chemicals from Tables 1 and 2 are evaluated as follows:

1. Maximum initial concentrations for each chemical components are obtained from Table I-1 or I-2 (wt % or ppm).
2. The total weight of this chemical component is determined. This is the maximum amount of chemical component present in the tank 101-SY which can be released.
3. The concentration levels in the Columbia river is determined by combining the total weight of the chemical component and the dilution volume.

**TABLE I-3
ANALYSIS INPUTS**

Parameter	Value	Units
101-SY Tank Volume	1090	Kgals
101-SY Tank Volume	4.14E+06	liters
Density	1.74	gm/ml
Tank Weight	7.20E+06	Kg
River Flow Rate	3.40E+03	m ³ /s
Annual Flow Volume	1.07222E+11	m ³
Tank Volume Fraction Released	100.00%	none
Tank Volume Released	4.14E+06	m ³
Duration Of Release	12.00	months
Dilution Volume	1.07222E+14	liters

**TABLE I-4
ANALYSIS OUTPUTS**

Chemical Component	Weight Fraction	Total Weight (Kg)	Concentration Downstream of River (mg/liter)	EPA Max Contaminant Level (mg/liter)*	Days of Mixing to Achieve EPA Levels
Nitrites	13.70%	9.87E+05	9.20E-03	1	3.36
Chromium	0.02%	1.58E+03	1.48E-05	0.1	0.05
Nitrates	16.10%	1.16E+06	1.08E-02	10	0.39
Fluoride	0.04%	2.88E+03	2.69E-05	4	0.00
Ammonia	0.01%	7.20E+02	6.72E-06		
Cyanides	394 (ppm)		16 (ppt)		
Aluminum	3.38%	2.43E+05	2.27E-03		
Molybdenum	0.01%	8.64E+02	8.06E-06		
Nickel	0.01%	7.20E+02	6.72E-06		
Zinc	0.02%	1.58E+03	1.48E-05		

*Maximum contaminant level goals for Inorganic Compounds 40CFR141.50.

2.3. Comparison of Chemical Component Levels with EPA Standards

Code of Federal regulations 40CFR141.50 (Ref. 3) lists the maximum contaminant levels goals for select inorganic compounds as a part of the National primary drinking water regulations. As can be seen from Table I-4, the concentration levels calculated in the present analysis are much lower than the EPA standards. The concentration levels are so low that the entire tank contents would have to be released to the river within a very short period (ranging from a few days to a few hours) before exceeding the EPA drinking water standards.

Although the EPA standards are not available for all the toxic chemicals present in 101-SY, the calculated concentrations for all chemicals are quite low and would most likely meet the EPA regulations for drinking water. This needs to be confirmed.

3.0. CONCLUSIONS

The scoping analysis shows that even with bounding pessimistic assumptions, the concentration levels of various chemicals in the Columbia River upon contamination with the tank 101-SY contents did not exceed the Maximum Contaminant Levels as determined by EPA. This conclusion alleviates the need to perform a detailed dispersion analysis and hazards evaluation for the chemical contents of the 101-SY tank.

REFERENCES

1. "Final Environmental Impact Statement—Disposal of High Level Transuranic and Tank Wastes, Hanford Site," US Department of Energy report DOE/EIS - 0013 (December 1987).
2. Westinghouse Hanford Company, "Laboratory Characterization of Samples Taken in May 1991 from Hanford Waste Tank 241-SY-101," prepared for the US Department of Energy Office of Environmental Restoration and Waste Management, WHC-SD-WM-DTR-024, Rev. 0 (February 1992)
3. "Code of Federal Regulations, Protection of Environment 40, Parts 100 to 149," Environmental Protection Agency (July 1, 1992).

APPENDIX J

ECONOMIC RISK

1.0. INTRODUCTION

The economic risks resulting from accidents associated with Tank 101-SY will be strongly influenced by the political and economic environments prevailing at the time of such accidents. These considerations will dictate the extent of remediation to be performed. In addition, the current database for remediation costs is extremely limited. This database will expand dramatically as data from ongoing remediation activities at DOE and other facilities becomes available. With these limitations in mind, the remainder of this section discusses a framework for calculating the economic risks associated with Tank 101-SY accidents and provides estimates for these risks using this framework and available data.

2.0. MEASURES OF ECONOMIC DAMAGE

To assess the economic risk associated with the Tank 101-SY accidents identified earlier in this PSA, it was first necessary to qualitatively identify the measures of economic damage associated with the sequences representing each of the release categories. Table J-1 summarizes the various types of economic damage expected for each of the representative sequences/release categories. Based on this qualitative evaluation, the following four measures of economic damage were selected.

1. Surface Contamination
2. Tank Replacement
3. Cleanup of Soil Contaminated by Tank Leaks
4. Ventilation System Repair

The tank replacement costs includes an estimate for the transfer of the contents remaining in Tank 101-SY to a new tank and stabilization of the damaged tank.

As shown in Table J-1, some of the above damage measures appear in more than one release category and individual release categories generally contain more than one damage measure. Although some damage measures are qualitatively similar between release categories, the materials released to the environment (i.e.,

**TABLE J-1
ECONOMIC DAMAGE MEASURES**

Release Category	Damage To							Excessive Contamination to						
	Primary Tank	Secondary Tank	Vent System Ducting	Deent.	HEPA Filters	Inst.	Fan	Ground	Bldgs.	Vent System Ducting	Deent.	HEPA Filters	Inst.	Fan
BPL	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No
HEPAL	No	No	Possible	Possible	Breached	Breached	Possible	Yes	Yes (?)	Yes	Breached	Breached	Yes	Yes
HEPAH	No	No	Possible	Possible	Breached	Breached	Possible	Yes	Yes (?)	Yes	Breached	Breached	Yes	Yes
DCH	Yes	Yes	Yes	Yes	Yes	Yes	Likely	Yes	Yes (?)	Yes	Yes	Yes	Yes	Yes
DCVH	Yes	Yes	Yes	Yes	Yes	Yes	Likely	Yes	Yes (?)	Yes	No (?)	No (?)	No (?)	No (?)
SLK	Small Leak	Failure	No	No	No	No	No	Small Leak	No	No	No	No	No	No
LLK	Large Leak	Failure	No	No	No	No	No	Large Leak	No	No	No	No	No	No
SSP	No	No	No	No	No	No	No	Water Intrusion / Overflow	No	No	No	No	No	No
DCLLK (DCH + LLK)	Yes	Yes	Yes	Yes	Yes	Yes	Likely	Airborne & Leak	Yes (?)	Yes	Yes	Yes	Yes	Yes

NOTE: SLK & LLK result in below grade leakage (considerable excavation required before contaminated soil can be reached).

the source terms) are different. Thus, to obtain an overall measure of economic risk, all damage measures within a given release category must be summed and the risk from each release category must be summed.

The following sections provide a brief discussion of the above damage measures including the basis for the probabilistic estimates for various remediation activities, results for the important release categories, and results for the overall economic risk (summed over all of the release categories considered) associated with the Tank 241-SY-101 accidents identified earlier in this report.

2.1. Surface Contamination

For any release category involving an airborne release of material, there will be some level of ground (i.e., surface) contamination. Since the amount of material released through airborne pathways varies from release category to release category, this measure of economic risk must be addressed for each release category which has a unique airborne source term.

The important parameters associated with generating the economic risk curves associated with ground contamination are as follows:

1. The area of land that is deemed to be contaminated and thus subject to some form of remediation activity.
2. The unit costs (\$/m²) associated with lowering the extent of contamination to "acceptable" levels.

Probabilistic estimates of the land which becomes contaminated for a particular release category were determined with the AP-RISK dispersion code using site meteorological data and predicted source terms for the various release categories. The extent of such contamination for Release Categories DCVH, DCH, HEPAH, and HEPAL and low, medium and high estimates for the source terms is summarized in Tables J-2 through J-5. As indicated in these tables, the total area of ground contamination is subdivided into areas corresponding to various levels of contamination. The extent of contamination is implied by the amount of decontamination required to restore the land to an acceptable level. (See Sec. 6.2.4.)

The unit costs involved with decontamination depend on the procedure(s) selected to accomplish the decontamination. Reference 1 discusses a variety of techniques to decontaminate land and their associated costs. Figure 2.5.7 of Ref. 1

TABLE J-2
SURFACE CONTAMINATION AREAS—RELEASE CATEGORY DCVH

**Decontamination Levels Required to Meet PAG for Land within Downwind
Distances (m): 1.20E+02 - 2.60E+04
(Weather Weighted)**

Decontamination Factor Range	57 kg		113 kg		283 kg	
	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher
1.0E+07 - 3.3E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+06 - 1.0E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+06 - 3.3E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+05 - 1.0E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+05 - 3.3E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+04 - 1.0E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+04 - 3.3E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+03 - 1.0E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.10E+02	9.10E+02
1.0E+03 - 3.3E+02	0.00E+00	0.00E+00	1.69E+03	1.69E+03	4.45E+03	5.36E+03
3.3E+02 - 1.0E+02	3.30E+03	3.30E+03	6.01E+03	7.70E+03	1.27E+04	1.81E+04
1.0E+02 - 3.3E+01	7.34E+03	1.06E+04	1.15E+04	1.92E+04	3.83E+04	5.64E+04
3.3E+01 - 1.0E+01	2.80E+04	3.87E+04	4.64E+04	6.55E+04	1.31E+05	1.88E+05
1.0E+01 - 3.3E+00	6.01E+04	9.88E+04	1.36E+05	2.01E+05	2.33E+05	4.21E+05
3.3E+00 - 1.0E+00	1.30E+05	2.28E+05	2.26E+05	4.27E+05	4.97E+05	9.18E+05

TABLE J-3
SURFACE CONTAMINATION AREAS—RELEASE CATEGORY DCH

**Decontamination Levels Required to Meet PAG for Land within Downwind
Distances (m): 1.20E+02 - 2.60E+04
(Weather Weighted)**

Decontamination Factor Range	14.7 kg		32.8 kg		55.2 kg	
	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher
1.0E+07 - 3.3E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+06 - 1.0E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+06 - 3.3E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+05 - 1.0E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+05 - 3.3E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+04 - 1.0E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+04 - 3.3E+03	0.00E+00	0.00E+00	7.94E-01	7.94E-01	6.95E+00	6.95E+00
3.3E+03 - 1.0E+03	5.80E+00	5.80E+00	1.80E+01	1.88E+01	2.80E+01	3.50E+01
1.0E+03 - 3.3E+02	2.33E+01	2.91E+01	2.86E+01	4.74E+01	4.50E+01	8.00E+01
3.3E+02 - 1.0E+02	4.33E+01	7.24E+01	1.16E+02	1.64E+02	1.93E+02	2.73E+02
1.0E+02 - 3.3E+01	1.32E+02	2.04E+02	2.34E+02	3.98E+02	3.02E+02	5.75E+02
3.3E+01 - 1.0E+01	3.35E+02	5.39E+02	6.41E+02	1.04E+03	1.19E+03	1.77E+03
1.0E+01 - 3.3E+00	9.04E+02	1.44E+03	1.65E+03	2.69E+03	2.48E+03	4.24E+03
3.3E+00 - 1.0E+00	2.10E+03	3.55E+03	5.21E+03	7.89E+03	8.05E+03	1.23E+04

TABLE J-4
SURFACE CONTAMINATION AREAS—RELEASE CATEGORY HEPAH

**Decontamination Levels Required to Meet PAG for Land within Downwind
Distances (m): 1.20E+02 - 2.60E+04
(Weather Weighted)**

Decontamination Factor Range	4.1 kg		6.9 kg		10.2 kg	
	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher
1.0E+07 - 3.3E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+06 - 1.0E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+06 - 3.3E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+05 - 1.0E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+05 - 3.3E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+04 - 1.0E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+04 - 3.3E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+03 - 1.0E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.82E-01	8.82E-01
1.0E+03 - 3.3E+02	3.85E+00	3.85E+00	8.74E+00	8.74E+00	1.63E+01	1.72E+01
3.3E+02 - 1.0E+02	2.31E+01	2.69E+01	3.03E+01	3.90E+01	3.18E+01	4.90E+01
1.0E+02 - 3.3E+01	3.60E+01	6.30E+01	7.16E+01	1.11E+02	1.03E+02	1.52E+02
3.3E+01 - 1.0E+01	1.24E+02	1.87E+02	2.07E+02	3.17E+02	2.52E+02	4.05E+02
1.0E+01 - 3.3E+00	2.63E+02	4.50E+02	3.63E+02	6.81E+02	5.96E+02	1.00E+03
3.3E+00 - 1.0E+00	6.54E+02	1.10E+03	1.17E+03	1.85E+03	1.44E+03	2.44E+03

TABLE J-5
SURFACE CONTAMINATION AREAS—RELEASE CATEGORY HEPAL

**Decontamination Levels Required to Meet PAG for Land within Downwind
Distances (m): 1.20E+02 - 2.60E+04
(Weather Weighted)**

Decontamination Factor Range	0.8 kg		1.8 kg		2.8 kg	
	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher	Area within this Range (sq meters)	Area with this DF or Higher
1.0E+07 - 3.3E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+06 - 1.0E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+06 - 3.3E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+05 - 1.0E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+05 - 3.3E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+04 - 1.0E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+04 - 3.3E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.3E+03 - 1.0E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.0E+03 - 3.3E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.52E-01	3.52E-01
3.3E+02 - 1.0E+02	0.00E+00	0.00E+00	7.66E+00	7.66E+00	1.49E+01	1.53E+01
1.0E+02 - 3.3E+01	1.29E+01	1.29E+01	2.69E+01	3.45E+01	2.67E+01	4.20E+01
3.3E+01 - 1.0E+01	2.83E+01	4.12E+01	5.72E+01	9.18E+01	9.73E+01	1.39E+02
1.0E+01 - 3.3E+00	8.51E+01	1.26E+02	1.73E+02	2.65E+02	2.21E+02	3.60E+02
3.3E+00 - 1.0E+00	1.82E+02	3.08E+02	3.01E+02	5.66E+02	4.74E+02	8.35E+02

contains a plot of decontamination costs (in 1982 dollars) as a function of decontamination factor (i.e., the level of contamination). As the level of contamination increases, the methods for decontamination change somewhat. The various decontamination operations, along with their representative costs, portrayed in the reference are defined as follows:

Method	Definition	Cost (1982 \$/m ²)
L	Leaching with FeCl ₃	0.052
W	Low pressure water	0.0219
X	Scrape 4 in. to 6 in.	0.31
x	Double scrape	0.62 (2 x 0.31)
G	Cover with 6 in. soil	0.371
T	Surface sealer, fixative	0.2061
N	Clear, harvest	0.026

As noted in Ref. 1, a sequence of decontamination operations could be required rather than a single operation. For example, for a level of contamination corresponding to a decontamination factor of 1000 the cost is based on the "string" of decontamination methods denoted as TNxX. As indicated by the above table, this string involves three scrapings (xX), the application of a surface sealer/fixative (T), and clearing of the decontaminated land (N). A detailed review of Fig. 2.5.7 indicates that the following strings of decontamination operations can be applied to the ranges of decontamination factors (DF) associated with the contaminated land areas. In this context the DF is the initial contamination level (Ci/m²) divided by the final.

DF Range	Operations String
1-3.3	L-WWW
3.3-10	WWWW-XG
10-33	XG-TNx
33-100	TNx
100-330	TNx
330-1000	TNx-TNxX
1000-3300	TNxX

An investigation of the basis for Fig. 2.5.7 of Ref. 1 indicated that the identified decontamination actions were intended to reduce long-term ground shine and inhalation dose to acceptable levels and would not necessarily eliminate the potential for internal dose due to ingestion (i.e., restore the land for unlimited agricultural use). Thus, even though the cleanup exposure scenario was based on the assumption that site access would be limited for the next 50 yr, for conservatism it was assumed that the contaminated soil must be removed after scraping. It was assumed that each scraping would remove 6 in. of soil and that this soil would be transported 5 miles (a round trip of 10 miles) where it again would be covered. Based on Table 2.4.11.1 of Ref. 1 and the above assumptions, the representative costs for hauling were assumed to be \$4.15/m³ or \$0.63/m²/scraping. In addition, it was assumed that the hauled material would be covered at the point of storage at a cost of \$0.371/m² regardless of the number of scrapings. Furthermore, Ref. 2 notes that pre-cleanup and post-cleanup radiation surveys, at \$480/acre/survey, would be required in any decontamination activity. The costs of these surveys were also included as they did not seem to be included in the costs associated with the decontamination operation strings identified above. All costs identified above are in 1982 dollars.*

Based on the assumptions and base costs discussed above, estimates for the total costs of decontamination for the various decontamination factor ranges were determined. These estimates are provided in Table J-6. In addition to best-estimate calculations, "low" and "high" estimates are provided. Each of the estimates are assigned a probability; 0.1 for low, 0.8 for best estimate, and 0.1 for high.

The mean annual frequency of the cost exceeding various levels of damage (i.e., dollars) due to ground contamination for the four release categories identified above are shown in Fig. J.1. As indicated in this figure, the costs associated with restoring contaminated land are not significant.

2.2. Tank Replacement

The total cost of tank replacement is equal to the sum of the costs associated with construction of a new tank and the remediation costs associated with the old tank, including transfer of the remaining contents of the old tank to the new tank.

*The radiation survey costs were actually given in 1981 dollars but were treated as 1982 dollars.

TABLE J-6
ESTIMATED GROUND DECONTAMINATION COSTS

DF Range	Method ¹	Cost (1992 \$/m ²)					Cost (1994 \$/m ²)			
		Base Cost for Method ²	Radiation Surveys ³	Hauling ⁴	Cover Hauled Material ⁵	Cost Range	Midpoint of Range	Low (-20%)	Med (Midpoint)	High (+20%) ⁶
1-3.3	L-WWWW	0.052-0.0876	0.237	—	—	0.289-0.325	0.307	0.394	0.492	0.589
3.3-10	WWWW-XG	0.0876-0.681	0.237	—	—	0.325-0.918	0.622	0.797	0.966	1.19
10-33	XG-TNX	0.681-0.85	0.237	0.63-1.26	0.371	1.918-2.72	2.319	2.98	3.71	4.45
33-100	TNx	0.85	0.237	1.26	0.371	2.72	2.72	3.48	4.35	5.22
100-330	TNx	0.85	0.237	1.26	0.371	2.72	2.72	3.48	4.35	5.22
330-1000	TNx-TNxX	0.85-1.16	0.237	1.26-1.89	0.371	2.72-3.66	3.194	4.09	5.11	6.13
1000-3000	TNxX	1.16	0.237	1.89	0.371	3.66	3.66	4.69	5.86	7.03

¹See Fig. 2.5.7, NUREG/CR-3413

²See Table 2.4.4.1, NUREG/CR-3413

³See Table A-1, LANL-3098-DOC-38

⁴See Table 2.4.11.1, NUREG/CR-3413 (10 mi round trip, 6 in. per scraping)

⁵See Table 2.4.4.1, NUREG/CR-3413

⁶Costs escalated at 4%/yr

Fig. J.1.
Remedial cost for ground contamination.

Cost of a New Tank:

The costs associated with the cost of a new tank are based on Ref. 3. This reference divides the costs associated with construction of a double shelled tank farm into the following: (1) technology, (2) design, (3) construction, (4) startup, (5) regulatory compliance, and (6) project management. The estimates were stated to be accurate within plus or minus 30%.

Although no specific definition of "technology costs" was provided, for the purpose of this evaluation, it was assumed that such costs were not appropriate for a "replicated" tank.

Thus, the cost of a new tank can be expressed as follows:

$$\text{Total Cost} = \text{Design Costs} + \text{Construction Costs} + \text{Startup Costs} + \\ \text{Regulatory Compliance Costs} + \text{Project Management Costs.}$$

The design costs discussed in Ref. 3 include conceptual and preliminary design costs. These costs were also deemed to be inappropriate for a replicated tank. The detailed design (\$2 million) and field engineering (\$3 million) costs, however, were considered appropriate for this evaluation.

With the exception of the costs for the ventilation and enclosure buildings and a "discount" for site preparation and restoration, all of the construction costs identified in Ref. 3 were included in this evaluation. It was assumed that 50% of the site preparation and restoration costs were related to the buildings and 50% (\$3 million) to the tank itself. The cost of constructing the tank itself is \$16.5 million. Although it was assumed that no new buildings would be necessary, the entire cost of major equipment (\$5.8 million) was included in this evaluation. All of the construction costs were assumed to be accurate within +/- 30%. Construction management costs were assumed to be 10% of the total of the other costs identified as construction costs.

The full value of the Ref. 3 costs associated with startup (\$2.4 million) and regulatory compliance (\$3.6 million) were included in this evaluation. These costs were also assumed to be accurate to +/- 30%.

Based on the Ref. 3 percentage, the costs associated with project management were assumed to be 2% of all other costs.

The costs discussed above were represented by truncated (the minimum estimate was not allowed to be 20% lower than the median value) lognormal

distributions with the medians set equal to the values tabulated in Ref. 3 and the 90th percentiles set equal to 1.3 times the medians.

A distribution for the total cost of a new tank was generated with the Crystal Ball™ software. The results of this calculation are expressed as a cumulative distribution function as shown in Fig. J.2. This distribution was used as input to the STADIC program to reflect the cost of a new tank.

Remediation Costs Associated With Damaged Tank:

Figure J.2 does not include the costs associated with remediation activities associated with the failed tank and the transfer of its remaining contents to the new tank. To account for such costs, a second distribution (identical to that for the cost of a new tank) was included in the STADIC model.

Although the second distribution had identical parameters, the distribution associated with remediation activities involving the damaged tank was assumed to be completely independent of the costs associated with the new tank. Thus, for any given sample, the total cost was the sum of the independently sampled distributions for the new tank and for remediation of the old tank.

Total Costs:

Figure J.3 shows the CCDFs for the costs associated with replacement and remediation of a damaged tank for Release Categories DCH, DCLLK, and DCVH.

2.3. Cleanup of Contamination Caused by Tank Leaks

The costs associated with the cleanup of contamination caused by tank leaks is based on information supplied in Refs. 4 and 5, and leak size distributions for both large leaks (Release Categories LLK and DCLLK), small leaks (Release Category SLK), and water intrusion/overflow events (Release Category SSP).

The costs associated with leak termination are not included in this measure of economic damage.

Reference 5 states that it would cost \$656,200 to clean up (including excavating, washing, vitrification, temporary storage on site, transportation to a final repository, and backfilling) 500-gal. leak. The estimate for a 100,000-gal. leak is \$9,846,000. An evaluation of these estimates indicates that there is some "economy of scale," and therefore, the cost to process a leak of x gallons could be represented by

$$\text{Total cost (\$) to process X gallons} = A + B * X$$

Fig. J.2.
Cost of a replacement tank. Cost does not include remediation activities associated with damaged tank.

Fig. J.3.
Cost of tank replacement (including activities associated with old tank).

results in $A = \$610,000$ and $B = \$92.36/\text{gal}$. These values were treated as the medians of two probability distributions. For A, the 95th percentile was arbitrarily set at \$1.0 million and for B the 95th percentile was arbitrarily set at \$150/gal.

By definition (see Sec. 5.5.1) Release Category SLK represents leaks of 5000 gal. or less with a mean of 3000 gal. The distribution for small leaks was assumed to be lognormal with a mean of 3000 gal. and the 99.99th percentile equal to 5000 gal. The stated mean value for large leaks (per Sec.5.5.2) is 120,000 gal. The large leak distribution was also assumed to be lognormal with a 90th percentile of 240,000 gal. For Release Category SSP, the mean value of the water intrusion/overflow is taken as 300 gal. (see Sec. 5.5.3) and the "low" value is assumed to be 100 gal. The low value was assumed in this evaluation to correspond to the 20th percentile.

Figure J.4 displays the economic risk CCDFs associated with the release categories involving leaks and water intrusion/overflow.

2.4. Ventilation System Repair

A number of the release categories involve onsite (i.e., the immediate vicinity of the tank) contamination and possibly damage to the ventilation system but not tank failure or leakage. The degree of damage resulting from hydrogen burns is extremely difficult to estimate and therefore, the costs associated with the repair of such damage are even more difficult to estimate. For Release Categories HEPAL and HEPAH (both of which involve hydrogen burns), the cost of ventilation system repair was represented by the sum of lognormal distribution for equipment replacement (identical to that for "major equipment" in the tank replacement algorithm) and a lognormal distribution for cleanup/contamination of the equipment and area affected by the event. The lognormal distribution for new equipment had a median value of \$5.8 million and an error spread of 1.3. The assumed lognormal distributions for cleanup/decontamination had median values of \$5.0 million for Release Categories HEPAL and HEPAH and \$1.0 million for Release Category BPL. An error spread of 2.0 was used for both of these distributions. Since Release Category BPL did not involve a hydrogen burn, only its distribution for onsite cleanup/decontamination was considered.

Figure J.5 shows the CCDFs for this measure of economic damage for Release Categories BPL, HEPAL, and HEPAH.

Fig. J.4.
Remediation of contamination caused by tank leaks.

Fig. J.5.
Cost of ventilation equipment replacement repair.

3.0. RELEASE CATEGORY TOTAL COSTS

Figures J.6 through J.12 show the total economic risk, in terms of CCDFs for the mean annual frequency of exceeding various damage levels for all of the release categories.

As shown in Fig. J.10, the cost associated with remediating ground contamination is only "significant" for Release Category DCVH. Since this release category has a mean annual frequency of occurrence of approximately 3.1×10^{-9} /yr, one can conclude that ground contamination is not a major concern for accidents associated with Tank 101-SY.

The release category totals are also shown in Fig. J.13.

4.0. TOTAL ECONOMIC RISK FOR ALL RELEASE CATEGORIES

The total economic risk for Tank 241-SY-101 accidents represented by the release categories discussed above is shown in Fig. J.13. Based on current interpretations of existing remediation cost data and assuming that remediation would be required and performed, the economic consequences of Tank 101-SY accidents could be substantial (more than \$100 million at a frequency greater than 1×10^{-4} /yr). The results displayed in Fig. J.13 for damage levels less than approximately \$20 million are dominated by Release Category HEPAL, which in turn, is dominated by the costs associated with replacement and decontamination of the ventilation system and equipment. The mean frequency of Release Category HEPAL is approximately 1.2×10^{-1} per year. Therefore, it is not surprising that this release category dominates the low end of the CCDF for total costs.

In the damage level range of approximately \$20 to \$130 million, Release Category DCH (mean annual frequency of 6.7×10^{-4} /yr) is the major contributor, indicating the significance of the costs associated with the construction of a new tank and remediation of the damaged tank. Beyond \$130 million and at frequencies less than approximately 5×10^{-6} /yr, Release Category DCLK appears to be the dominant contributor. This release category involves activities associated with the remediation of a large leak as well as tank damage.

REFERENCES

1. J. J. Tawil et al., "Off-Site Consequences of Radiological Accidents: Methods, Costs and Schedules for Decontamination," prepared by the Pacific Northwest Laboratory for US Nuclear Regulatory Commission, NUREG/CR-3413 (August 1985).

Fig. J.6.
Total cost - BPL.

Fig. J.7.
Total cost - HEPAL.

Fig. J.8.
Total cost - HEPAH.

Fig. J.9.
Total cost - DCH.

Fig. J.10.
Total cost - DCVH.

Fig. J.11.
Total cost - DCLLK.

Fig. J.12.
Total cost - SLK, LLK, SSP.

Fig. J.13.
Total for all release categories.

2. "Supplementary Documentation for an Environmental Impact Statement Regarding the Pantex Plant, Decontamination Methods and Cost Estimates for Postulated Accidents," Los Alamos National Laboratory report LA-9445-PNTX-N (December 1982).
3. M. Butner, Los Alamos National Laboratory unnumbered memo (May 21, 1993).
4. "Draft Environmental Impact Statement (EIS) for Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes," Department of Energy Report DOE/EIS-0113 (March 1986).
5. M. Butner, Los Alamos National Laboratory unnumbered memo (April 15, 1993).