CONF-9507140--1

LA-UR-95-1759

TITLE: HAZARDS AND ACCIDENT ANALYSES, AN INTEGRATED APPROACH, FOR THE PLUTONIUM FACILITY AT LOS ALAMOS NATIONAL LABORATORY

AUTHOR: Paul Y. Pan, Los Alamos National Laboratory, Los Alamos NM 87544
Lawrence K. Goen, Los Alamos National Laboratory, Los Alamos NM 87544
Bruce C. Letellier, Los Alamos National Laboratory, Los Alamos NM 87544
M. Kent Sasser, Los Alamos National Laboratory, Los Alamos, NM 87544

SUBMITTED TO: 1995 13th International System Safety Conference
July 12-16, 1995
San Jose, California

LOS ALAMOS NATIONAL LABORATORY

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Paul Y. Pan, Los Alamos National Laboratory, Los Alamos, NM 87544
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M. Kent Sasser, Los Alamos National Laboratory, Los Alamos, NM 87544

Abstract

This paper describes an integrated approach to perform hazards and accident analyses for the Plutonium Facility at Los Alamos National Laboratory. A comprehensive hazards analysis methodology was developed that extends the scope of the preliminary/process hazard analysis methods described in the AIChE Guidelines for Hazard Evaluations. Results from the semi-quantitative approach constitute a full spectrum of hazards. For each accident scenario identified, there is a binning assigned for the event likelihood and consequence severity. In addition, each accident scenario is analyzed for four possible sectors (workers, on-site personnel, public, and environment).

A screening process was developed to link the hazard analysis to the accident analysis. Specifically, the 840 accident scenarios were screened down to about 15 accident scenarios for a more thorough deterministic analysis to define the operational safety envelope. The mechanics of the screening process in the selection of final scenarios for each representative accident category, i.e., fire, explosion, criticality, and spill, is described.

A seismic risk assessment was performed to quantitatively evaluate the source term for seismic-induced hazards. A more stringent set of siting criteria were developed because of more recent regulatory requirements. The methodology and groundrules developed in the seismic risk assessment are described.

1.0 Hazards Analysis

A hazard analysis (HA) methodology was developed that extends the scope of the preliminary and process hazard analysis methods described in the American Institute of Chemical Engineers (AIChE) report* to provide the details necessary for the Final Safety Analysis Report (FSAR) accident screening process. To be of value for the FSAR accident analysis, estimates of frequency and consequences for each accident scenario, were developed. The HA methodology was developed to consider various possible sectors (workers, on-site personnel, public, and environment) rather than the single public receptor historically considered in an FSAR.

The HA is a semi-quantitative method that identifies a broad range of potential hazards, accident scenarios, and their estimated frequency and consequences. Detailed quantitative analyses require an expenditure of large resources to develop detailed facility and system models and to conduct consequence and uncertainty analyses. Conversely, the HA is more cost effective and was conducted initially to screen out those hazards that are of least concern to overall risk, either due to their low consequences or low frequency of occurrence. A multidisciplinary team of senior technical personnel was assembled to conduct this study. The team included specialists in nuclear and chemical engineering,

* *Guidelines for Hazard Evaluation Procedures*, 2nd Edition with Worked Examples, AIChE, 1992.

process chemistry, risk analysis, environmental engineering, human reliability, and facility operations staff.

Methodology

The HA methodology was developed as a systematic approach to identify hazards associated with a process and to assess qualitatively, or semi-quantitatively, the risk of those hazards.

The purpose of performing an HA is to answer the following questions:

- What can happen?
- How likely is it (frequency estimate)?
- What is the damage (consequence estimate)?

HA is a formal, systematic, and in-depth method for assessing the entire set of possible accident scenarios for a given facility. Frequency estimates of occurrence for all scenarios are assessed along with estimates of the damage level. To be consistent with the passive safe shutdown philosophy at the Plutonium Facility, the ground rule of the HA was set that no credits would be taken for active protection systems. Each accident scenario is assigned a "risk rank" based on the estimates of the frequency of occurrence and the consequence severity level.

HA Preparation: This task identifies the information sources from such as flow sheet inventories, maximum historical inventories, vessel sizes, contamination analyses, etc. The interpretation of the data used to derive conservative inventory values also needs to be provided.

Information that is necessary to perform the HA for a maintenance, material handling, or utility activity includes: process system and facility design data, process and system descriptions, hazard studies on similar processes, incident histories, and other empirical information. Throughout the HA, this is supplemented with input from subject matter experts involved with facility, process, or maintenance operations.

A thorough understanding of basic process and facility operation information is necessary. The chemicals involved in any step of a process must be identified. In addition, data are required for various batch processing steps and applicable process parameters including pressure and temperature, as well as information on reactants and products, chemical reaction kinetics, and chemical impurities. Major equipment, safety-related equipment, and component interfaces must be noted. Knowledge of the operating environment (that is, earthquakes, winds, flooding, and transportation systems) provides insight into potential hazards and guidance on how to reduce the risk. Existing or draft procedures relating to operation, maintenance, inspection, and emergencies are also required. A facility layout drawing places the process in the context of other processes and the external surroundings.

HA team members collected or developed, as needed, the documentation for each process or system to be reviewed. This documentation included process design specifications, equipment drawings and specifications, drawings showing locations of equipment, process or activity descriptions, and procedures. Process block diagrams were developed from the collected process information. These diagrams define sequences of discrete or multiple processing steps. In addition, a glovebox database was developed. The information included description of process or operation, materials in the glovebox (type, form, inventory), energy sources, potential hazards, inventory limits, and procedures.

The HA team primarily consisted of an HA team leader, a facilitator, an HA scribe, one or more Laboratory staff members (i.e., full-time team members), and one or more process engineers, process specialists, or technicians who are intimately familiar with the activity or system being reviewed.

Training and Information Gathering: Before the HA sessions, full-time team members who had not previously participated in an HA were given a half-day training session on the methodology by the HA facilitator. This half-day course is designed to introduce course participants to the HA approach, which forms the basis for evaluating process designs and procedures. In addition, a brief HA orientation was conducted during the first day of each series of HA sessions in order to orient part-time participants. Topics included:

- Method of conducting the HA;
- Schedule for the HA;
- Processes, systems, or activities within the facility to be evaluated during that session;
- Hazards present in each section of the process, design, and operating conditions;
- Identification and recording of recommendations;
- Assignment of likelihood and severity rankings for consequences so that all significant hazards can be listed in an ordered ranking; and
- Resolution of recommended actions.

HA Process: The principal steps to be followed in performing an HA are described below:

- Identify processes and equipment to be analyzed and construct process block diagrams. The facilities, utility systems, processes, and equipment analyzed in an HA are identified based on a review of the facility organization and mission and on discussions among the HA team members. Process block diagrams depicting the relevant processing, handling, and storage steps are prepared and reviewed by the HA team members. The process block diagrams are organized into study segments or "activities" to facilitate the HA process.

- Examine each activity for possible hazards and assess impacts. An HA focuses on the identification of accident scenarios by asking the fundamental question, "What can go wrong?" For each activity, a predefined set of possible hazards is reviewed for applicability. For example, the question, "What happens if there is a spill?" is considered for each activity where applicable. If the HA team agrees that the spill does create a problem, then the team assesses the problem in terms of its consequences, causes, and expected frequency of occurrence.

- Assign hazard severity category, frequency, and risk ranking. For those accident scenarios that pose potential problems with consequences, causes, and/or expected frequency of occurrence, a qualitative assessment of risk is performed using team consensus judgment and predefined criteria. Specifically, Figures 1 and 2 present a summary of the criteria used to select consequence severity ranking and frequency ranking for those hazard scenarios considered to have significant consequence or frequency. Using these severity and frequency rankings, Figure 3 then presents the risk-ranking matrix that is used to assign a qualitative risk measure to each significant accident scenario.

- Assignment of recommended actions. The team agreed to develop consensus recommendations for reducing risks for any risk rank 1 or 2 scenarios. Optionally, in some cases, actions also are listed for risk rank 3 and 4 scenarios.

  This task identifies the higher vulnerability scenarios that facility management should first evaluate and then take further action to reduce facility risk. For example, a risk rank 1 or 2 scenario would be a candidate for immediate actions. Risk rank 3 and 4 scenarios involve optionally recommended actions that may represent good practices for consideration.

After all of the accident scenarios are identified, the results are organized by risk, consequence severity, and/or frequency of occurrence. Each ranking parameter provides a unique perspective on how hazards impact the process being studied. These results serve as the basis for determining if a more detailed, quantitative risk assessment of one or more accident scenarios is required to better assess the risk of possible on- or off-site consequences associated with selected hazard scenarios.

Category	Maximum Possible Consequences			
	Public	Co-Located	Worker	Environment
A	• Immediate health effects.	• Immediate health effects.	• Loss of life.	• Significant off-site contamination requiring cleanup.
B	• Long-term health effects.	• Long-term health effects.	• Severe injury or disability. • Radiation > MPBB uptake.	• Moderate-to-significant on-site contamination. • Minor off-site contamination.
C	• Irritation or discomfort but no permanent health effects.	• Irritation or discomfort but no permanent health effects.	• Lost-time injury but no disability. • Radiation uptake or dose causing temporary radiation worker restriction.	• Significant contamination of originating facility. • Minor on-site contamination. • No off-site contamination.
D	• No significant off-site impact.	• No significant off-site impact.	• Minor or no injury and no disability.	• Minor or no contamination of originating facility. • No on-site contamination. • No off-site contamination.

Figure 1. Consequence severity categories.

Frequency Ranking	Description of Frequency Ranking
I (1 to 0.1 /yr)	**Normal Operations:** frequency as often as once in 10 operating years or at least once in 10 similar facilities operated for 1 year.
II (0.1 to 0.01 /yr)	**Anticipated Events:** frequency between 1 in 100 years and one in 10 operating years or at least once in 100 similar facilities operated for 1 year.
III (10^{-2} to 10^{-4} /yr)	**Unlikely:** frequency between 1 in 100 years and 1 in 10,000 operating years or at least once in 10,000 similar facilities operated for 1 year.
IV (10^{-4} to 10^{-6} /yr)	**Very Unlikely:** frequency between 1 in 10,000 years and once in 1 million years or at least once in a million similar facilities operated for 1 year.
V ($<10^{-6}$ /yr)	**Improbable:** frequency of less than once in a million years.

Figure 2. Consequence likelihood categories.

	V	IV	III	II	I
Consequence Level A (High)	Review Only (3)	(3)	(2)	(1)	(1)
Consequence Level B	Review Only (4)	(3)	(2/3)*	(2)	(1)
Consequence Level C	(4)	(4)	(3)	(3)	(2)
Consequence Level D (Low)	(4)	(4)	(4)	(4)	(3)

Frequency

* Assign 3 for workers and 2 for other sectors.

Figure 3. Generic risk matrix with Stage 1 risk review region shaded.

2.0 Accident Scenarios Selection

An accident selection process was developed that 1) considers accidents during normal and abnormal operating conditions, 2) considers both design basis and beyond design basis accidents, 3) characterizes accidents by category (operational, natural phenomena, etc.) and by type (spill, explosion, fire, etc.), and 4) identifies accidents that bound all foreseeable accident types. The accident selection process described here is considered applicable to all types of DOE facilities.

The screening process consists of three stages. The first two stages are mechanical and are based on the initial placement of the HA scenarios into a risk matrix (Figure 3) according to their qualitative frequency and consequence designations. The risk rank assignments in each cell of the matrix form the basis for prioritizing among similar scenarios that might be appropriate representative accidents for quantitative analysis. Risk rank definitions provided in Figure 4 conform to standard industrial safety practice, but they may be changed to suit a particular location or facility. These definitions of relative risk must be stated before scenario screening can proceed.

Risk Level	Recommendation
1	Should be mitigated to risk rank 3 or lower as soon as possible.
2	Should be mitigated to risk rank 3 or lower within a reasonable time period.
3	Verify that procedures, controls, and safeguards are in place.
4	No action necessary.

Figure 4. Risk rank definitions.

Stage 1, performed solely to facilitate manual screening of a large number of scenarios, removes from preliminary consideration all scenarios below an arbitrarily defined risk review region. The risk review region shown as the shaded cells in Figure 3 was defined to exclude incidental events that are expected during normal operation, but to include high frequency (I), moderate consequence (C) events which may indicate facility or procedural deficiencies that warrant further attention. Levels C (except CI) and D were also excluded because it was unlikely that sufficiently bounding events would be found with low to moderate consequences. Approximately 140 of the HA scenarios lie in the risk review region.

The objective of Stage 2 screening is to retain at least one entry for each sector of each accident type that is present in the risk matrix. This objective is achieved by prioritizing similar scenarios according to the following selection rules:

- Retain the highest risk scenario(s) of each accident type,
- For scenario(s) of equal risk, retain those of highest consequence,
- For scenario(s) of equal risk and equal consequence, retain those of highest frequency,
- If this process selects an improbable event (frequency V), retain for review, but also select the next most dominant scenario(s) identified by the prioritization.

Implement these rules methodically by scanning each matrix from top (high consequence) to bottom (low consequence) and from right (high frequency) to left (low frequency) noting the occurrence of each accident type. For the Plutonium Facility, this step results in a set of 48 scenarios.

The Stage 3 process of selecting final scenarios for detailed quantitative analysis is both mechanical and judgmental in nature. The mechanical part is enforced by the following selection rule: Choose at least one scenario for each sector and accident type combination that remains.

Judgment is needed for cases where more than one scenario is present for a given sector and accident type combination. Judgment is also needed in cases involving scenarios with frequency V (<1.0E-6/yr).

Additional information from plant walk-downs and professional input from process technicians and specialists such as criticality or fire safety personnel may be required to choose the most appropriate representative accident scenarios for detailed analysis, so the rationale for screening or retaining each Stage 2 scenario should be carefully documented. If the HA was comprehensive, some scenarios such as external floods, air-craft crash or nuclear materials accountability may be referred to existing safety or security documentation for resolution rather than being carried through quantitative accident analysis. Some HA scenarios may be too generic to define a meaningful accident sequence, so interaction with the original HA team members may also be required.

Following Stage 3, some assessment of the final accidents should be conducted to ensure completeness. Approximately 15 final scenarios were chosen for the FSAR including the following major accident types: criticality, explosions involving radionuclides, fires involving radionuclides, chemical releases, radiological releases, and seismic events. This range of accidents was deemed sufficient for describing the operational activities. However, if some accident type appears to be missing from the final selection for a particular facility, then the screening for that accident type should be repeated with a more inclusive risk review region at Stage 1. While each scenario was chosen for the highest risk it posed to any one evaluation category, secondary concerns for the other categories will also be addressed during quantitative analysis.

No single prescription for accident selection exists that will satisfy every safety review board. However, the combined scrutiny of a facility wide HA and a methodical selection process provide a very satisfactory framework for documenting the safety analysis process. Some observations regarding the effectiveness of this method include:

- Additional hazards that may be identified can be evaluated in a logically consistent manner.
- Final scenarios are directly linked to facility specific hazards identified in the HA.
- Redundant selection rules give each scenario multiple opportunities for being chosen.
- Risk prioritization is appropriate for defining the facility safety envelope, but additional moderate risk accidents may be needed to adequately specify safety significant structures, systems, and components
- Mechanical selection of large data bases can easily be automated.
- The definition of mechanical selection rules, particularly frequency vs. consequence risk ranking, encourages logical and effective broad screening and minimizes personal bias from later stages.

3.0 Seismic Risk Assessment

The Plutonium Facility was designed and constructed to withstand the site specific seismic criteria developed by Dames and Moore in 1972. Since then, rules and regulations have changed in the seismic evaluation of DOE nuclear facilities. Specifically, LANL initiated a seismic evaluation for the Laboratory site in 1993, and results indicate that siting criteria will be more conservative than those used in the original design.

In addition, LANL has performed a seismic hazards analysis, a seismic margins analysis, and a seismic evaluation basis analysis. For the seismic hazards analysis, a walkdown was performed and capacities of risk-related components including gloveboxes and some system components were identified. The seismic hazards associated with these components were qualified and ranked using the risk categorization schemes developed by the HA team.

Results from the preliminary seismic hazard analysis are

- All components have risk ranks of 3 or 4.
- The total amount of material released will be insignificant.
- Given the lower seismic event at a peak ground acceleration of 0.1 *g* (400-yr return period), only one or two boxes might fail and the release would be localized.
- Given a moderate seismic event at a peak ground acceleration of 0.4 *g* (14,000-yr return period), perhaps as many as half of the boxes will fail. However, because of the high resistance of the building confinement, no significant release to the environment is predicted.

Following the preliminary seismic hazard analysis, LANL started a seismic margins analysis for the components that the FSAR team determined to be candidates for either safety class or safety significant structures, systems, and components (SSCs). The product of the seismic margins analysis is the high-confidence/low-probability failure (HCLPF) capacities for seismically vulnerable components.

The seismic risk assessment is a continuation of the seismic margins analysis with an objective to identify the source term for the Plutonium Facility under an evaluation basis earthquake, i.e., 0.3*g*.

Methodology

Boundary Conditions:

Based on the seismic margins analysis, most of the plant safety-related systems would lose their safety functions from the impact of a postulated 0.3 *g* earthquake. The seismic margins analysis shows that the HCLPF capacities of safety-related systems are all under 0.15 *g*. As a result, no credit can be taken for any systems to suppress fires induced by the earthquake. In addition, the HCLPF capacities of the HVAC exhaust plenums and ductwork are also lower than or equal to 0.2 *g*. The probability of losing theses systems during a 0.3 *g* is high. Consequently, no credit was taken for the exhaust filtration in the leak path factor calculation.

The seismic margins analysis, however, shows that the Plutonium Facility building has HCLPF capacities well above 0.3 *g*, indicating no building structure failure would be present. As a result, the only unfiltered leak paths would be through exterior door cracks and building penetrations, assuming that the leakage through the damaged exhaust plenums and stacks is minimum.

Basic Equation:

The basic equation to determine the source term is

$$S = \sum_i S_i = \sum_i CFP_i * MAR_i * DR_i * ARF_i * RF_i * LPF_i \qquad (1)$$

where

S_i is the source term for the ith glovebox/tank, g
CFP_i is the conditional failure probability for the ith glovebox/tank at 0.3 *g*,
MAR_i is the material at risk for the ith glovebox/tank, g
DR_i is the damage ratio for the material in the ith glovebox/tank,
ARF_i is the airborne release fraction for the material from the ith glovebox/tank,
RF_i is the respirable fraction for the material from the ith glovebox/tank, and
LPF_i is the leak path factor for the material from the ith glovebox/tank to leak outside.

Each of the parameters is determined as follows:

1. Conditional Failure Probability, CFP

Fragility curves for SSCs have been estimated from the results of the seismic margins analysis. The HCLPF capacities were determined using the conservative deterministic failure margin (CDFM) methodology and represent a 1 - 2 percent probability of failure for the structures, systems, and components (SSCs) evaluated. The 1 - 2 percent probability of failure is dependent upon the ground motion being defined such that there is an 84 percent probability that the motion will not be exceeded at any frequency (of the response spectrum defining the earthquake).

For development of fragility curves used in seismic probabilistic risk assessments, ground motion is typically defined at the 50 percent (median) non-exceedance probability. To achieve the same probability of failure for the median ground motion, the HCLPF capacity at the 84 percentile ground motion must be modified. Reference document by Kennedy and Reed, "Fragility Evaluation for Nuclear Power Plant Seismic Probabilistic Safety Assessments - A Utility Training Course" (Section K14), Electric Power Research Institute, Palo Alto, California, October 1993, suggests:

$$HCLPF_{50} = \frac{HCLPF_{84}}{1.2} \quad (2)$$

For purposes of determining the median capacity of the component, the same reference suggests:

$C_{1\%} = HCLPF_{50}$ where $C_{1\%}$ is the capacity at the 1% conditional failure probability.

$$C_{50\%} = C_{1\%} e^{X_{1\%}\beta} \quad (3)$$

$X_{1\%} = 2.326$ where $X_{1\%}$ is the factor associated with the failure probability of 1% for the standard normal distribution.

$0.3 \leq \beta \leq 0.5$ where ß is the composite variability due to randomness and uncertainty. For this seismic study, ß = 0.4 is selected.

The conditional failure probability, CFP, at a ground motion level of 0.3 *g* can be determined from:

$$CFP = \Phi\left(\frac{\ln\left(\frac{0.3}{C_{50\%}}\right)}{\beta}\right) \quad (4)$$

where Φ is the standard normal cumulative distribution function.

2. Material at Risk, MAR

The material at risk is the amount of radionuclides available to be acted on by the earthquake. For the Plutonium Facility, the criticality limit for each glovebox or pressure vessel was used. The criticality limits were used for the MAR to provide a bounding case, considered overly conservative because the criticality limit does not represent the plant operational configuration. Other major assumptions made in the MAR determination are included as follows:

- The highest quantity is chosen for a glovebox or pressure vessel when multiple forms of material are processed.
- No MAR is considered for gloveboxes designated as inactive, to be operational, to be removed, or pass through.
- MAR is chosen for Pu if both Pu and U are present and no distinction in mass limits is made between the two.

- No tritium MAR is used, based on dose conversion factor considerations

3. Damage Ratio, DR

The damage ratio is the fraction of the MAR actually impacted by the earthquake. Major assumptions are made that the damage ratios are zero when the MAR is encapsulated, contained in a safe, or in any other confinement configuration. Otherwise, the damage ratio is designated as unity.

4. Airborne Release Fraction/Respirable Fraction, ARF/RF

The airborne release fraction is the coefficient used to estimate the amount of a radioactive material suspended in air as an aerosol and thus available for transport. The respirable fraction is the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system. The respirable fraction is commonly assumed to include particles 10 μm aerodynamic equivalent diameter and less.

Standard DOE guidelines were used to determine the ARF/RF. However, because of the nature of the diverse R&D activities, additional assumptions were made as follows.

- If the data sheet for the glovebox indicates any (or no) forms, or no restrictions, and/or if either powder or oxide is present, use powder's ARF/RF of 1E-3/0.1.
- If the data sheet for the glovebox indicates any form (except powder), use the process state to determine the ARF/RF: i.e., use 2E-4/0.5, if liquid; or use 3E-5/0.04 if metal, or use 0/0 (insignificant) for anything else.
- If the data sheet for the glovebox shows furnaces (or crucibles), or molten metal, are present, use 1E-2/1.
- If the data sheet for the glovebox shows pyrophoric metal self heating (no ignition), use 3E-5/0.04 (bound).
- If the data sheet for the glovebox indicates rags (Pu-238), use 1E-2/1.
- If the data sheet for the glovebox indicates particle size greater than 10 micron, use 0/0.
- If the data sheet for the glovebox indicates nonmetallic compound, use 0/0 if solid, use 2E-4/0.5 if liquid, or use 1/1 if gas.

5. Leak Path Factor, LPF

The leak path factor is the fraction of the radionuclides in the aerosol transported from the source area to the outside atmosphere via diffusion/convection mechanisms. Given a 0.3 *g* earthquake, the building structure will remain intact because of its high HCLPF capacity of at least of 0.44 *g*. The intake valves also remain functional for their HCLPF capacities of 0.3 *g*. However, the exhaust plenums and the exhaust fan bases as portions of the passive shutdown would fail because of their lower HCLPF capacities of 0.2 *g* (20% failure probability) and 0.12 *g* (66% failure probability) respectively. As a result, the building would not be able to breathe through the exhaust plenums at a 0.3 *g* earthquake and no credit was taken from the filtration function for the LPF.

An earlier seismic evaluation in the DOE Safety Survey indicates that, at a 0.5 *g* earthquake, use of 1% LPF would bound. The 1% LPF is consistent with the building leak factor from the bounding fire analysis. Therefore, 1% is selected for the LPF.

4.0 Conclusion

The core of a facility safety analysis is the hazards/accident analysis that defines the technical safety requirements for safe operations. The methodology developed for the Plutonium Facility uses an approach that integrates the hazards analysis and accident analysis: the hazards analysis creates a full spectrum of facility hazards; the screening process determines the most bounding accidents for internal/external events; and the seismic risk analysis ensures the ultimate protection requirements for safe operations.

Biography:

Paul Y. Pan, MS K489, Los Alamos National Laboratory, Los Alamos, NM 87544

Dr. Pan has more than 16 years experience in nuclear safety and risk assessment. He has worked on nuclear facilities including nuclear material processing facilities, nuclear reactors including power, research, and production, and waste storage and processing facilities.

Lawrence K. Goen, MS P946, Los Almos National Laboratory, Los Alamos, NM 87544

Mr. Goen has more than 14 years experience in the analysis and design of structures, systems, and components to resist seismic induced forces. He has worked on both non-nuclear and nuclear facilities including projects at Los Alamos, Rocky Flats, and Hanford.

Bruce C. Letellier, MS K557, Los Alamos National Laboratory, Los Alamos, NM 87544

Mr. Letellier has 5 years of experience in probabilistic consequence assessment, specializing in the phenomenology of postulated accident scenarios involving nuclear weapons. This background has more recently been applied to accident selection and consequence analysis for safety studies of DOE facilities using special nuclear materials.

M. Kent Sasser, MS K557, Los Alamos National Laboratory, Los Alamos, NM 87544

Mr. Sasser has 19 years experience in performing probabilistic risk analysis, safety analysis, human reliability analysis, conduct of operations, and accident investigation/root cause analysis for the defense nuclear facilities (11 years) and for the commercial nuclear industry (8 years).